

# report

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## Environmental Impacts of Marine SO<sub>2</sub> Emissions





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## ABSTRACT

This report details work that was carried out to study the impact of emissions from international shipping on air quality, with a focus on sulphur dioxide (SO<sub>2</sub>) emissions. Emission inventories are discussed and put into perspective versus emissions from natural sources. Air quality modelling tools have been used to assess impacts on air quality in EU countries as a function of distance from shore of shipping emissions. This work demonstrates that, compared to further land based emission reductions, it is generally not cost-effective to reduce emissions from shipping outside of coastal zones. Options to reduce fuel sulphur levels as a route to mitigate SO<sub>2</sub> emissions from international shipping are compared with the use of on board techniques to remove SO<sub>2</sub> from the exhaust gas stream. Finally the likely climate impact of such mitigation actions are assessed.

## KEYWORDS

Marine, bunker, emissions, sulphur, SO<sub>2</sub>

## INTERNET

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## SUMMARY

This report details work that was carried out to study the impact of emissions from international shipping on air quality, with focus on sulphur dioxide (SO<sub>2</sub>) emissions.

SO<sub>2</sub> emissions are of concern because of their potential harmful effects to human health and the environment. Emissions from land based sources and shipping are regulated. In Europe, there has been a significant reduction in land based SO<sub>2</sub> emissions from the 1990s, outstripping the reduction of SO<sub>2</sub> from shipping. As a result, emissions from international shipping in European waters now represent a larger fraction of the remaining emissions. At the global level, international shipping currently represents about 10% of man-made SO<sub>2</sub> emissions. Natural sources of atmospheric sulphur are also significant, e.g. volcanoes. Emissions of dimethyl sulphide from biomass in the world's oceans are particularly relevant. As an example, it is anticipated that in 2020 in the European sea areas there will be significantly more SO<sub>2</sub> originating from biomass than from shipping emissions.

Regulations on fuel sulphur content from the International Maritime Organisation have mandated the use of low sulphur fuels in so-called Emission Control Areas (ECAs). Further emission reductions have been agreed and will result in a global sulphur cap of 0.50% starting in 2020. Apart from using low sulphur fuels, ship operators will have the option to use alternative fuels such as LNG or to make use of an exhaust gas cleaning system (scrubber) to achieve equivalent SO<sub>2</sub> emissions while continuing to use higher sulphur fuels.

The impact of SO<sub>2</sub> emissions from maritime transport to SO<sub>2</sub> concentrations on land is a strong function of the distance from shore. To illustrate this, data obtained by the MATCH model has been analysed to determine how the sulphate related fine particulate matter concentrations on land get reduced as the emission occurs further away from shore. On the basis of the potency of emissions thus derived, Concaawe's in-house Integrated Assessment Tool has been used to estimate air quality impact reductions on European populations by reducing SO<sub>2</sub> emissions in coastal zones varying in width from 12 to 200 nautical miles. This work demonstrates that, compared to further land based emission reductions, it is generally not cost-effective to reduce emissions from shipping outside of coastal zones.

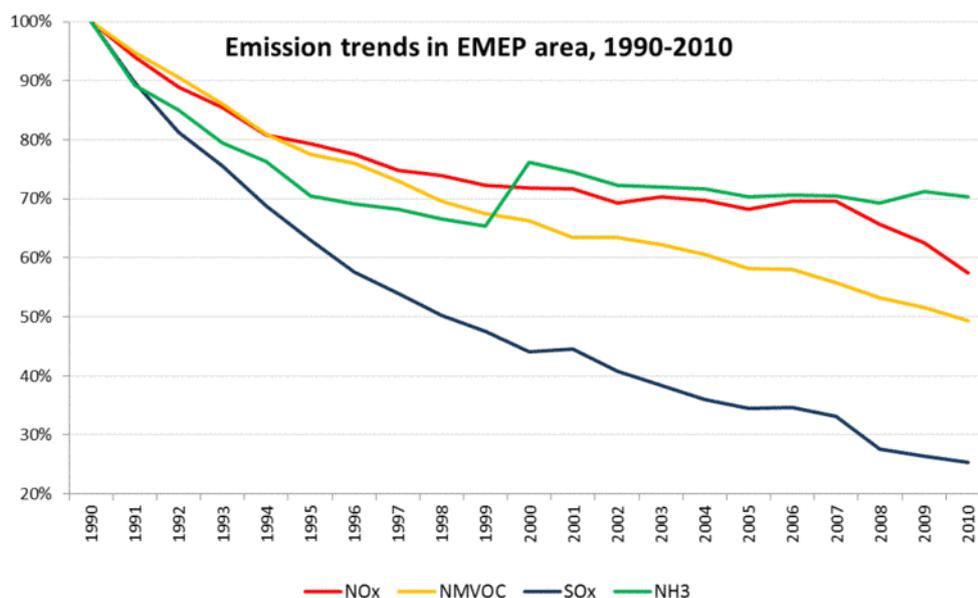
The report also considers the greenhouse gas and climate impacts of shipping emission regulations. The production of fuels with lower sulphur will lead to increased CO<sub>2</sub> emissions from the refining industry. Making use of on-board scrubbers will result in lower overall CO<sub>2</sub> emissions versus desulphurisation of fuels in refineries. Furthermore there is an impact on short-lived climate forcing related to the cooling effect of sulphate aerosols. Due to this effect, emissions from international shipping have a net cooling effect on a 20+ year horizon. This cooling effect will be largely eliminated with the introduction of the lower global sulphur limit in 2020.

# 1. INTRODUCTION

## General Background & Objectives

SO<sub>2</sub> emissions are of concern because of their potential harmful effects to human health and the environment. Since the 1990's land based emissions of the main pollutants (SO<sub>2</sub>, NO<sub>x</sub>, NH<sub>3</sub>, VOC) contributing to one or more effects (acidification, eutrophication, ground-level ozone and secondary aerosols) have been reduced substantially (**Figure 1**). In particular for SO<sub>2</sub>, emission reductions from land-based sources have been very substantial. Since a number of years attention at the European and global level has also focussed on emissions from international shipping [1].

**Figure 1** Twenty year emission reductions for SO<sub>x</sub> and other pollutants, from European Monitoring and Evaluation Programme (EMEP, 2013)



This report aims to contribute scientific information to the debate. The specific objectives of this report are to:

- Provide a brief overview of marine SO<sub>2</sub> emissions and place these into context of global and European emissions from all sources;
- Explore the contribution of international shipping SO<sub>2</sub> emissions to air quality concerns on land;
- Provide an overview of potential routes to compliance with international regulations governing international shipping;
- Explore the relationship between air emissions policy and climate impacts.

### **Technical Background**

Combustion of fuels containing sulphur leads to emissions of sulphur oxides. Most sulphur oxides will be in the form of SO<sub>2</sub>, but a small fraction (typically 2-4% after the engine) of the release may be in the form of SO<sub>3</sub> [2]. For this reason, sulphur oxide emissions are often referred to as SOx emissions, to indicate the total sulphur oxides emissions. SOx emissions can be estimated accurately on the basis of the sulphur content of the fuel and are expressed in SO<sub>2</sub> weight equivalent.

Once released to the atmosphere, SO<sub>2</sub> will readily be absorbed by water droplets and will be oxidized to SO<sub>3</sub>, leading to the formation of sulphate, SO<sub>4</sub><sup>2-</sup> and sulphate aerosols. The ultimate fate of SO<sub>2</sub> is formation of sulphate salts, which may deposit on land or over the oceans. The average lifetime of SO<sub>2</sub> in the atmosphere before conversion is of the order of days [3]. These atmospheric transformation mechanisms are incorporated into the air quality models used to assess the impact of emissions.

Air quality models are used broadly to assess impacts of emissions and explore potential impact of regulatory measures under consideration. This report refers to modelling work by various European research institutes. In addition some specific modelling work has been undertaken using Concaawe's in-house model, SMARTER, developed and maintained by Aeris Europe.

A technical introduction to air quality modelling in the policy development context is provided in **Appendix 3**.

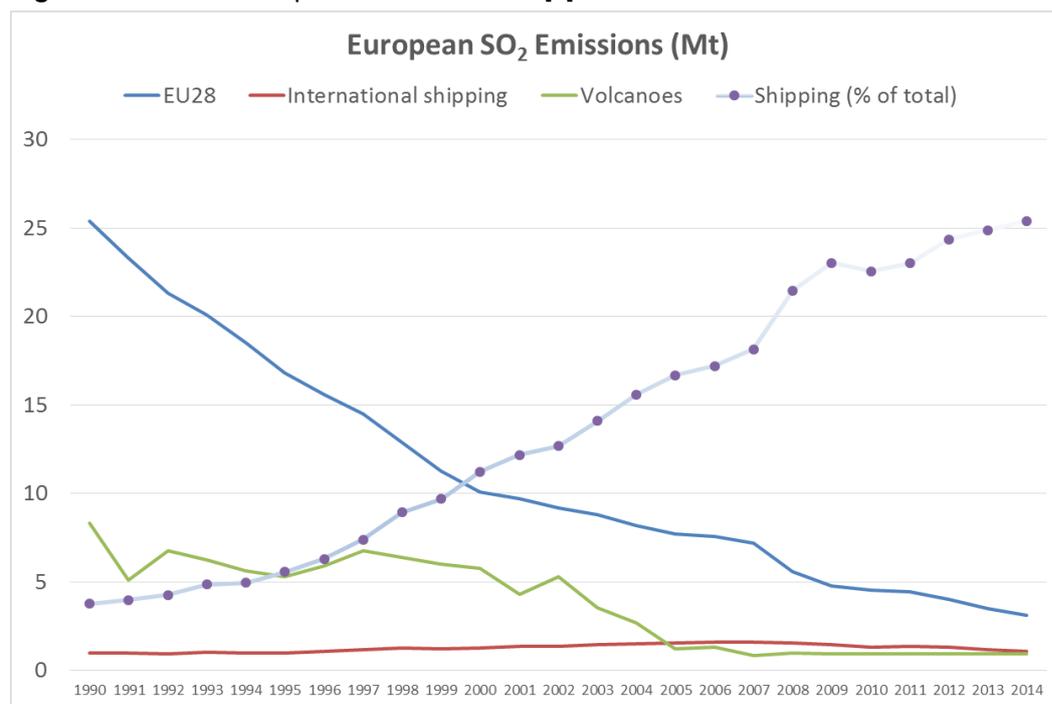
Furthermore reference is made to a number of relevant scientific articles and technical publications.

## 2. SHIPPING EMISSIONS INVENTORIES (SO<sub>2</sub>)

### 2.1. EUROPE

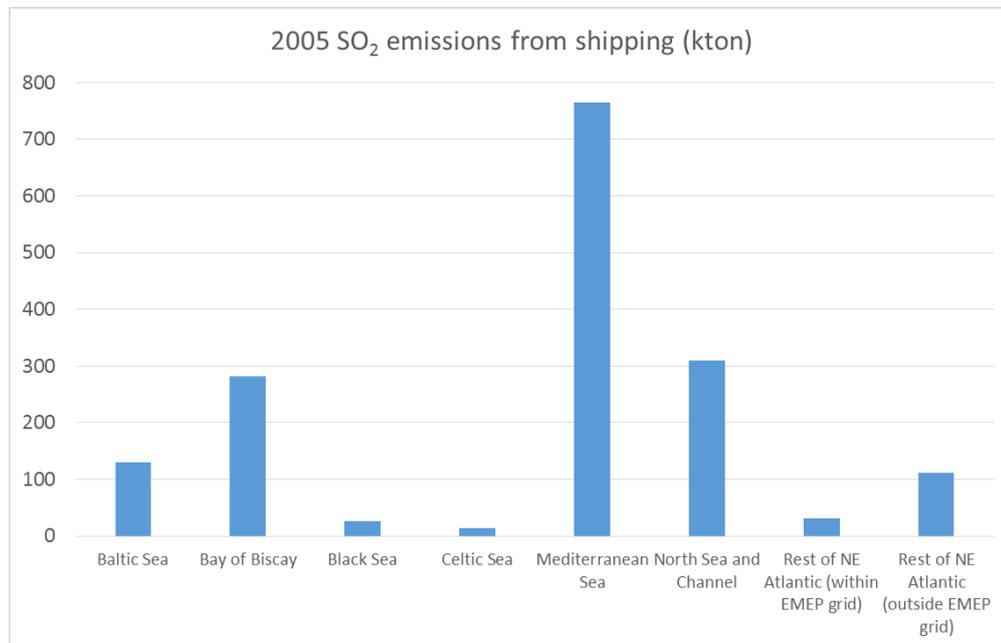
While European land based SO<sub>2</sub> emissions have been reduced significantly since the 1990's, emissions from international shipping in European waters have been increasing slowly despite maximum fuel sulphur levels being limited to 4.5% in 2008 and 3.5%S since 2012. This is illustrated by **Figure 2**, which shows that current SO<sub>2</sub> emissions from international shipping in European waters represent about 25% of the total SO<sub>2</sub> emissions over the combined European Union's land and sea areas [4]. Emissions of SO<sub>2</sub> from natural sources is discussed in detail in Section 5.2.2 and Appendix 2. In **Figure 2**, the contribution from volcanoes has been included to highlight the relative importance of natural sources, particularly in more recent years, where land based anthropogenic emissions have been substantially reduced.

