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The impact of international shipping on European air quality and climate forcing

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Executive summary

Due to its dependence on fossil fuel combustion and the fact that it is one of the least regulated anthropogenic emission sources, emissions from the marine transport sector contribute significantly to air pollution and climate change.

The main objective of this report is to provide a comprehensive review of recent literature and reports, taking into account expert knowledge, on the maritime transport sector. The report addresses the sector's impact on air quality and climate forcing in Europe. In order to provide this overview a broad range of topics have been addressed.

These include:

- registration of ships, international maritime law and international and European environmental legislation (Chapter 2);
- monitoring and modelling of maritime fuel consumption and resulting emissions (Chapter 3);
- past and future trends of air pollutants and greenhouse gas (GHG) emissions from shipping (Chapter 4);
- attribution of air quality problems to emission from the maritime transport sector by evaluating atmospheric observations and modelling data (Chapter 5); and
- understanding the climate forcing characteristics of ship emissions and atmospheric modelling (Chapter 6).

Main findings from the report

Key findings, as highlighted below, focus on the importance of emissions compared to other sectors; present and future air quality issues; and, the contribution of the sector to present day and future climate forcing.

Emissions from maritime transport in European waters constitute a significant share of worldwide ship emissions of air pollutants and greenhouse gases.

The sector's environmental impact is significant as emissions such as carbon dioxide (CO_2), nitrogen oxides (NO_X), sulphur dioxide (SO_2) and particulate matter ($PM_{2.5}$) from shipping occurring in European waters can contribute up to 10–20 % of overall worldwide shipping emissions. When considering all ship traffic from national and international shipping arriving or departing from EU-27 ports the contribution can be up to 30 % for CO_2.

This report also shows that the number of ships registered in the EU-27, combined with ships owned by European companies but registered in third countries, is substantial. In 2011, about 19 % of the world merchant vessel fleet above 100 gross tonnage (GT) were registered in European countries. When taking into account ships registered abroad by European ship owners the European share of the global merchant fleet will be higher.

Emissions of nitrogen oxides from international maritime transport in European waters are projected to increase and could be equal to land-based sources by 2020 onwards.

The report includes a review of recently developed scenario studies on ship emissions and shows that NO_X emissions could be equal to land-based emissions sources from 2020 onwards. SO_2 emissions in European waters will continue to decrease further from 2020 onwards due to legislation on the sulphur content in fuel. It is expected that this will also lead to a decrease in emissions of $PM_{2.5}$.