**Figure 2** European SO<sub>2</sub> emissions [4]



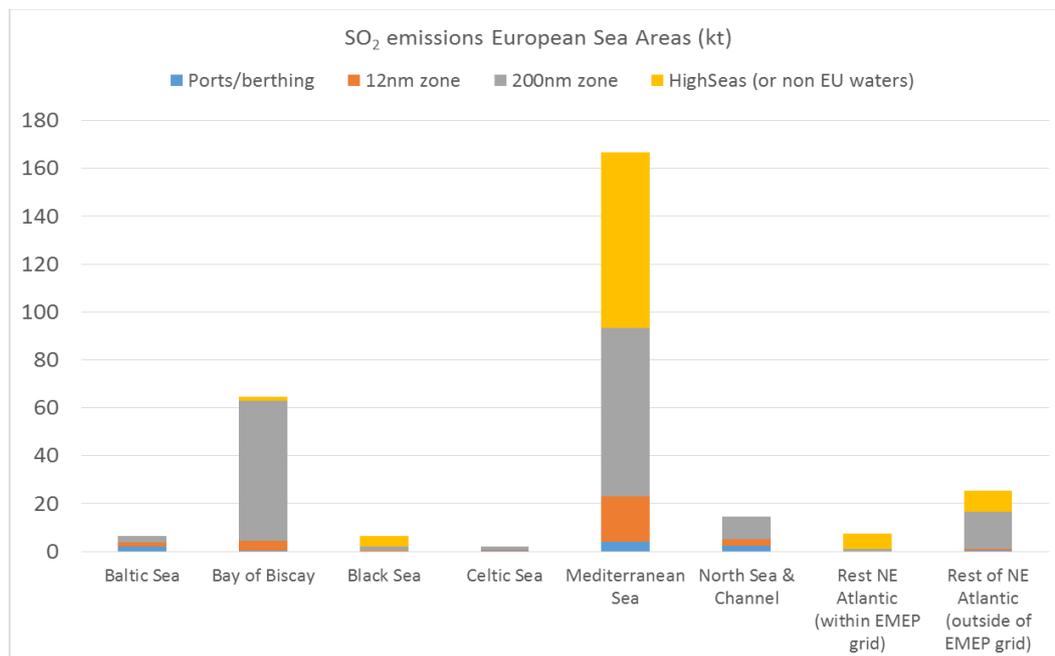
Data on emissions for each European Sea Area can be found in a 2013 Report by VITO [5]. **Figure 3** compares emissions in the main European sea areas. These figures compare well with an emission inventory for the Mediterranean developed by Entec for Concaawe in 2007 [6]. Entec estimated the 2005 Mediterranean emissions at 863 kton, which is 13% higher than VITO's estimate.

**Figure 3** Shipping SO<sub>2</sub> emissions by sea area [5]



**Figure 4** provides a more detailed overview for a 2020 base case. This base case takes into account the reduction in fuel S level from 3.50% to 0.50% outside of ECAs. This chart also distinguishes between emissions while in port or at berth (where S level of 0.10% is mandated) and in coastal zones versus the open seas.

**Figure 4** Shipping emissions by sea area – 2020 base scenario [5]



## 2.2. GLOBAL

The International Maritime Organisation (IMO) has commissioned several studies to assess the total greenhouse gas (GHG) emissions from shipping. The most recent update has been published in 2014 and is generally referred to as the IMO 3<sup>rd</sup> GHG report. Global shipping CO<sub>2</sub> emissions were assessed to represent 2.6% of total global CO<sub>2</sub> emissions [7]. The report also includes an estimate of global SO<sub>2</sub> emissions from international shipping, based on the estimated total fuel consumption and average S content of the fuels. IMO's 3<sup>rd</sup> Greenhouse Gas Study is now widely used as a reference for global marine fuel demand.

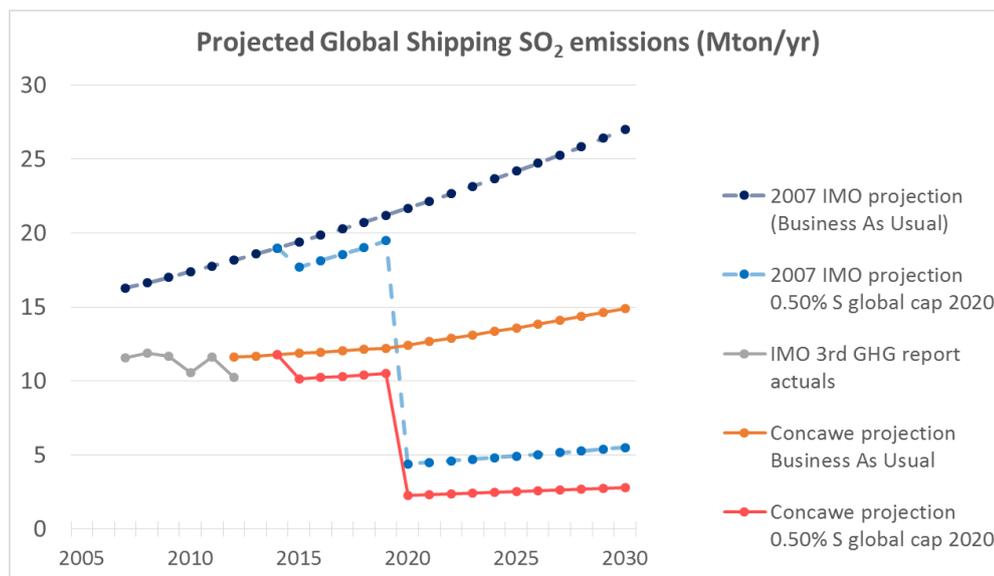
Current emission inventories are significantly lower than the projections that were made ahead of the 2008 financial crises. This is illustrated by the projections that were considered by IMO at the time of the revision of Annex VI in the 2007-2008 timeframe [8] as shown by the top curves in **Figure 5. Table 1** illustrates that overall fuel demand in 2012 is lower than what had been estimated for the total fuel demand in 2007. Furthermore projected growth rates, as used for the 2016 assessment of fuel availability (see also chapter 3.1) are significantly less bullish, resulting in a projected fuel use in 2020 that is 30 to 37% lower than the 2007 estimates on which the revision of Annex VI has been based.

In reviewing this data, we noted that the IMO 3<sup>rd</sup> Greenhouse Gas Study appears to underestimate the SO<sub>2</sub> emissions reported for 2012. Based on the average fuel S level reported by IMO for 2012 [9] of 2.51% and 0.14% for heavy fuel oil and distillate fuels respectively, we estimate a total SO<sub>2</sub> emission of 11.61 Mton/yr rather than the 10.24 Mton/yr reported.

**Table 1** Global shipping fuel demand estimates

Source	Year	Residual fuel (Mton/yr)	Distillate fuel (Mton/yr)	SO <sub>2</sub> emissions (Mton/yr)
IMO Scientific Group of Experts 2007	2007	286	83	16.2
	2020	382	104	22.7
IMO 3 <sup>rd</sup> GHG report	2007	266	80	11.581
	2012	228	64	10.2
Concaawe extrapolation	2020	244	69	12.43
CE Delft (2016) – base case	2020	269	39	
EnSys (2016)	2020	253	88	

**Figure 5** Projected global SO<sub>2</sub> emissions from international shipping



Data sources: IMO Scientific Group of Experts Report, BLG 12/6/1, 2007  
 IMO 3<sup>rd</sup> GHG report (2014), Marine and Energy Consulting Ltd, Outlook for Marine Bunker & Fuel Oil to 2035, May 2014

For the extrapolations based on the current marine fuel demand estimates in **Figure 5** we have used the IMO reported sulphur levels for 2012 [9].

The current projections in **Figure 5** are still slightly higher than the data used in a recent scientific study that evaluated the health impacts of SO<sub>x</sub> emissions from international shipping[10]. They are aligned with historical ship fuel consumption and emissions estimates[11].

In summary, the discussion at MEPC (Marine Environment Protection Committee) to agree the update of MARPOL Annex VI in 2008 was based on assumptions of high GDP growth, with shipping demand linked to GDP growth resulting in a significant growth of shipping SO<sub>x</sub> emissions. When new fuel consumption data and revised projections for demand growth are taken into account significantly lower SO<sub>x</sub> emissions, even without a 0.50%S global cap from 2020 are evident. With the emissions cap in place, global shipping emissions will be very significantly reduced.

It is relevant to compare emissions from international shipping with emissions from other man-made sources and emissions from natural sources. SO<sub>2</sub> emissions from international shipping represent about 10% of anthropogenic emissions. Amongst the natural sources of SO<sub>2</sub> emissions, both volcanoes and emissions of dimethylsulphide (DMS) from biomass in the oceans are larger sources of atmospheric sulphur than international shipping. In 2014, the contribution of volcanic sources of SO<sub>2</sub> emissions in the European region were officially reported at some seven times those from shipping sources; the contribution of DMS at some 1.3 times shipping SO<sub>2</sub> emissions [12]. At the same level of DMS emissions, in 2020 this source would be some seven times higher than emissions from ship sources in the same sea areas. Further information on natural sources of atmospheric sulphur emissions is provided in **Appendix 2**.

### 3. REGULATORY CONTEXT

#### 3.1. INTERNATIONAL MARITIME ORGANIZATION

International shipping is regulated at the international level by the International Maritime Organization (IMO). IMO is a UN organization, based in London. Air pollution from international shipping is regulated under the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto and by the Protocol of 1997( MARPOL). Air emissions are covered by Annex VI of MARPOL which entered into force in 2005. The Annex was substantially modified in 2008 with the modifications taking effect in 2010.

SOx emissions from international shipping

One key provision of MARPOL Annex VI, Regulation 14, concerns SOx emissions. These are regulated by specification of a maximum sulphur level in the fuel.

The regulation specifies different limits for operating inside and outside Emissions Control Areas (so called SOx ECAs) and these follow a stepped reduction over time as shown below:



The Baltic Sea, the North Sea, the English Channel, and the coastline of North America (200NM) are currently Emission Control Areas (ECAs) where special emission limits apply. In the ECAs, on 1 January 2015, the maximum permitted sulphur content for marine fuel was reduced from the previous 1% to 0.10%.

ECAs can also be applicable to NOx emissions. Any ECA, whether for SOx or NOx, should be set up in accordance with the criteria given under Appendix III of Annex VI which includes the requirement to demonstrate that the implementation of such an ECA is cost effective compared to further land based controls.

Figure 6 shows the geographical extent of the SOx ECA areas. The rest of the world is subject to the “global IMO” limit. The implementation date of the reduction in the maximum “global IMO” sulphur content from 3.50% to 0.50% was subject to a fuel availability review to be completed by 2018. IMO has already considered the fuel availability study at the October 2016 meeting of the Marine Environment Protection Committee and concluded that the refining industry “has the capability to supply sufficient quantities of marine fuels with a sulphur content of 0.50% m/m or less”. Hence the implementation date for reducing the maximum fuel S level to 0.50% was confirmed as January 1, 2020 [13].

**Figure 6** Sulphur Emission Control Areas (Source: Exhaust Gas Cleaning Systems Association, [www.egcsa.com](http://www.egcsa.com))



MARPOL Annex VI Regulation 4 allows flag administrations to approve alternative means of compliance that are at least as effective in terms of emission reduction as the prescribed sulphur limits in the fuels.. This means that a ship may operate on fuel with a higher sulphur content than that allowed by the regulations, provided that SOx emissions are controlled to a level which is no higher than the levels emitted if using compliant fuel.

#### NOx emissions from international shipping

MARPOL Annex VI Regulation 13 limits NOx emissions from marine diesel engines. The limits are divided into three 'tiers'. How these tiers apply depends on the ship's construction date and the engine's rated speed.

Tier I and Tier II limits apply to engines installed on ships built on or after 1 January, 2000, and 1 January, 2011, respectively. Tier III limits (~ -80% vs. Tier I) apply to ships built on or after 1 January, 2016, if operating within the North American and US Caribbean ECA-NOx. The North Sea, Channel and Baltic Seas are scheduled to become NOx ECAs effective January 1, 2021.

#### Particulate Matter emissions from international shipping

Particulate matter (PM) emissions are not regulated as such in MARPOL Annex VI but are considered jointly with SOx emissions on the basis that lower sulphur in fuels results in lower PM emissions. These lower PM emissions are directly associated to a lower level of condensed sulphate aerosol particles in the exhaust.

#### CO<sub>2</sub> emissions from international shipping

In 2011 the IMO added a regulatory chapter to Annex VI to include requirements on energy efficiency of ships to reduce the amount of CO<sub>2</sub> emissions from international

shipping. These regulations introduce the concept of the Energy Efficiency Design Index, applicable to new ships. Baselines have been established for all common ship types. Newly built ships need to improve their design efficiency in three phases, applicable as of 2015, 2020 and 2030 respectively. For most ship types improvements of 10, 20 and 30% respectively are linked with each phase. In addition, all ships must develop a Ship Energy Efficiency Management Plan (SEEMP). These energy efficiency requirements can be expected to further curb growth in fuel consumption from international shipping. Consequently, this should also lead to lower emissions of SO<sub>x</sub>, PM and NO<sub>x</sub>.

IMO continues to debate further measures to reduce GHGs from international shipping. As a first step IMO will implement mandatory requirements for ships of 5000 gross tonnage and above to record and report their fuel consumption. Data collection will start with calendar year 2019.

In addition to the IMO rules, local regulations may be imposed by national authorities in coastal waters and estuaries.

### **3.2. EUROPEAN REGULATIONS**

The EU Sulphur Directive (2012/33/EC) translates the IMO regulations into European law, while adding some specific requirements applicable in the European waters (territorial seas, exclusive economic zones and pollution control zones). The introduction of 0.50% sulphur fuels was independent of the conclusions of the global IMO study regarding fuel availability. In light of the October 2016 decision by IMO to implement the global S cap of 0.50% in 2020, this European requirement will remain consistent with the global requirements under Annex VI of the IMO MARPOL Convention.

The European Directive however has a more stringent requirement for ships at berth in a European port. Within two hours of arrival, the ship has to switch to 0.1% S fuel until two hours before its departure at the earliest. Furthermore, passenger ships on a regular schedule outside of the ECAs may use fuel with a maximum S content of 1.5% until 2020, when the lower limit of 0.50% sulphur will apply to all ships.

## 4. COMPLIANCE OPTIONS AND SCRUBBERS

### 4.1. COMPLIANCE OPTIONS

Regulation 14 of Annex VI of IMO's MARPOL Convention specifies a maximum sulphur level in the fuel. Petroleum based fuels are by far the largest fraction of marine fuels currently in use. However, Regulation 18.3 of Annex VI also allows use of fuels derived by methods other than petroleum refining. In recent years LNG has received a lot of attention as an alternative fuel for marine use and there are a number of vessels either operating exclusively on LNG or having the flexibility to use either LNG or a traditional fuel. Methanol is also considered as a low S alternative fuel and biofuels are named as another option.

The most popular alternative so far is enabled by Regulation 4 of Annex VI, which allows equivalent methods to achieve the environmental objectives of Annex VI, provided such methods are approved by the Ship's Administration. Several companies are offering Exhaust Gas Cleaning Systems (EGCS), also called scrubbers, which remove SO<sub>2</sub> from the exhaust to a level that is at least equivalent to the SO<sub>2</sub> emission that would be achieved when low sulphur fuels are used. More details on scrubbers and their performance compared to low sulphur fuels are provided in **Appendix 4**.

### 4.2. SCRUBBER CONSIDERATIONS

#### 4.2.1. Performance

Each supplier of scrubber will provide guarantees on the levels of pollutants that their exhaust gas cleaning system can remove from a ship exhaust stream but typical figures for SO<sub>x</sub> removal are ~ 98% [14].

Wet scrubbers may also contribute to remove a significant part of Particulate Matter and a few % of NO<sub>x</sub>.

#### 4.2.2. Energy requirements, chemicals and waste

The use of a scrubber increases the ship's fuel consumption due to the additional energy required for the operation of the on-board scrubbing equipment: typically by around 0.3% for a freshwater scrubber (not taking into account the energy needed for the production of chemicals) and up to 2-3% for a seawater scrubber [15].

When the life cycle energy consumption of the different fuels and chemicals is taken into account, removing SO<sub>2</sub> from exhaust gas has been shown to be less energy consuming than the alternative of removing the sulphur from fuels in refineries [15].

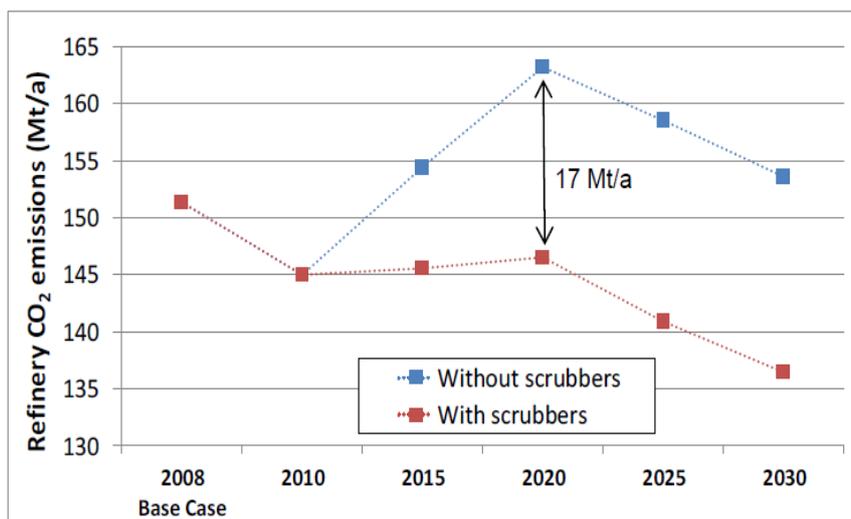
Fuels desulphurization requires energy: need of hydrogen, high temperatures and pressures <sup>1</sup> and Concaawe has estimated that significant CO<sub>2</sub> emission savings can be achieved by scrubbing. A 100% scrubber case scenario would avoid a 17 Mt/y

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<sup>1</sup> Sulphur is removed from fuels using the hydrodesulphurization process.. It requires the application of hydrogen, to break up the molecules containing sulphur and transform this sulphur to hydrogen disulphide. This in its turn can then be absorbed from the process gas, and ultimately is converted into elemental sulphur that can be stored and transported as a heated liquid or solid. These processes are energy intensive: they happen at elevated temperatures and pressures and the hydrogen required has to be produced on the basis of natural gas, whereby the carbon from the natural gas is emitted to the atmosphere as CO<sub>2</sub>

increase in EU refinery CO<sub>2</sub> emissions partially offset by 8 Mt/y increase CO<sub>2</sub> emissions from scrubber energy need resulting in a net saving of 9 Mt/y [16] as shown in **Figure 7**.

**Figure 7** Effect of on-board scrubbers on EU refinery CO<sub>2</sub> emissions



Effluent treatment of most scrubbers will generate some sludge, which needs to be collected and disposed of. The amount of sludge generated by scrubbers is approximately of 0.1 to 0.4 kg/MWh, depending on the amount of water mixed [15]. This represents less than 10% of the ‘normal’ sludge production, which stems from purification of the fuel by centrifugation. Tests and analyses carried out on freshwater scrubbers indicate that the properties and treatment of the sludge from scrubbers are very similar to other engine room sludge but with lower calorific value due to higher water contents.

### 4.2.3. Environmental impact of effluent

While at first sight, a scrubber may be seen as a device that moves pollution from air to water, the discharge of sulphate into the ocean does not result in an environmental concern. The ultimate fate of atmospheric SO<sub>2</sub> emissions, whether manmade or from natural sources, is conversion to sulphate salt and oceans are a large sink of naturally occurring sulphate salts.

IMO has published guidelines for the certification of scrubber systems, covering amongst others the allowable sulphur content in emissions, and limits on relevant components that may be present in the waste water discharge [17]. While the document is described as a “guideline,” it is given mandatory effect under MARPOL Annex VI, Regulation 4 and the EU Sulphur Directive (2012/33/EC).

The guidelines specify requirements for the testing, survey and certification of an EGCS. The guidelines also establish limits for pH, PAHs, turbidity, nitrites and nitrates in wash water discharge.

Several reports [15] [18] [19] have considered the environmental impact of scrubbers in marine environments. All the reports concluded, or referred to literature stating, that the toxicants discharged with the wash water will not lead to an exceedance of the

water environmental quality criteria in open seas or coastal areas and that the change in pH or alkalinity is expected to be low in the short run. On the long-term impact the assessments differ. While the Danish EPA (2012) emphasizes that the impact of wash water from scrubbers is negligible, UBA (2015) and CE Delft (2015) conclude that more research in these fields is necessary to be in line with the precautionary principles considering the cumulative effects for pH, alkalinity and non-degradable toxicants particularly in specific geographic areas such as ports (due to prolonged and concentrated pressures, limited mixing and cumulative loads from other sources) and ecological sensitive or vulnerable areas (e.g. Natura 2000 and/or coastal ecosystems).

Nevertheless, the Danish EPA report has made a very thorough analysis, comparing maximum concentrations that may occur as a result of extensive use of scrubbers to the European and Danish water quality standards. The study considered a worst case scenario and demonstrated that ambient concentrations should remain below European and Danish environmental quality standards. Hence the study did not identify any concerns with the broad use of scrubbers.

More details on the impact on seawater pH of open loop scrubber effluent can be found in **Appendix 4**.

## **5. ENVIRONMENTAL IMPACT OF SO<sub>2</sub> EMISSIONS**

### **5.1. EUROPEAN SEA AREAS PROJECT**

#### **5.1.1. European Air Quality Modelling work**

As part of the European Air Policy review process in 2013, the European Commission commissioned integrated air quality studies that evaluated different scenarios for further emission reductions. These scenarios included options for emission reductions from shipping in European waters through the establishment of further SO<sub>x</sub> Emission Control Areas (SECAs). This work concluded that establishment of further SECAs in European waters would not be a cost-effective means to achieve the European air quality objectives [20].

Concaawe modelling work, described in section 5.1.2 leads to conclusions that are consistent with this European study.

#### **5.1.2. Impact as a function of distance from shore**

##### **5.1.2.1. Background**

The EMEP model is a chemical transport model for regional atmospheric dispersion and deposition of acidifying and eutrophying compounds (sulphur and nitrogen), ground level ozone and particulate matter covering Europe. It is a key tool within European air pollution policy assessments. Further information on air quality modelling for policy making is provided in Appendix 3. To date the EMEP model has been used to generate an understanding of the contribution of emissions from a given country or sea area to the pollutant concentrations or deposition in each receptor grid in the EMEP region. Through a large number of simulations, this provides country-to-grid or sea area-to-grid 'source receptor' relations. This approach however gives no information on the contribution from a sub area within a country or sea area.

In the case of sea areas, in order to provide additional information on near shore contributions, a single scenario representing emissions from ships within 12 NM of EU shores was modelled. This was in addition to the sea area scenarios for each European sea i.e. 'the 200 NM zone' (from 12 NM to 200 NM) and 'the beyond 200 NM zone'. The resulting source receptor functions however do not provide for an assessment of the relationship between 'ship distance from shore' and the 'impacts on each land grid. Such an understanding is crucial for the design of cost-effective ECAs as required by Annex VI of MARPOL.

##### **5.1.2.2. Building an understanding of Impacts versus Distance from Shore**

In order to overcome this limitation, this present study used data from a small study by the Swedish Meteorological and Hydrological Institute (SMHI); carried out in the margin the Euro-Delta Project [21]. That work was undertaken using the Euro Delta II version of the MATCH model. A hypothetical ten kilo tonne change in SO<sub>2</sub> emissions from a ship travelling west from Lisbon was modelled in the MATCH CTM model at various distances from shore. The resulting changes in secondary PM<sub>2.5</sub> concentrations in every terrestrial grid were calculated. For this work the modelling domain of the MATCH model was modified to include a larger part of the Atlantic, near Portugal.

The baseline emissions in the Lisbon study were the emissions from the 'Base Case 2020 Mediterranean Sea emission scenario' in Euro-Delta II, (scenario 54). For each

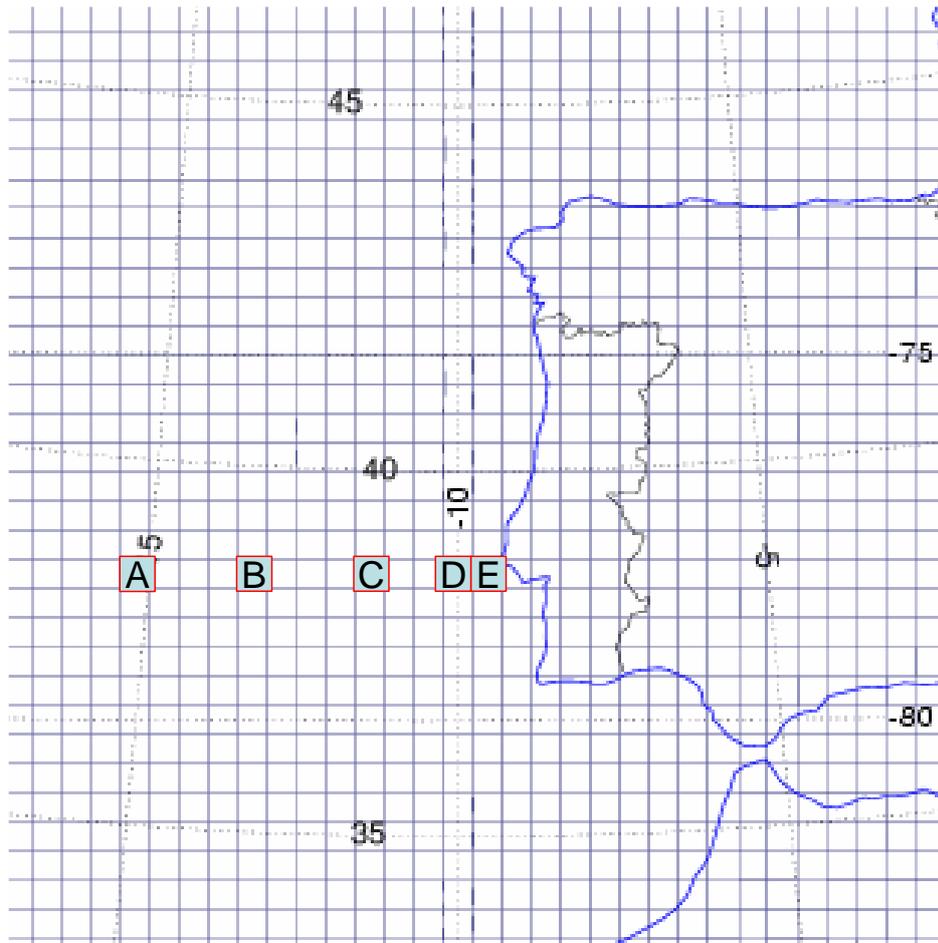
additional “distance from shore scenario”, calculations were performed with additional SOx (10kT/y; 95% SO<sub>2</sub> + 5% sulphate) and primary PM<sub>2.5</sub> (1kT/y) emissions on top of the baseline at five different grid points. The “extra emission” grid points were located at the coordinates shown in **Table 2**. For detailed technical information about the MATCH model (and the Euro-Delta II project) see the report from Euro-Delta [21]

**Table 2** Coordinates of Grid squares used in this study

	Latitude	Longitude	Distance to shore-grid point E (km)	Distance to Lisbon (km)
A	38.42599	-15.2314	497	525
B	38.52946	-13.3331	331	360
C	38.58704	-11.4293	166	194
D	38.60000,	-9.98022	40	69
E	38.59856	-9.52358	0	32

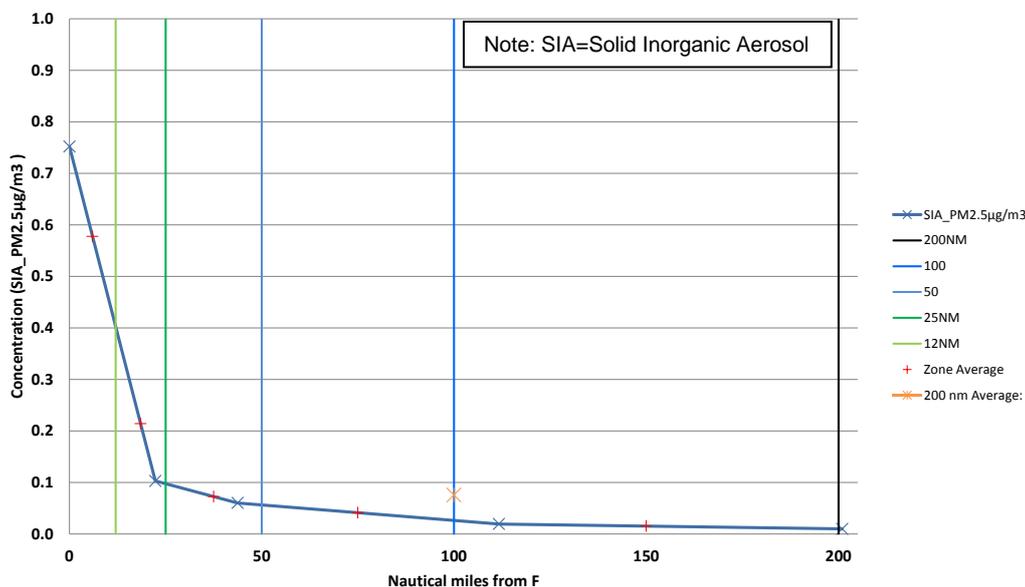
The corresponding grid squares are shown in **Figure 8**.