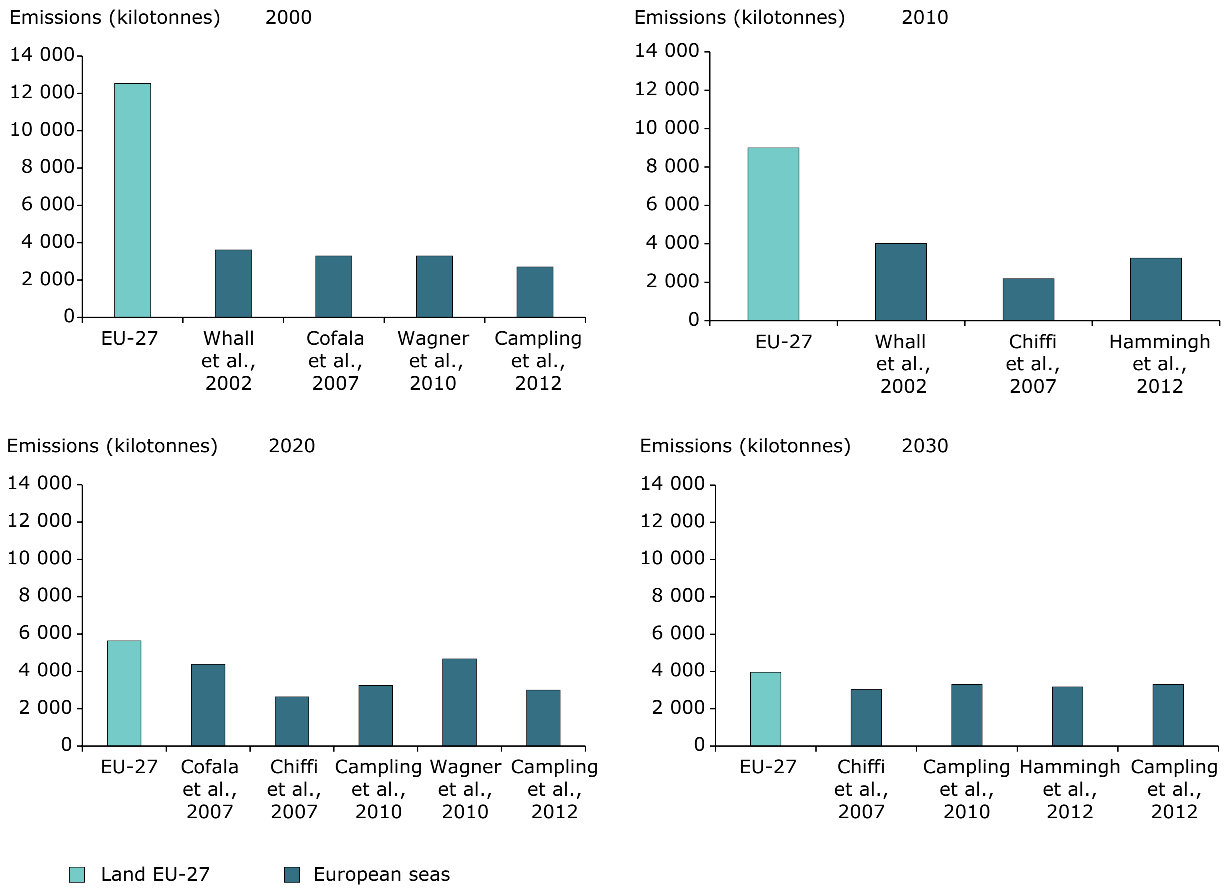
Shipping emissions can contribute significantly to local air quality problems in Europe, but the pan-European knowledge and observation base needs to be improved to provide a more complete picture.

The review of available observation data shows that there are relatively few measurement data available to attribute the contribution of ship emissions to local air pollution. Available data shows that the contribution of particulate matter from shipping to local concentrations can be up to 20–30 %, especially for fine particulate matter.

Due to the limited availability of observation data, the attribution of ship emissions to air quality has been estimated by performing sensitivity studies

Figure ES.1 Comparison of NO_x emission trends between EU-27 land-based sources and emissions from international shipping within European seas

NO_x emissions in the EU-27 and the European seas compared, 2000–2030



using atmospheric chemistry models. Existing studies and model runs performed in support of this report show that there are several hotspot areas in Europe where the contribution of shipping can be up to 80 % for NO_x and SO_2 concentrations, up to 25 % for $PM_{2.5}$, up to 40 % for secondary sulphur aerosol and up to 15 % for ozone (O_3). Results from model studies confirm the potential for an increased contribution from the shipping sector to air quality in the future. An improved assessment at the European level is needed to better understand the potential impact on air quality in urban and coastal areas.

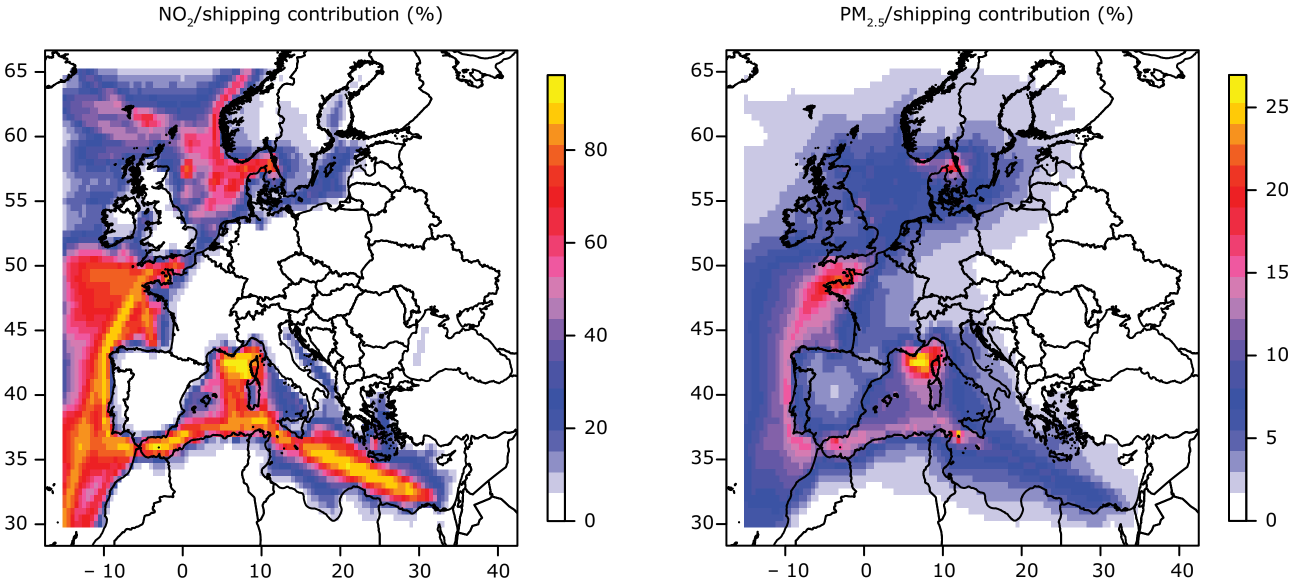
European legislation aiming to reduce the sulphur content of marine bunker fuels is improving local air quality in Europe.