**Figure 8** Grid locations



The results were used to generate an emissions potency,  $P_z$ , relationship representing the decreasing contribution of  $SO_2$  emissions to on-shore concentrations with increasing distance from shore. The points of this emissions potency relationship reflect the change at Lisbon in  $PM_{2.5}$  concentration per kiloton of  $SO_2$  emissions at each of the grid points above. This trajectory was chosen because the prevailing on shore winds would make this a “worst case” (i.e. conservative) analysis. The resulting emissions potency relationship is shown in **Figure 9** below. A full modelling exercise run for the entire European coastline with gridded emissions would be a worthwhile and informative future exercise.

**Figure 9** Sulphate PM<sub>2.5</sub> Concentrations at Lisbon Centre (F) Versus Distance from Shore & Designation of Zones within 200 NM



In combination with zoned emissions data, the potency relationship described above was used to create weighted emissions values for use in Concaawe’s in-house IAM tool; SMARTER. This was done by first calculating the % of total emissions attributable to each zone:

$$\% E_i = E_i / \sum_{i=1}^5 E_i \quad \text{Equation 1}$$

In order to maintain calibration with the total sea area emissions and concentration potency, these zoned emissions shares, % E<sub>i</sub>, were given a relative emissions potency weighting, RP<sub>z</sub>, such that:

$$\sum_{i=1}^n RP_i * \% E_i = 1 \quad \text{Equation 2}$$

The relative emissions potency, RP<sub>z</sub> for each band was calculated from:

$$RP_z = P_z * \text{adjustment coefficient} \quad \text{Equation 3}$$

Where the adjustment coefficient was:

$$Adj. Coeff = \sum_{i=1}^5 E_i / \sum_{i=1}^5 (E_i * P_i) \quad \text{Equation 4}$$

Having established the zonal concentration response potencies, the next step of the analysis was to determine the zonal impact response potencies. This used the emissions detailed in **Table 3<sup>2</sup>** in each zone, weighted by the ratio of potency in the zone divided by the average potency of the whole sea area.

<sup>2</sup> The emissions dataset was supplied by EMEP and corresponded to the 2020 base case emissions used in their source – receptor generating runs

**Table 3** Banded SO<sub>2</sub> Emissions

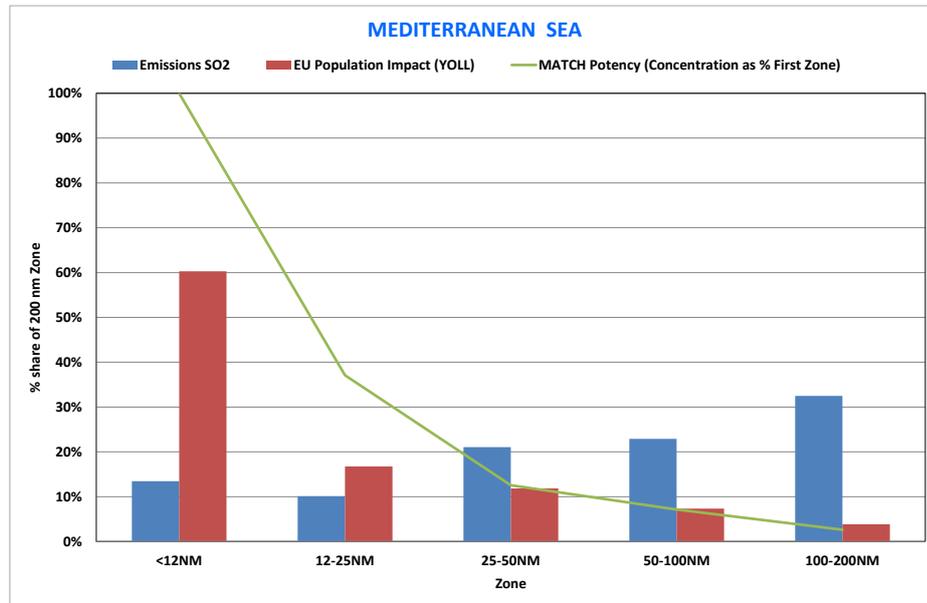
sea	Zone_id	Buffer (NM)	Emissions SO <sub>2</sub> (kt)	% of total
Celtic Sea and Bay of Biscay	5	200	25	33%
Celtic Sea and Bay of Biscay	4	100	30	39%
Celtic Sea and Bay of Biscay	3	50	15	19%
Celtic Sea and Bay of Biscay	2	25	6	7%
Celtic Sea and Bay of Biscay	1	12	1	2%
Total			77	100%
Mediterranean Sea	5	200	33	32%
Mediterranean Sea	4	100	23	23%
Mediterranean Sea	3	50	21	21%
Mediterranean Sea	2	25	10	10%
Mediterranean Sea	1	12	14	13%
Total			101	100%

The zonal impact response potencies allowed the statistical Years of Life Lost (YOLL) impacts attributable to emissions reductions to be determined in each of the following zones: 0-12 NM, 12 – 25 NM, 25 – 50 NM, 50 – 100 NM and 100- 200 NM. As the EMEP S-R functions only provide for a single 12 to 200 NM zone, this was done by calculating an equivalent single zone emissions value from the weighed emissions potency relationship when each of the hypothetical zones was subjected to an emissions reduction of 50%. This single equivalent emissions value was then used in SMARTER to generate a delta YOLL value for the zone as a percentage of the delta YOLL value for a reduction of 50% for the emissions in the zone as a whole. In this way the impact contribution of each zone is revealed. The results are presented below.

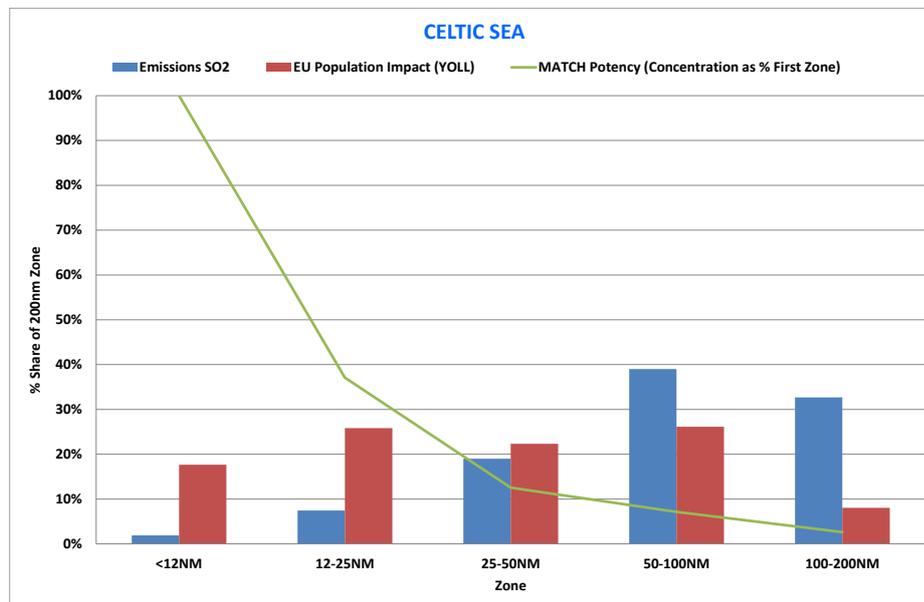
**5.1.2.3. Results**

Using the banded emissions data of **Table 3**, **Figure 10** and **Figure 11** show the percentage splits of total sea area emissions and land based impacts for the Mediterranean Sea and the combined Celtic Sea and Bay of Biscay areas:

**Figure 10** Emissions and Impact Contribution by Zone within 200NM of EU Land: Mediterranean Sea



**Figure 11** Emissions and Impact Contribution by Zone within 200NM of EU Land: Celtic Sea and Bay of Biscay



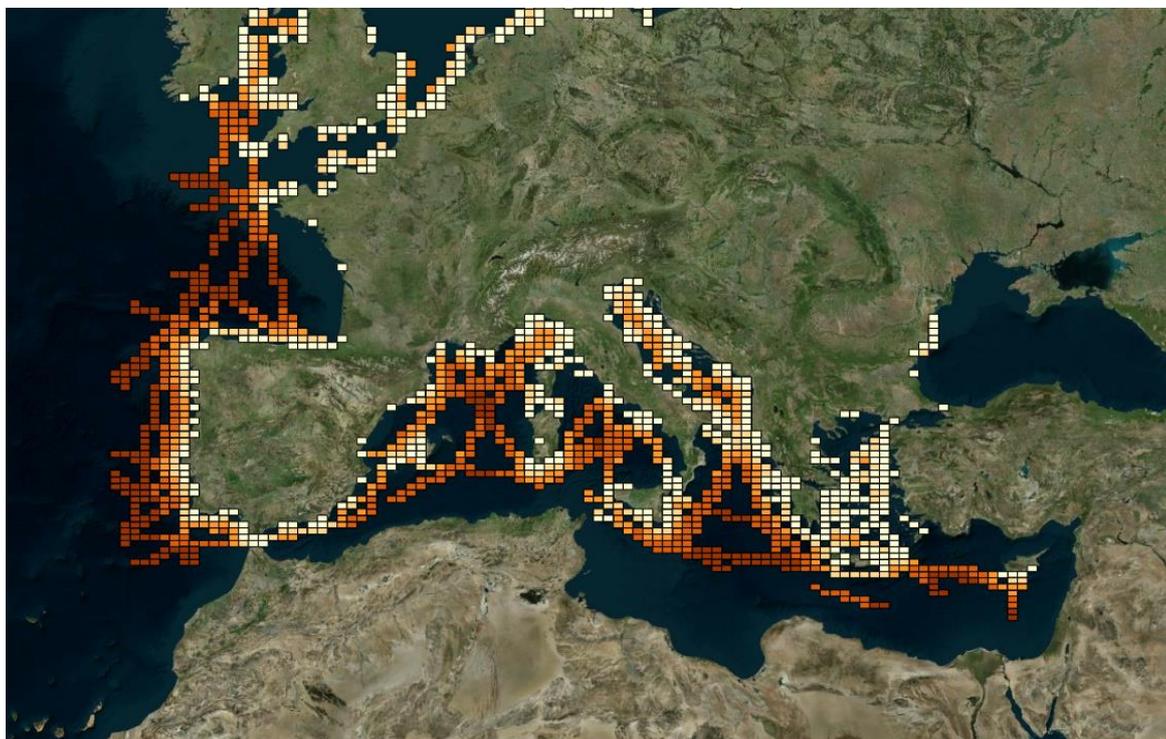
**5.1.2.4. Findings**

In the Mediterranean Sea 23% of the SO<sub>2</sub> emissions from shipping are emitted within 25 NM of the shore and these are responsible for 77% of the impacts. In the Celtic Sea and Bay of Biscay 9% of the SO<sub>2</sub> emissions from shipping are emitted within 25 NM of the shore and these are responsible for 43% of the impacts. The lower share

of near shore emissions in the Celtic Sea and Bay of Biscay compared to the Mediterranean can be seen on the gridded emission map in **Figure 12** below where the shortest path across the Bay of Biscay is obviously taken.

In the Mediterranean, emissions beyond 50 NM are responsible for only 11% of the impacts and in the Celtic Sea and Bay of Biscay, emissions beyond 50 NM are responsible for 34% of the impacts, but it should be noted that overall SO<sub>2</sub> impacts in this region are low.

**Figure 12** Gridded Ship Emissions shaded by proximity to shore; lightest colour within one EMEP grid (~28km) to shore



These findings have significant implications for the justification of further SECAs in Europe. As outlined in Appendix III of MARPOL Annex VI, any application must include a detailed assessment of the cost-effectiveness versus distance from shore. Furthermore, given the steep near shore gradient of emissions versus impact, it is recommended that this be done in appropriately small increments of distance, particularly in the first 50nm from shore. Finally, any application should be based on a move from 0.50% sulphur to 0.10% sulphur to ensure the move to a global sulphur cap in 2020 is accounted for in the cost-effectiveness analysis compared to further land based controls.

### 5.1.3. Global Cap versus Coastal Zone ECA

Given the significant and rapid attenuation of impacts as a ship sails away from the shore, with a focus on the Mediterranean Sea we explored the question: “at what distance from shore would a coastal SECA at 0.10% sulphur and a 3.50%S global cap give the same impacts reduction as the global sulphur cap of 0.50%?”

To answer the above question two cases were analysed:

i) The distance from shore at which the impacts of a 0.1% sulphur coastal zone within a 2.94% sulphur EEZ would be equal to the impacts of a 0.5% sulphur fuel throughout the 200 NM EEZ.

ii) The distance from shore at which the impacts of a 0.1% sulphur coastal zone within a 2.94% sulphur Mediterranean Sea would be equal to the impacts of a 0.5% sulphur fuel throughout the Mediterranean Sea

Three levels of sulphur in fuel used in the Mediterranean were modelled for their emission impacts on shore: 2.94% (representative actual [5]), 0.5% and 0.1%. The banded emissions and the derived impact potency on the EU population used were as those described in section 5.1.2.2 (**Figure 9**). Details of the methodology that has been used are provided in Appendix 5.

The results are shown in **Figure 13** for case i) and **Figure 14** for case ii).

Results

Figure 13 Case i

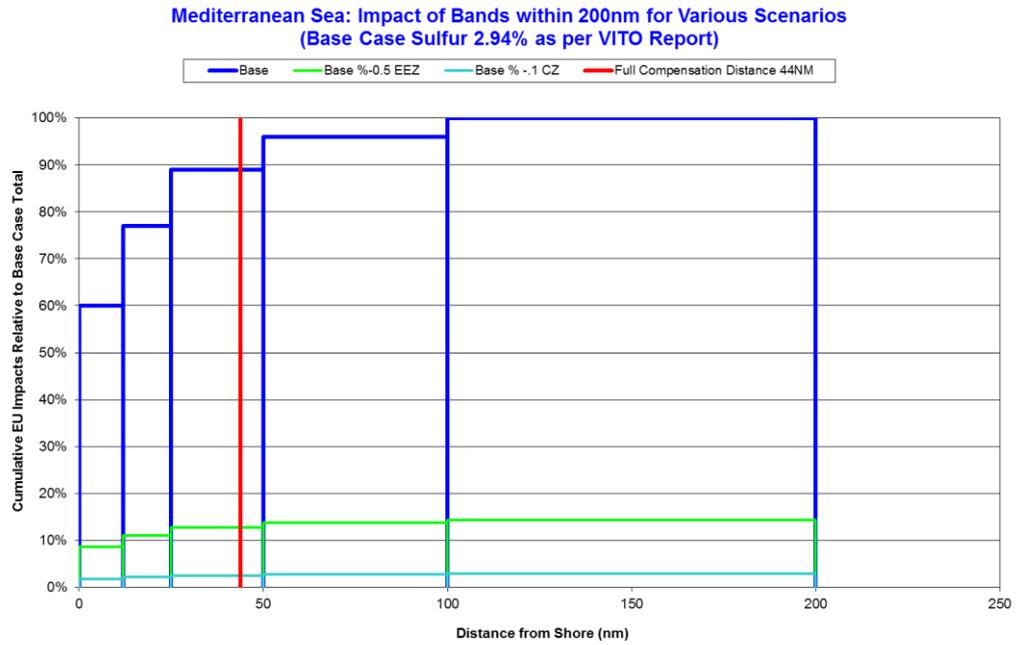
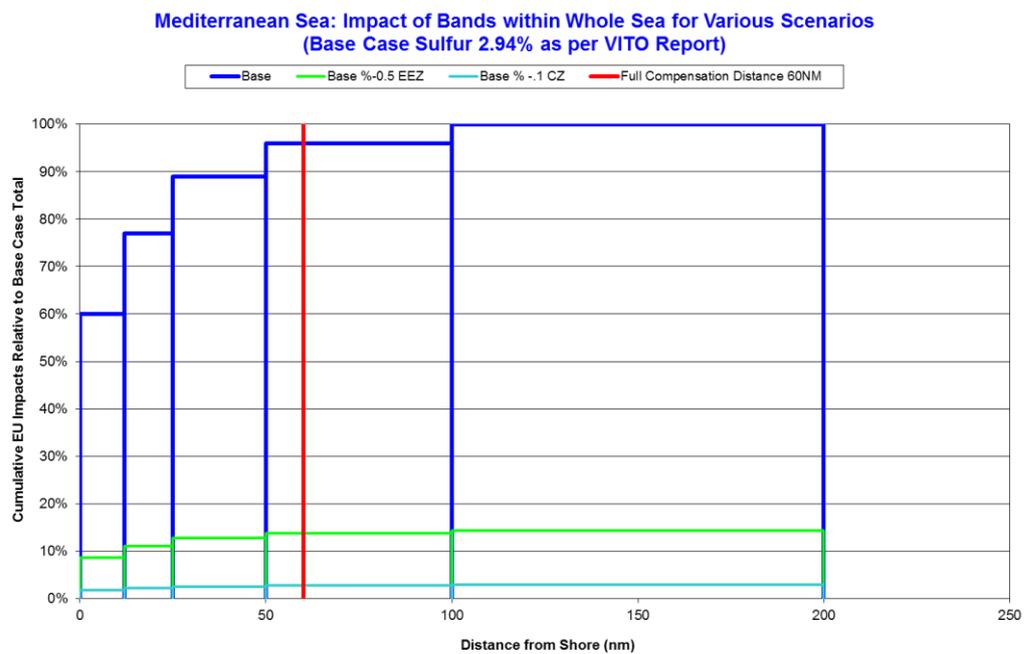


Figure 14 Case ii



## Findings

This analysis shows that:

- A coastal zone SO<sub>x</sub> ECA out to less than 45 NM would provide the same reduction in impacts on the EU population from exposure to fine particulates as would the application of the Global Sulphur Cap to the whole 200 NM zone;
- A coastal zone SO<sub>x</sub> ECA out to some 70 NM would provide the same reduction in impacts on the EU population as the whole Mediterranean Sea complying with the global sulphur cap.

## 5.2. EVALUATION AND COMPARISON WITH LITERATURE

### 5.2.1. Global health impact assessments

A 2007 article in Environmental Science and Technology [22] drew headlines as it asserted that shipping emissions were responsible for 60000 deaths around the world. These assertions were based on extrapolation of epidemiological data that is widely used in assessing health impacts from air pollution. There are however a number of issues with this approach that have been elaborated in an IPIECA paper submitted to IMO [23].

First, it needs to be clearly recognised that such studies concern attributions to a number of different sources of pollutants, in other words, there is no direct causal relationship between a specific emission and mortality. Secondly, the study did not consider any threshold of effect. As a result, this study attributed mortality within large inland populations on the basis of extremely low contributions from international shipping to inland air quality, typically less than 0.1 µg/m<sup>3</sup> out of total urban concentrations that may average 20 µg/m<sup>3</sup> or more.

More detailed analysis of impact data confirms that reducing shipping emissions will only have measurable impact when they occur relatively close to receptors. An illustration of this can be found in the VITO/GAINS analysis of 2013 [5] [19], which showed that additional ECAs in European waters would not be cost effective versus further land based measures that are available, with the possible exception of emissions within territorial waters (< 12 NM).

An updated global impact study has been completed in 2016 to support the IMO decision making process [10]. This study concluded that reduced shipping emissions as a result of the 0.50% sulphur implementation would lead to significant reductions in ambient sulphate concentrations in coastal communities while Impacts on inland communities would be less pronounced.

### 5.2.2. Contribution from natural sources

A recent paper by M. Yang et al [24] provides some interesting insights into the relative contributions of SO<sub>2</sub> emissions from shipping and from natural sources. The authors set out to assess the impact of the reduction of the maximum sulphur level from 1.00% to 0.10% in the North Sea and Channel Emission Control Area (ECA) as of January 2015. They analysed continuous monitoring data from the Penlee Point Atmospheric Observatory near Plymouth. By observing diurnal variations, they were able to distinguish between SO<sub>2</sub> originating from man-made sources and SO<sub>2</sub>

generated through the oxidation of dimethylsulfide (DMS) emanating from marine biota.

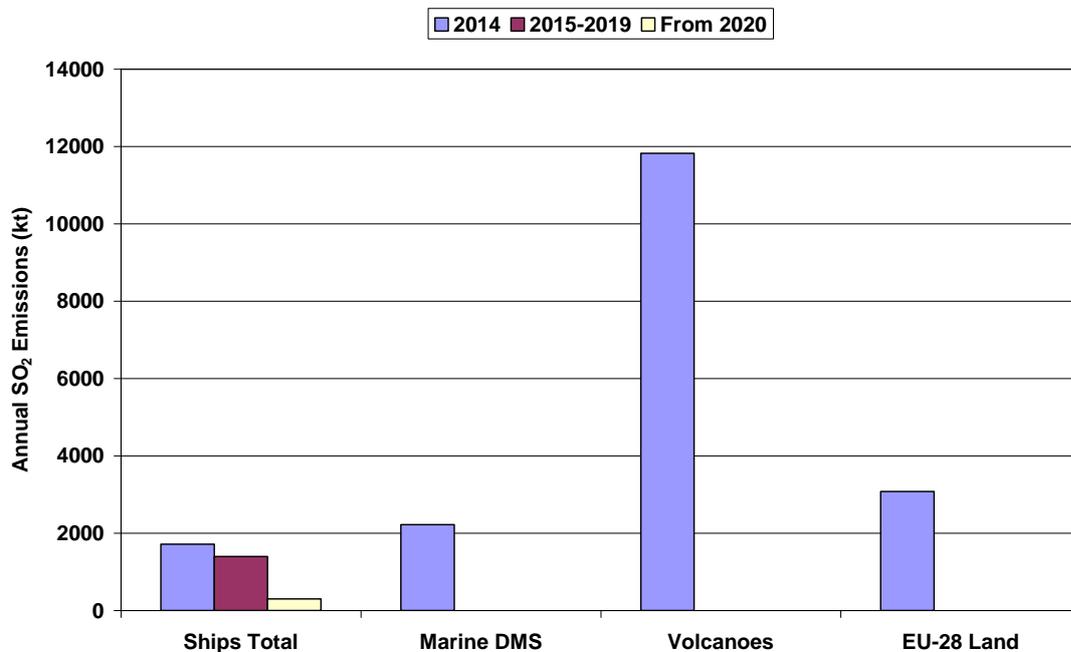
Their work confirmed a significant reduction in SO<sub>2</sub> emissions from shipping in the Channel, in line with expectations. They observed that now half of the SO<sub>2</sub> above the Channel should be attributed to DMS. Evaluation of the diurnal cycle with south-westerly winds indicates that when winds are blowing from the Atlantic Ocean, photo-oxidation of DMS is the primary source of SO<sub>2</sub>.

A further and important source of data on the contribution of natural sources of SO<sub>2</sub> emissions is provided by the work undertaken under the UN Convention on Long Range Transport of Air Pollution (CLTAP) under their European Monitoring and Evaluation Programme (EMEP). Each year, under this programme, regional emissions both from anthropogenic and natural sources are reported for the whole European region. These data are used in their long range transport of air pollution modelling work. In their most recent Status Report (1/2016) they provide detailed data on both emissions (including DMS and emissions from volcanic activity in the region) and on the modelled impact of these emissions on European land areas in 2014.

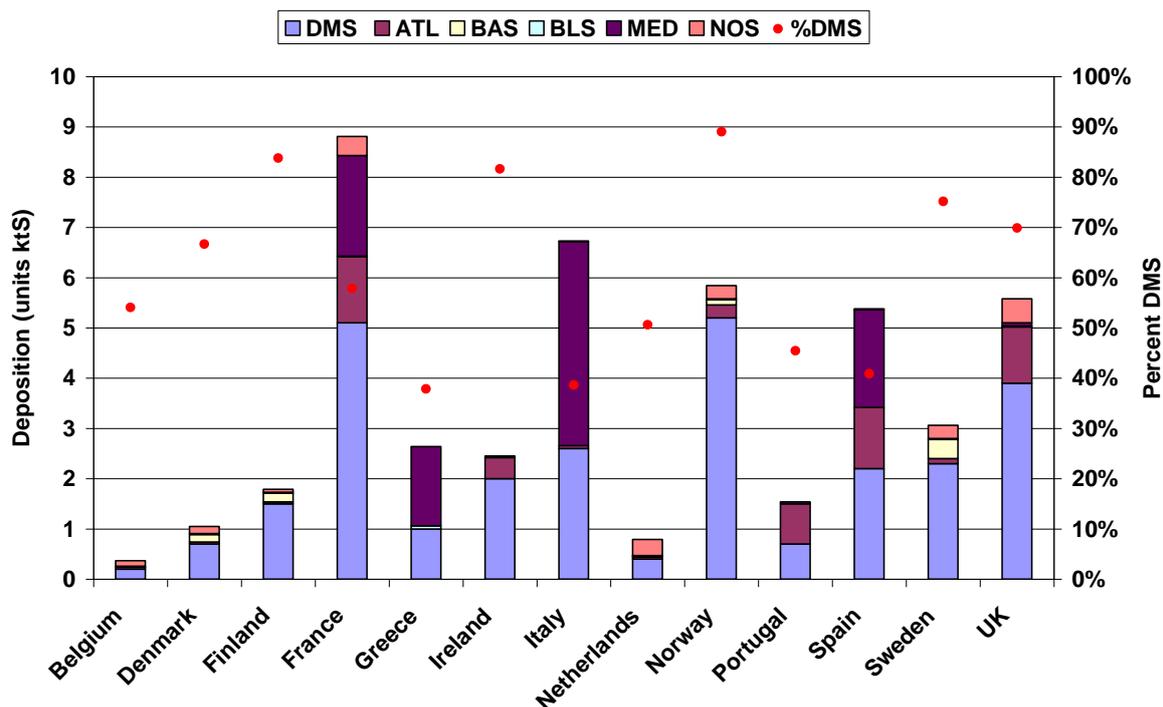
**Figure 15** is derived from the SO<sub>2</sub> emissions data provided in this report. For SO<sub>2</sub> emissions from ships in all the European Sea areas, the 2014 data is as reported. However to provide a perspective on the impact of the 0.10% sulphur limit in SECAs from 2015 and the mandatory global sulphur cap of 0.50% in 2020, the emissions from ships were adjusted based on the sulphur levels in each of the European Seas in 2014 and the 2015 and 2020 regulatory limits. The SO<sub>2</sub> emissions in 2014 from natural sources and from EU land based emissions are also shown. What this figure highlights is that in 2014 ship emissions in European seas are of the same order as DMS emissions from those same sea areas. However, by 2020, ship emissions (following the application of the global sulphur cap) are small compared to DMS emissions which are some seven times higher. It is also worth noting that in 2014 volcanic activity in the region dwarfed all other contributions.

Of course we also need to consider what impact these emissions have on populations and land ecosystems. In the same EMEP status report, data on the contribution of these sources to individual countries are provided. **Figure 16** is based on these data using the contribution of these SO<sub>2</sub> emissions to deposition of sulphur in a given country as a surrogate for their impact. Here the 2020 situation is represented (i.e. post the application of the global sulphur cap) assuming DMS emissions remain at 2014 levels – a robust assumption based on previous EMEP reports. The stacked bar charts show the contribution to deposition of sulphur in a number of selected EU Member States from ship activity in European Seas (Atlantic (ATL), Baltic (BAS), Black Sea (BLS), Mediterranean (MED) and North Sea (NOS). In addition the contribution from DMS emissions from all these sea areas is also shown. The single points (right Y-scale) show the percentage contribution of DMS (expressed as a percent of DMS+Ship emissions). What is very clear from this figure, consistent with **Figure 15**, is that after the entry into force of the global sulphur cap, DMS emissions dominate.