The value of local studies in providing relevant information is highlighted by one example focusing on the port of Rotterdam. One study, highlighted in the report, showed the impact of sulphur legislation and economic trends on air quality levels in the port of Rotterdam. The trends clearly show a decoupling between cargo transported in the port and average measured and modelled SO_2 concentrations in the Rotterdam area. This finding confirms results from earlier studies in the Mediterranean area that EU sulphur legislation is effectively improving local air quality.

At the global scale, studies shows that present-day ship emissions of both air pollutants and GHGs and their contribution to direct and indirect climate forcing indicate a net cooling effect.

Emissions of greenhouse gases and air pollutants from international maritime transport contribute to climate forcing in a rather complex manner. This can come via a variety of processes such as the absorbing (leading to a warming effect) or scattering of radiation (leading to a cooling effect) as well as influencing cloud formation over oceans (cooling, the so-called indirect aerosol effect) and depositing

Figure ES.2 **Relative contribution of international shipping emissions (in %) on annual mean NO_2 and $PM_{2.5}$ concentrations in the year 2005**



black carbon on snow and ice (warming). The net warming or cooling effect is rather uncertain but most recent studies indicate that currently at a global level, the indirect aerosol effect (cooling) is more important than the other processes.

The projected reduction of SO_2 and $PM_{2.5}$ emissions from international shipping will lead to a reduction of the direct aerosol cooling effect over Europe.

Based on a model simulation prepared for this report, it has been shown that at present aerosol emissions from international shipping have a cooling effect over Europe. The study suggests that existing agreed and implemented policies will not change the direct aerosol forcing effect from cooling to warming over Europe by 2020, although the net effect of cooling is reduced due to reduction of SO_2 and PM emissions. The report suggests that further work is required to also assess the impact of emission reductions on indirect climate forcing over Europe.

There is a strong need for further harmonization of emissions information from the shipping sector across Europe.

The review of maritime emissions inventories, undertaken as part of this report, revealed relatively large differences between emissions occurring in European waters. These differences are the result of applying different models, statistical data and, moreover, coverage of different geographic domains or shipping activities. In particular, it has been found that a relatively large share of GHG and air pollutants emissions from international shipping within Europe is not accounted for in national inventories supporting key conventions.

A consistent, European wide approach for monitoring, reporting and verification of both GHGs and air pollutant emissions from the shipping sector is key to address its contribution to climate change and air quality in tandem.

The report shows the importance of taking into account the dual impact of emissions from international shipping on air quality and climate forcing. Therefore, an integrated measurement, reporting and verification (MRV) system covering emissions of air pollutants and GHG will contribute to provide better information on the co-benefits and trade-offs on related policies in Europe.

This report notes that there is a large variety of monitoring tools available to support a future MRV system, but that their application in monitoring GHG and air pollution emission depends on the objective and scope of such an MRV system. Existing monitoring tools can provide information, inter alia, on ship movements, fuel consumption, fuel quality and resulting emissions. Some tools focus on individual ships in order to monitor fuel consumption, meeting fuel quality standards or compliance with emission limits whereas others focus on sectors at specific geographic areas over a given time.

1 Introduction

The maritime transport sector is an important component of the European economy. Not only is it responsible for a large fraction of the international transport of goods between the EU-27 and the rest of the world, it also provides a significant contribution to intra-EU transport of goods. According to the EU (2012a), in 2010 the shipping sector was responsible for freight transport of approximately 1 400 billion tonne-kilometres (tkm) in the EU-27, second to road transport (1 800 billon tkm). Shipping is less important for the transport of passengers within the EU-27 when it comes to number of passengers being transported; however, it remains an important transport mode in areas where other modes of transport are limited by geographic setting (e.g. islands).

Due to its dependence on fossil fuel combustion and the fact that it is one of the least regulated anthropogenic emission sources, emissions from the marine transport sector contribute significantly to air pollution and climate change. In international and European air quality and climate policymaking, the need for international regulation on ship emissions has been identified.

Against the backdrop of the current EU environmental policy process focusing on the shipping sector from a more thematic perspective such as implementing stricter sulphur regulations in 2012, the review of air quality legislation in 2013, and the forthcoming proposal on Monitoring, Reporting and Verification (MRV) of maritime carbon dioxide (CO_2) emissions in 2013, the objectives of this report are to:

- provide an overview of key characteristics of the shipping sector, such as contribution to global trade, the ownership of the global vessel fleet and the dependence on marine bunker fuel oil;
- provide an overview of international and EU environmental legislation on the release of air pollutants and greenhouse gases (GHGs) from shipping;
- provide a detailed overview of the various monitoring and modelling tools that can be or are currently applied to quantify fuel consumption and emissions from shipping, and to what extent these can be used to support environmental policymaking;
- summarise the state of knowledge on present-day and future shipping emission trends as a result of socioeconomic developments as well as environmental policymaking;
- present to what extent the impact of ship emissions on European air quality is known and present new results from a model study evaluation of what potential future changes in this contribution to air quality might be realised due to air pollution and climate change mitigation policies;
- provide an overview on the impact of the shipping sector on global and regional radiative forcing (RF) and present new results from a model study evaluation on the extent to which co-benefits or trade-offs on direct RF can be expected from air pollution policies.

2 An overview of the shipping sector and environmental legislation

2.1 Some characteristics of the shipping sector

As mentioned in the introduction, there are various activities within the shipping sector, including its support by land-based activities, that contribute to the problem of air quality and climate change. This report focuses especially on international shipping and domestic shipping of goods and passengers. Other activities that lead to emissions of air pollutants and GHGs that are not discussed in much detail in this report are fuel combustion and use of refrigerants by fishing boats, and evaporative emissions from loading-offloading of fuels and bulk goods (e.g. non-methane volatile organic compounds (NMVOC), particulate matter (PM)).

The importance of shipping and the role of the EU in this can be illustrated via statistics on world seaborne trade, number of vessels operated by European countries and companies, and the consumption of bunker fuel oil.

Seaborne trade

Except for loading of crude oil, European countries have an important contribution to worldwide seaborne trade by using shipping to load (indicator of export) or unload (import) goods (UNCTAD, 2011). For example, Europe is responsible for about 25–30 % of the worldwide unloading of oil products transported via shipping, and 25–27 % of loading of oil products and unloading of crude oil. Also, Europe had a contribution of 25 % to the unloading of dry goods in 2006; however, this contribution has dropped since then to 18 % in 2010 (estimated). This could be due to the economic downturn in Europe in the period 2008–2010. Further information on ship movements and trade within Europe can be found in IHS Fairplay (2011).

Number of registered ships

The world merchant vessel fleet consists of more than 100 000 merchant ships with a weight of over 100 gross tonnage (GT) and about 45 000 cargo vessels over 1 000 GT (UNCTAD, 2011). The United Nations Conference on Trade and Development (UNCTAD) information for the EEA-32 countries on ownership by type of vessels is summarised in Table 2.1. Within Europe about 19 500 ships are registered with a weight over 100 GT. This is approximately 19 % of the world vessel fleet. The largest share of these vessels is in the so-called other category (1), 17 % are general cargo ships, 11 % oil tankers, 7 % bulk carriers and 5 % container ships. The data show that, of the EEA member countries, Norway, the United Kingdom and Malta are the countries with most ships registered (1 995, 1 938 and 1 724 ships, respectively). The fact that Malta has so many registered ships is due to the practice of the so-called 'flag of convenience'. This registration of ships in other countries is explained in Box 2.1. When this registration is taken into account, just 13 European countries for which data have been found have about 30 % of the world vessel fleet over 1 000 GT registered directly or indirectly to their country. This shows the importance of the European influence on the world vessel fleet and the European companies/countries responsible for them. Although not discussed in detail in this report, Europe also hosts a fishing fleet. According to The Community Fishing Fleet Register (EC, 2012), there are about 75 000 fishing vessels registered in Europe. Less than 5 000 of these are over 100 GT, with the majority under 10 GT.