**Figure 15** European Marine SO<sub>2</sub> Emissions in the Perspective of Total European Emissions (Based on data from EMEP Status Report 2016)



**Figure 16** Deposition of Sulphur from Ships and DMS on a Selection of EU Countries for 2020 (Based on data from EMEP Status Report 2016)

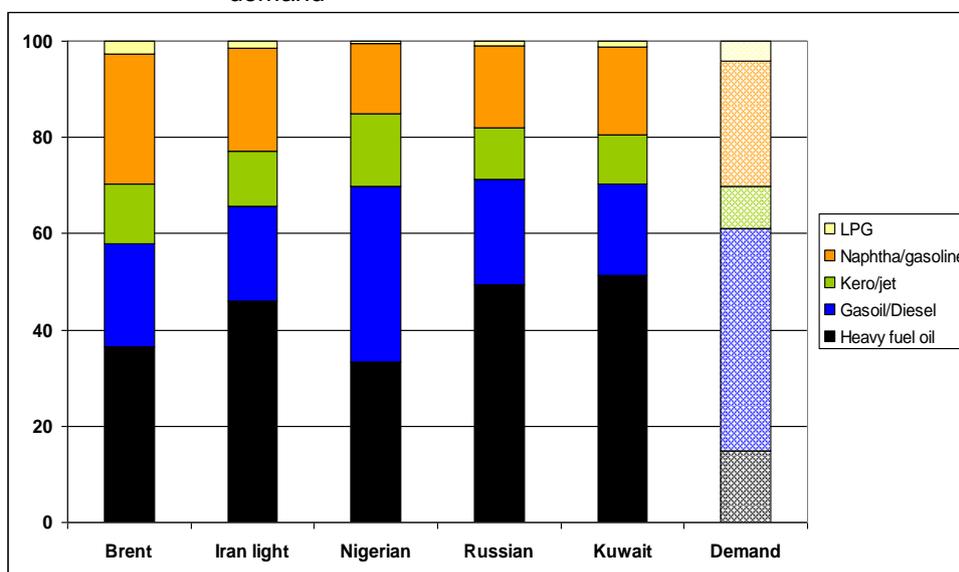


## 6. GREENHOUSE GAS AND CLIMATE IMPACTS

### 6.1. REFINERY GHG IMPACTS

. Crude oils have different compositions, but none of them match the market demand. Typically crudes are heavier and contain an excess of heavy fuel oil but not enough distillates compared to market demand (see **Figure 17**).

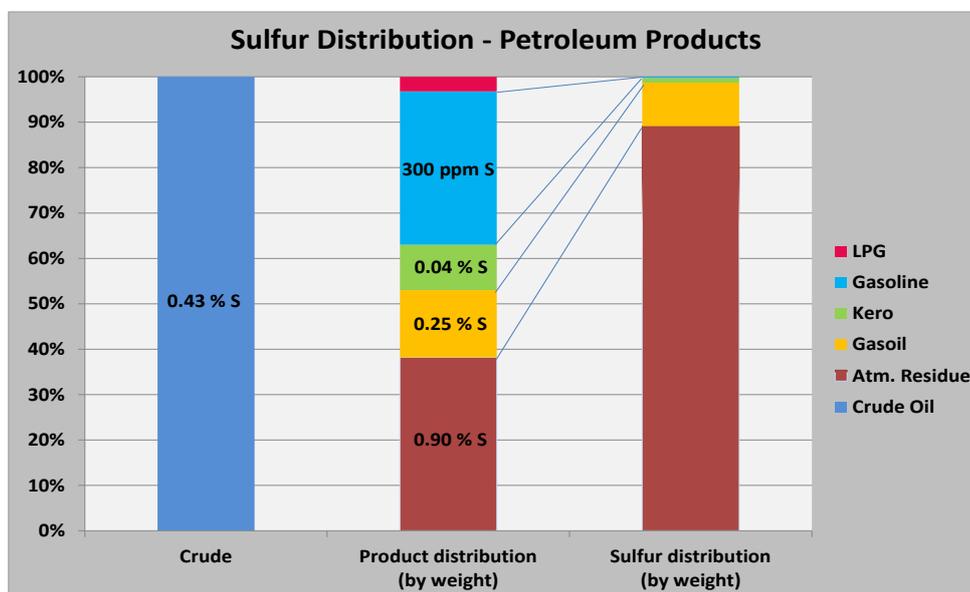
**Figure 17** Typical crude oil compositions versus European oil product demand



Refineries use available crudes to produce all the desired products at the same time, while allowing for crude quality variations.. More complex refineries have invested in conversion units (distillate hydrocracking and residue conversion) to transform the lower demand heavy fuel oil into lighter, higher value products (light and middle distillates).

The density and sulphur content in the crude depends on the origin, and affects the market value of the crude. Once the crude is split into boiling range fractions in the crude distillation unit (CDU), the sulphur is distributed in all the CDU output fractions, but is more concentrated in the heavier, high-boiling point fractions. **Figure 18** illustrates, for example, the output of a distillation unit processing a typical Brent crude with a sulphur content of 0.43% m/m. This crude produces a straight run heavy fuel oil with 0.90% m/m sulphur content.

**Figure 18** Sulphur distribution of petroleum products



Considering the existing sulphur limits imposed in all refined products, refineries have to remove sulphur from output streams by the use of hydrodesulphurisation units. These units remove sulphur by reacting the sulphur-containing compounds with hydrogen to form hydrogen sulfide (H<sub>2</sub>S). Subsequently the elemental sulphur is removed in a recovery unit and sold as a product.

Conversion and hydrodesulphurisation units consume large amounts of hydrogen). For this reason refineries must ensure that there is enough hydrogen production and sulphur recovery unit capacity to satisfy the increasing demand for lighter and lower sulphur products.

Conversion and hydrodesulphurisation units are also high-energy consuming processes. Therefore, higher demand of distillates and more stringent sulphur limits result in more energy consumption in the refinery industry. Any increase in energy consumption leads to more GHG emissions, which have an important climate impact.

Focusing on Europe, Concaawe estimated that European refineries will need 1.0 Mt/y of additional hydrogen production capacity and will increase their GHG emissions by 7 Mt/y to meet the demand imposed by the marine fuel 0.50% sulphur cap in 2020 [16]. The estimated residual marine fuel demand in Europe in 2020 amounts to 28 million tonnes, around 5% of the total European petroleum products demand.

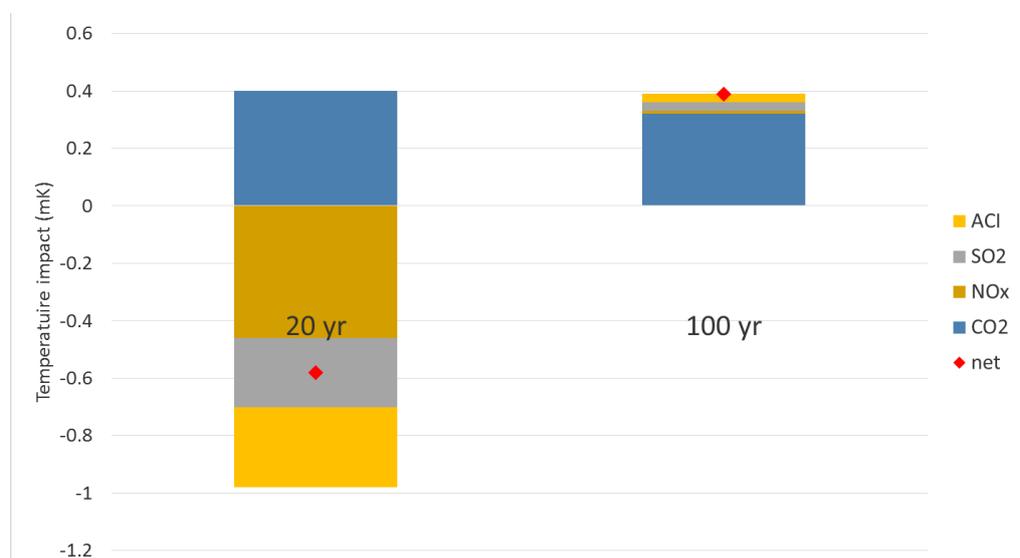
Considering that the total global residual marine fuel demand in 2020 is estimated to be about 10 times the demand in Europe, the introduction of a global 0.50% sulphur limit in marine fuels can be expected to have an important climate impact due to the increase in GHG emissions from the global refining industry. This has indeed been confirmed in the 2016 EnSys/Navigistics study [25] which estimated an increase of 21 to 44 Mton/yr to the global refining industry CO<sub>2</sub> emissions which represents a 2.1 to 4.4% increase.

## 6.2. AIR QUALITY AND CLIMATE COUPLING

Net man-made impacts on the Earth’s climate are the result of complex processes. The largest impact on the climate due to human activity is the warming effect due to increasing atmospheric CO<sub>2</sub> concentrations. However many other atmospheric pollutants also affect the climate. Some have a warming affect, e.g. methane and black carbon, while others have a cooling effect. These pollutants are called Short Lived Climate Forcers (SLCFs) and dealing with them is considered to be important to address global warming concerns, in particular as some of these compounds have a significantly more potent warming effect than CO<sub>2</sub>. The climate impact of these compounds is expressed as a Global Warming Potential (GWP) relative to the warming potential of CO<sub>2</sub>. As the lifetime of these compounds is substantially shorter than the lifetime of CO<sub>2</sub>, a compound’s GWP depends on the time frame considered. 20 and 100 year timeframes are most commonly used to evaluate GWPs.

SO<sub>2</sub> emissions give rise to the formation of sulphate aerosols. These aerosols have a strong cooling effect. This effect is further reinforced through Aerosol Cloud Interactions (ACI). When considering a 20 year time frame, this overall cooling effect is significantly larger than the warming effect of CO<sub>2</sub> and other pollutants, resulting in a net cooling effect. Over a 100 year time frame, the warming effect of CO<sub>2</sub> becomes dominant, and shipping emissions will have a net warming effect. This is illustrated in **Figure 19**, based on data from the 5<sup>th</sup> Assessment Report of the International Panel on Climate Change [26]. Another indication of the significance of the sulphate aerosols effect can be found in the 2016 EMEP Status Report [12], which states: *“Reduced European sulphur emissions unleashes the Arctic greenhouse warming: Using the advanced climate model NorESM1-M, the reduction of sulphate in Europe (EMEP region) between 1980 and 2005 is found to explain as much as about half of the warming observed in the Arctic during the same period. In other words, as a result of regulations on emissions in Europe to improve air quality and acidification of water and soils, a substantial portion of the dampening effect of aerosol particles has been removed, and consequently more of the actual warming of the Arctic due to increased greenhouse gas levels has emerged.”*

**Figure 19** Shipping climate impact – 20 and 100 yr time horizon climate 1 year pulse emissions



Similar observations have been made in a paper by Haakon Lindstad et al. [27]. The authors estimated the average global warming impact over a 20- and 100-year period for different scenarios. In their conclusions, the authors suggest that from an overall climate and environmental perspective it would be better to allow continued use of high sulphur fuels in open waters and to focus emission reduction efforts on coastal waters only.

## 7. CONCLUSIONS

It is clear that emissions from international shipping are a significant source of anthropogenic SO<sub>2</sub>. However SO<sub>2</sub> emissions from international shipping are not the largest source of SO<sub>2</sub> that is generated above the oceans. The largest source of S emissions above the oceans is biomass, producing emissions of dimethyl sulphide that will oxidise to SO<sub>2</sub> when exposed to sunlight.

The impact of shipping emissions on health and environment on land is a strong function of distance from shore. Efforts to reduce emissions from international shipping should therefore be focused on ships operating in harbours and relatively close to shore. The introduction of the global S cap can be expected to significantly reduce contributions from shipping to ambient SO<sub>2</sub> and sulphate aerosol concentrations in coastal zones that are not already covered by a SO<sub>x</sub> Emission Control Area. The need and justification for the establishment of further SO<sub>x</sub> Emission Control Areas can be evaluated on a case by case basis using the IMO guidelines for the establishment of ECAs.

Removing sulphur from fuels will result in increased CO<sub>2</sub> emissions from refineries related to the additional processing, including hydrogen treatment. Removing SO<sub>2</sub> from a ship's exhaust by use of a scrubber offers an alternative with a lower overall GHG impact.

SO<sub>2</sub> emissions lead to the formation of sulphate aerosols that contribute to a substantial short-term (20 years) cooling effect. Reducing marine fuel S content as required under MARPOL's Annex VI Regulations will essentially eliminate this short-term cooling effect.

## 8. GLOSSARY

<b>CAFE</b>	Clean Air For Europe program
<b>CLRTAP</b>	Convention on Long-range Transboundary Air Pollution
<b>ECA</b>	Emission Control Area
<b>EEA</b>	European Economic Area
<b>EGCS</b>	Exhaust Gas Cleaning Systems
<b>EMEP</b>	European Monitoring and Evaluation Programme
<b>EPA</b>	Environmental Protection Agency
<b>GHG</b>	Greenhouse Gas
<b>GWP</b>	Global Warming Potential
<b>IMO</b>	International Maritime Organization
<b>LCV</b>	Lower Calorific Value (same as LHV)
<b>LHV</b>	Lower Heating Value (same as LCV)
<b>LNG</b>	Liquefied natural Gas
<b>MARPOL</b>	International Convention for the Prevention of Pollution from Ships
<b>MEPC</b>	Marine Environment Protection Committee
<b>MJ</b>	Megajoule
<b>Mton</b>	Million metric ton
<b>NM</b>	Nautical mile (1.852 km)
<b>PPE</b>	Personal Protective Equipment
<b>SECA</b>	Sulphur Emission Control Area
<b>SLCF</b>	Short Lived Climate Forcers
<b>TSAP</b>	Thematic Strategy on Air Pollution
<b>YOLL</b>	Years Of Life Lost

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## APPENDIX 1 - BACKGROUND ON SHIPPING

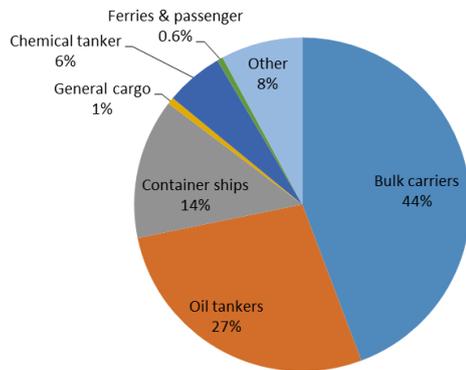
### Role of international shipping

International shipping transports around 90 per cent of global trade to peoples and communities all over the world [28]. More than 50,000 merchant ships are involved in international trade.

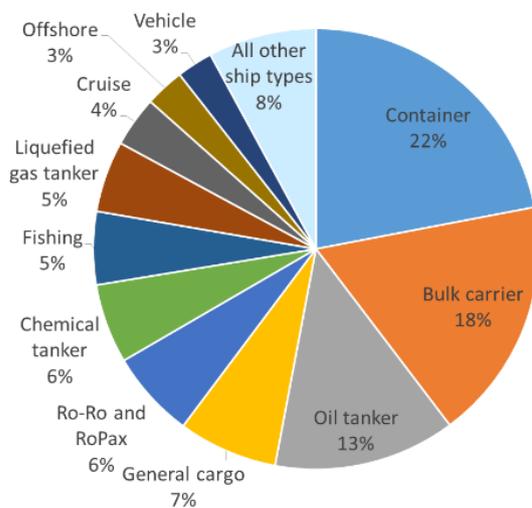
### World fleet

Bulk carriers are the largest shipping sector in terms of deadweight tonnage, followed by oil tankers and containers ships [29], as illustrated by **Figure A1.1**. However, in terms of fuel consumption, containerships are the biggest fuel consumers , see **Figure A1.2**

**Figure A1.1** World Fleet by Type (% dwt)

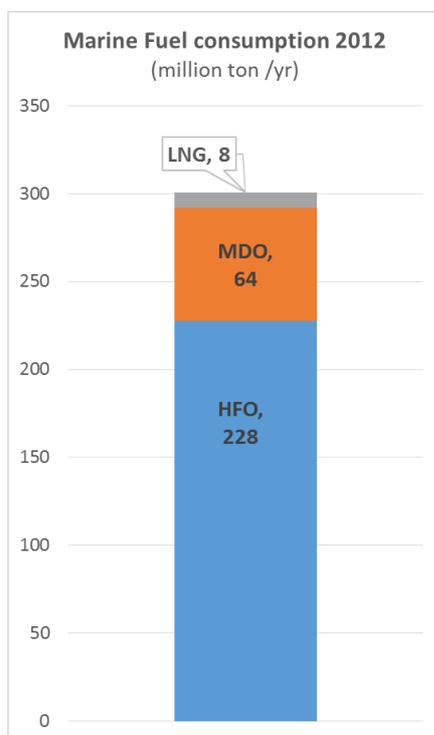


**Figure A.1.2** Fuel consumption by ship type (2012)



Almost all large ships use residual fuels (heavy fuel oil or HFO) as their main fuel. Distillate fuels such as marine diesel oil (MDO) and marine gasoil (MGO) are used by small ships and in some auxiliary engines on board ships. MGO is also the main fuel used in Emission Control Areas (ECAs) since 2015 when the maximum S level was reduced to 0.10%. A small number of ships are using LNG as their main fuel. **Figure A.1.3** shows the distribution of marine fuel types, whereby MDO and MGO have been grouped together as a single marine distillate category. In 2012, the total Marine Fuel demand represented approximately 6% of the global world oil demand. However, residual marine fuel accounted for almost half the global residual fuel demand.

**Figure A.1.3** Marine fuel type distribution



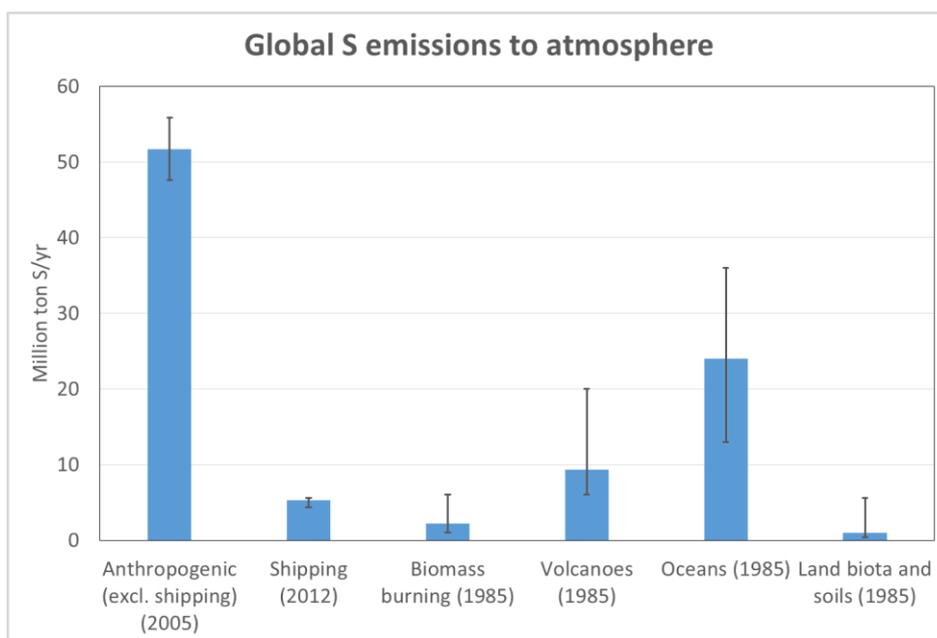
## APPENDIX 2 - NATURAL AND ANTHROPOGENIC SOURCES OF SULPHUR EMISSIONS

### Natural Sources

Sulphur is a naturally occurring element, essential for all life on the planet. Sulphate ions are assimilated by organisms and converted to organic sulphur compounds that form a building block of proteins. The major sinks of S are mineral compounds and the world's oceans.

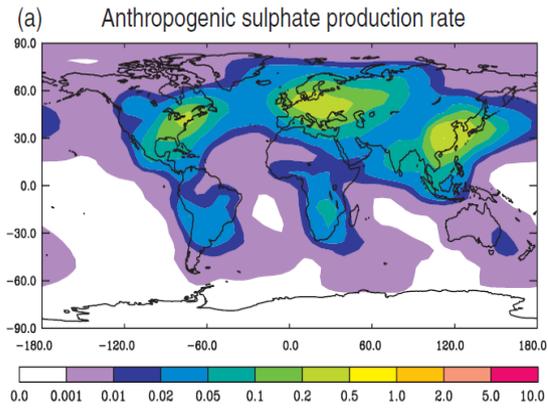
Natural levels of sulphur compounds in the atmosphere are low. The main natural sources are volcanoes and biogenic emissions, primarily dimethyl sulfide (DMS) generated by plankton in the oceans [30], see **Figure A.2.1**. Both SO<sub>2</sub> and DMS are oxidized to form sulphate aerosols through atmospheric chemistry processes.

**Figure A.2.1** Man-made and natural sources of sulphur emissions to atmosphere

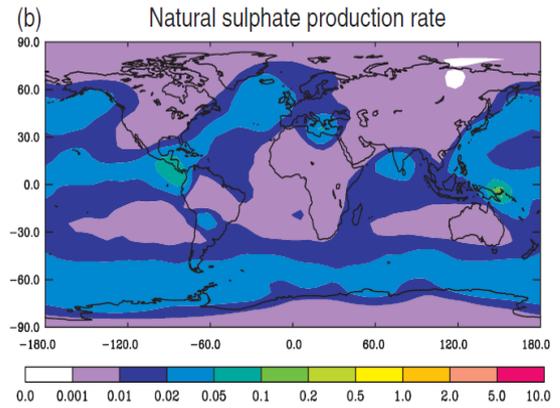


The relative importance of natural sources of sulphur emissions to atmosphere is illustrated very well by 2 charts from the 3<sup>rd</sup> Assessment Report of the International Panel on climate change that show the annual average source strength in kg km<sup>-2</sup> hr<sup>-1</sup> of the sulphate production rate from anthropogenic sources and from natural sources, **Figures A.2.2 and A.2.3** [31].

**Figure A.2.2**



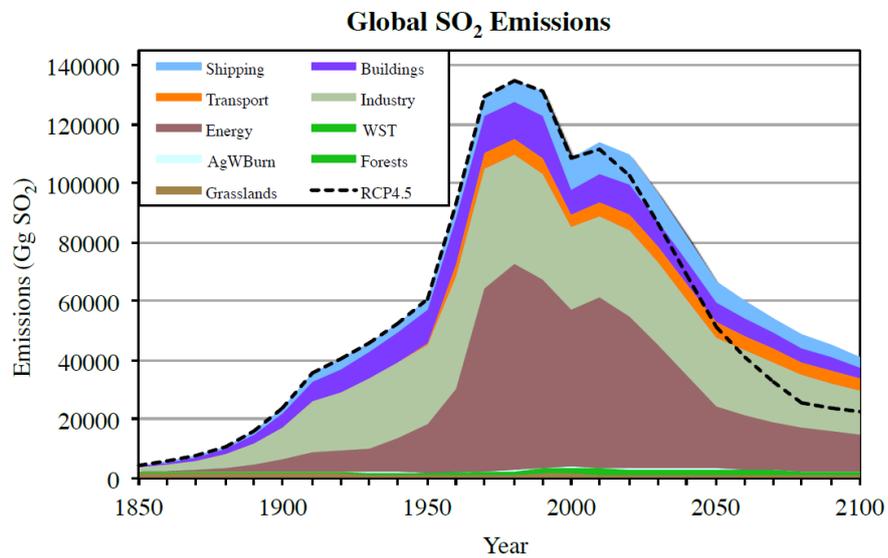
**Figure A.2.3**



**Anthropogenic Sources**

The largest man-made sources of global SO<sub>2</sub> emissions are land based. In 2005, SO<sub>2</sub> emissions from international shipping amounted to about 10% of global anthropogenic emissions. Land based emissions are projected to decrease substantially in coming decades. This is illustrated by **Figure A.2.4** [32].

**Figure A.2.4** Anthropogenic SO<sub>2</sub> emissions



## APPENDIX 3 - AIR QUALITY MODELLING FOR POLICY MAKING

### Background

This Technical Annex provides an overview of the field of Air Quality Modelling as currently applied to policy formulation. It is not intended to be a definitive work on the topic as that would be beyond the scope of the current report. It is intended to explain and provide references to the substantial technical foundation on which air quality policy formulation is built. The references given provide links to the detailed literature should specific follow up be required.

### Overview

The atmosphere is a complex dynamic system with multiple sources and sinks for its constituent components. Atmospheric modelling is undertaken for many reasons, of which weather and air quality are two of the most significant. Modelling techniques and methods vary according to the application and the pollutant of interest. In addition to the movement of air masses, atmospheric chemical transformation processes are modelled. In order to address a variety of problems, the modelling of air quality is undertaken at a variety of scales from the local sub kilometre range up to the hemispheric long range. An example of short range and relative short temporal scale is the modelling of accidental pollutant release in order to inform emergency response. An example of large scale multiyear modelling is that used for tracking and evaluating international collaborative air pollution control policy. It is this latter context which is relevant to this report on Maritime Emissions and on which the rest of this technical annex will focus.

### Long range air pollution modelling – history

The Convention on Long-Range Transboundary Air Pollution (LRTAP) was signed in Geneva, 13 November 1979. The convention was a response to the scientific work which had established that pollutant emissions from one country could have impacts in neighbouring countries due to their long range transport in the atmosphere.

An integral part of the Convention was the establishment of scientific support programmes of monitoring and modelling to enable proper management of policy initiatives designed to reduce the impacts of long range pollutants on human beings, eco systems, and environments (both natural and man-made). The European Monitoring and Evaluation Programme (EMEP) provides this scientific support to the LRTAP Convention including:

- Atmospheric monitoring and modelling
- Emission inventories and emission projections
- Integrated assessment modelling

The work of EMEP is carried out in collaboration with a broad network of scientists and national experts. This work includes (1) collection of emission data, (2) measurements of air and precipitation quality and (3) modelling of atmospheric transport and deposition of air pollutants.

EMEP produces detailed supporting documentation including progress reports and technical verification reports. Additionally they provide an open source code release of the model.

### Principles of the EMEP model

The current EMEP model is a three dimensional Eulerian gridded model. This means that the domain of study is subdivided using a grid reference system and the model inputs and outputs are related to their corresponding grid areas. Geographical boundaries typically do not coincide with

grid boundaries and any given grid area may contain a mix of sea and land, both of which may have a range of characteristics and attributes. It follows that as the size of a gridded area is reduced, the level of accuracy with which it can reflect these attributes increases. It also follows that the associated number of computations increases. In addition to using a grid to subdivide the domain of study, the EMEP model divides the atmosphere into 20 vertical layers, between the surface and an atmospheric pressure of 100hPa (approximately 16,180 m for a standard atmosphere).

The EMEP model is a “Chemical Transport Model”. This type of model uses weather data to drive the transport functions which map the source emissions to their receptor points. As emissions to the atmosphere participate in, and are subject to, chemical reactions (including photo-chemical) and transformations, the EMEP model includes chemical processing schemes to properly account for these changes. One process of particular note, especially in the context of shipping emissions, is the formation of secondary particulate matter. Primary particulate matter is emitted at source in particulate form whereas secondary particulate matter results from chemical transformation of primary pollutants during their atmospheric transport.

In order to reduce the computational work required to evaluate alternative emission scenarios, EMEP produces gridded sets of source to receptor coefficients, also called blame matrices. These coefficients are the result of a specific, calibrated and methodical set of EMEP model runs applied to systematically adjusted pollutant emissions. The results are published at the level of “Country to Grid” and a more aggregated “Country to Country” level. These coefficients provide a linear relationship between pollutant emissions and resulting atmospheric concentrations. Hence using these source-receptor relationships, alternative emissions scenarios can be evaluated for their impact on atmospheric concentrations without the need to perform a full run of the EMEP model for each scenario. This, along with Integrated Assessment Models discussed below, provides an efficient mechanism for policy appraisal.

A full description of the EMEP model is provided by Simpson et al 2012 [33]: The paper abstract gives the essential details of the model:

**Abstract.** *“The Meteorological Synthesizing Centre-West (MSC-W) of the European Monitoring and Evaluation Programme (EMEP) has been performing model calculations in support of the Convention on Long Range Transboundary Air Pollution (CLRTAP) for more than 30 years. The EMEP MSC-W chemical transport model is still one of the key tools within European air pollution policy assessments. Traditionally, the model has covered all of Europe with a resolution of about 50 kmx50 km, and extending vertically from ground level to the tropopause (100 hPa). The model has changed extensively over the last ten years, however, with flexible processing of chemical schemes, meteorological inputs, and with nesting capability: the code is now applied on scales ranging from local (ca. 5 km grid size) to global (with 1 degree resolution). The model is used to simulate photo-oxidants and, both inorganic and organic aerosols.”*

The above paper was published in a Special Issue of the European Geosciences Journal “Atmospheric Chemistry and Physics” which serves as a central location for the analysis of a range of scientific issues based on the EMEP programme - “EMEP – an integrated system of models and observations in support of European air quality and policy”.

Readers seeking further information should consult the “Atmospheric Chemistry and Physics” Special Issue as well as the extensive publications of EMEP [34].

### **Application of EMEP and Integrated Assessment models to policy design**

Using the atmospheric concentrations provided by the EMEP model as inputs to further models allows the impacts of emissions to be evaluated. A key concept is “impact potency” which is the

product of the pollutant concentration of interest and its power to induce effects. If a pollutant has a high concentration and it strongly induces an effect it will have high impacts and vice versa.

Impacts are valued with metrics appropriate to their effects. For impacts on morbidity a widely used standard is the “Year of Life Lost” (YOLL). This in turn is given a monetary value with a range of valuations to result in the metric “Value of a Life Year” (VOLY). It follows that, according to a selected VOLY, the assigned monetary value of morbidity impacts will vary. For impacts on ecosystems the metric of unprotected land area is used and this is essentially the area of land which is subject to a pollutant load which it cannot sustain without detriment.

Scenarios are constructed to reflect policy options – ranging from an extreme case such as a complete and immediate ban on a particular pollutant through to either the maximum possible reduction in emissions dependent on technical constraints or a phased reduction in emissions. Well-designed scenarios will take account of the practical implications of implementation and are (often) bookended by the Maximum Technically Feasible Reductions (MTRF) as a limit to what can be achieved. The baseline is often taken to be that which will be achieved under current initiatives and legislation, this current legislation equivalent is abbreviated to CLE. The gaps between these two end points is used to provide a measure of the ambition level of a particular policy option, referred to as Gap Closure. A 100% Gap Closure option would be the most ambitious possible scenario demanding implementation of all technically feasible emission reductions, whilst a 0% Gap Closure option would be a nil ambition proposal staying within the delivery of current initiatives.

Implementation of emission reduction measures will typically require capital expenditure. To provide analysis of the cost justification of proposals, the field of Integrated Assessment Modelling has been developed (IAM). IAM works by integrating the modelling steps from emissions through to concentrations, to impacts and to costs and benefits. The European Commission air quality policy tool is the Greenhouse Gas - Air Pollution Interactions and Synergies model (GAINS), developed and maintained by the Institute for Applied Systems Analysis (IIASA). The GAINS model uses the source-receptor relations produced by EMEP for the first of the modelling steps in the IAM chain. The subsequent steps are supported by other policy model inputs and extensive databases of technical and economic material.

In addition to being used to evaluate specific policy proposals, the GAINS model has optimisation functions which seek to deliver a given level of ambition at the minimum total cost to the EU as a whole. An important output of this optimisation process is the allocation of individual emission reduction targets to member states. These emission reductions are expressed as “ceilings” i.e. upper limits on emissions by member states. This optimisation function relies on the source-receptor derived impact potencies described above.

### **Application of EMEP and GAINS models to Marine Emissions**

From the point of view of emissions, the EMEP model treats sea areas in the same way as land areas. The source emissions from sea areas result in pollutant concentrations in the receptor grids of the EMEP model. These pollutant concentrations can then be evaluated by the GAINS integrated assessment model for their impacts as described above. The EMEP and GAINS model designate sea areas for the Baltic Sea, the Black Sea, the Celtic Sea and Bay of Biscay, the North Sea and the Mediterranean Sea.

Through use of the EMEP and GAINS models a comparison between the relative impacts and cost justification of marine and land based emission reductions can be made. This is essential in the context of MARPOL Annex VI which has a requirement that an application for an “Emission Control Area” (ECA) should only be adopted if it can be demonstrated that such designation of a sea area is more cost effective than further land measures.

### **The SMARTER and MATCH models**

SMARTER is the Concaawe in house integrated assessment model. It is built on the EMEP source-receptor relationship and the GAINS databases. It has been benchmarked against GAINS outputs and has been successfully used in policy analysis in significant EU legislative initiatives such as CAFE and TSAP. In addition to optimisation functions, SMARTER also has capabilities which enable a wide range of flexible sensitivity analyses to be undertaken.

In the current context these flexible sensitivity analysis capabilities have been used to apply the results of a previous experiment which was run using the Swedish Meteorological and Hydrological Institute (SMHI) Multi-scale Atmospheric Transport and Chemistry, MATCH model [35]. The experiment modelled the concentration impacts of emissions from a westbound vessel sailing from Lisbon. This trajectory was chosen such that the prevailing on shore meteorology would yield the most adverse concentration impacts. From the results of the experiment a concentration impacts potency versus distance from shore relationship was derived. This relationship was then in turn used to create pseudo banded sub divisions of the EMEP sea areas enabling the analysis of sulphur in fuel policy options according to distance from shore.

## APPENDIX 4 - EXHAUST GAS CLEANING SYSTEMS

### Scrubber technologies

Scrubbing technology is already a long established technology in shore-based situations cleaning up emissions from oil and coal-based power plants and industrial processes. The technology falls into two distinct categories – wet and dry.

For ships there are several different scrubber designs that remove SO<sub>x</sub> from exhaust gases. Space limitations and power consumption of the scrubbing equipment are rarely factors to consider when used ashore but they are of much greater importance for ship operators when considering scrubber on board integration.

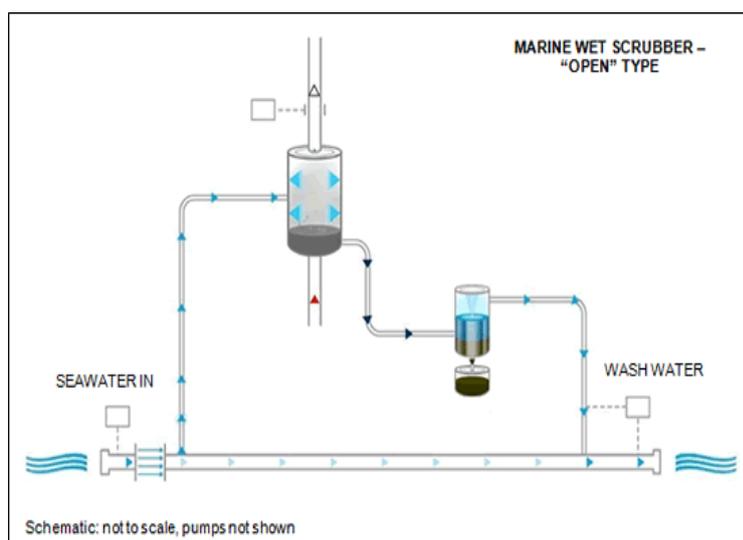
The majority of systems include 3 basic components [14].

- A vessel which enables the exhaust stream from an engine or boiler to be intimately mixed with water – either seawater or freshwater (or both).
- A treatment plant to remove pollutants from the “wash” water
- Sludge handling facilities

Most common systems are wet scrubbers:

- The system may be an “open” type as shown in **Figure A.4.1**, whereby water is taken from the sea, used for scrubbing, treated and discharged back to sea, with the natural chemical composition of the seawater being used to neutralize the results of SO<sub>2</sub> removal. *Typically “open” seawater systems use 45m<sup>3</sup>/MWh.*

**Figure A.4.1** Marine Wet Scrubber – Open Type

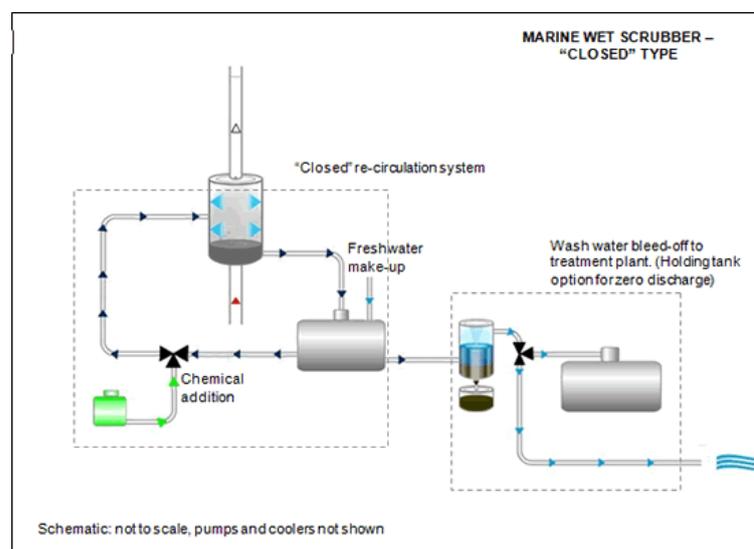


- Or,
- the system may be a “closed” type as shown in **Figure A.4.2**, whereby freshwater treated with an alkaline chemical (e.g. NaOH) is used for neutralization and scrubbing. The wash

water is re-circulated and any losses made up with additional freshwater. A small quantity of the wash water is bled off to a treatment plant before discharge to sea. Typically “closed” freshwater systems discharge 0.1-0.3m<sup>3</sup>/MWh (zero discharge possible for short periods).

- Closed loop systems typically consume sodium hydroxide NaOH in a 50% aqueous solution. Sodium hydroxide has a pH of 14 and is hazardous. Less hazardous alternative alkaline additives such as magnesium oxide and sodium bi-carbonate may be used.

**Figure A.4.2** Marine Wet Scrubber – Closed Type

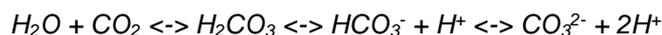


- To utilize the advantages of both systems, manufacturers also produce “hybrid” type scrubbing Systems which operate in open loop in high seas and can switch to closed loop (no discharge) in sensitive areas (ports and estuaries).

### pH impact for seawater scrubber and displacement of CO<sub>2</sub>

Changes in sea water pH are buffered by the carbonate system. Hydrogen ions (H<sup>+</sup>) react rapidly with inorganic carbon species (bicarbonate and carbonate ions) through the following set of reversible reactions:

*Equation 1 Carbonate equilibrium reactions*



SO<sub>2</sub> absorption in seawater is based on the following simplified reactions being in equilibrium:

*Equation 2 Sulphur equilibrium reactions*



Both reactions affect each other, resulting in a double buffering of the SO<sub>2</sub> impact on sea water pH. Increasing CO<sub>2</sub> in the atmosphere and dissolving CO<sub>2</sub> in seawater increases the hydrogen ion (H<sup>+</sup>) concentration in the ocean and thus decreases ocean pH.

The adding of SO<sub>2</sub> in seawater brings acid input and might cause out gassing of CO<sub>2</sub> back to the atmosphere. Therefore the pH decrease from these two processes cannot be just simply added.

The Danish EPA report [18] concluded that the impact of the discharges of acidic scrubber water on the pH and buffering capacity were negligible and that this conclusion also holds for areas with significantly lower buffer capacity than the Kattegat and for double the traffic intensity.

Other studies such as the modelling by Hassellöv et al [36] and the JRC report [37] had different conclusions. The impact on the pH decrease from discharging the scrubber acidic wash water into the seawater was found to be small, but not insignificant, and regionally varying. Seasonal coastal acidification might be more significant.

One has to keep in mind that in these available studies, the effects on acidification of scrubbers are compared with a situation with no scrubbers but do not consider that lowering sulphur in fuels in refineries will increase overall CO<sub>2</sub> emissions. This will also potentially contribute to additional ocean acidification impacts.

In summary: oceans are acidifying due to increasing CO<sub>2</sub> levels in the atmosphere. Sulphur acidifies as well, but overall impact is much lower than the effect of increasing atmospheric CO<sub>2</sub> levels. However, impact of acidic scrubber discharges may be more relevant regionally where there are high discharge rates and limited mixing (ports/estuaries where ships may be stationary). In these cases, the magnitude of the impact may be similar to the impact of CO<sub>2</sub>. CO<sub>2</sub> and sulphate impacts on pH are not additive, as increased acidity in the ocean releases some CO<sub>2</sub> to atmosphere.

## APPENDIX 5 - COASTAL ZONE MODELLING

Using the banded emissions and the derived impact potencies with a reference value of 0.5% S content, (consistent with the GAINS 2020 dataset), a reference total of potency adjusted emissions value was calculated:

$$\sum_{i=1}^5 (E_{ref_i} * P_i) \quad \text{Equation 1}$$

Using the same approach, pro rata calculations for sulphur contents of 2.94% and 0.1% sulphur, alternative potency adjusted emissions for each of the five zones were calculated.

To examine the two segregated sulphur zone cases, a combination of trial and error test and linear interpolation was used. Starting at zone 5 (furthest from shore) and working to zone 1, the 2.94% S potency adjusted emissions were sequentially totalled, subject to the condition that the sum did not exceed the 0.5% reference total calculated with equation 1. If including an additional zone at 2.94% S content caused the total to exceed the reference total, for this current additional zone (to be called the “transition zone”) and subsequent zones the alternative 0.1% S value potency adjusted was used. In this way, the segregated sulphur zone total of potency adjusted emissions was kept below the 0.5% S reference total - i.e.:

$$\text{Maximise } \sum_{i=1}^5 (E_{alt_i} * P_i) \text{ subject to constraint } \leq \sum_{i=1}^5 (E_{ref_i} * P_i)$$

The surplus between the segregated and 0.5% S totals was then used to pro rata the distance across the transition zone to find the distance at which the segregated case was equivalent to the 0.5% S reference case – i.e.:

$$\text{Pro rata distance (NM)} = \text{transition zone width (NM)} * \frac{\text{surplus}}{((E_{2.94\%S} - E_{0.1\%S}) * P_i)}$$

This method was used for both of the segregated sulphur zone cases; however for the whole Mediterranean Sea case, the banded emissions values were adjusted based on the ratio of potencies used in the GAINS model, both for emissions within the 200 NM EEZ and those on the High Seas, outside the EEZ.

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