Marine bunker fuel oil

Ship movement and other operations are mainly driven through the combustion of fuels. This includes the use of a ship's main engine(s) during sailing on the open sea and the manoeuvring in ports as well as running the main or auxiliary engines while at berth, loading or unloading cargo and/or passengers. For most vessel types it is common practice to switch off the main engine while at berth. This is normally not the case for oil tankers that use the main engines to power discharge and loading pumps and for passenger vessels that use extra power to ventilate and keep

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(1) The UNCTAD category 'other ships' includes oil/chemical tankers, chemical tankers, other tankers, liquefied gas carriers, passenger ro-ro, passenger, tank barges, general cargo barges, fishing, offshore supply.

general electrical services running while passengers and cargo are embarking or disembarking.

The fuel used in maritime transport is often referred to as marine bunker fuel oil. The term covers all types of shipping fuel such as marine heavy fuel oil (HFO), marine diesel oil (MDO), marine gasoline oil (MGO), and, recently, liquefied natural gas (LNG). Figure 2.1 presents the type and amount of bunker fuel oil delivered worldwide for international maritime transport (left panel) and for national maritime transport

Table 2.1 Overview of number and type of vessels > 100 GT registered in EEA-32 countries (status, January 2011) and an overview of ships 1 000 GT registered within an EEA country and the number of vessels registered under flag of convenience

Country	**Number of vessels (> 100 GT) registered under country flag**						**Number of vessels (> 1 000 GT) registered…**	
	Total	Oil tankers	Bulk carriers	General cargo	Container ships	Other	in country	in other country
Austria	2	0	0	2	0	0	No information	
Belgium	245	14	22	20	4	185	91	158
Bulgaria	92	11	14	20	0	47	No information	
Cyprus	1 014	132	275	184	198	225	No information	
Czech Republic	0						No information	
Denmark	987	159	6	119	93	610	383	592
Estonia	113	5	0	5	0	103	No information	
Finland	275	13	1	82	3	176	No information	
France	799	51	6	55	25	662	177	274
Germany	931	41	7	92	293	498	442	3356
Greece	1 433	429	267	105	32	600	758	2455
Hungary	0						No information	
Iceland	220	1	1	4	0	214	No information	
Ireland	233	2	0	35	1	195	No information	
Italy	1 649	250	89	141	21	1 148	616	220
Latvia	140	7	0	8	0	125	No information	
Liechtenstein	0						No information	
Lithuania	115	1	0	44	1	69	No information	
Luxembourg	133	17	2	14	10	90	No information	
Malta	1 724	439	528	424	107	226	No information	
Netherlands	1 302	56	2	548	68	628	522	320
Norway	1 995	179	62	379	1	1 374	818	1166
Poland	314	7	0	12	0	295	No information	
Portugal	464	23	7	59	7	368	No information	
Romania	76	7	0	6	0	63	No information	
Slovakia	19	0	1	17	0	1	No information	
Slovenia	7	0	0	0	0	7	No information	
Spain	1 469	38	9	51	6	1 365	163	226
Sweden	488	43	8	88	0	349	115	186
Switzerland	37	5	18	9	4	1	No information	
Turkey	1 334	186	101	494	41	512	551	648
United Kingdom	1 938	170	39	340	216	1 173	366	412

Note: In some cases, national statistical data show different vessel numbers compared to the UNCTAD data. Most likely this is due to definition of merchant/commercial vessels within countries and the fact that UNCTAD has a relatively broad category named 'other ships' which could include ship types not registered under merchant vessels, such as fishing vessels.

Source: UNCTAD, 2011.

over international and inland waters (right panel). As shown in the figure, according to the International Energy Agency (IEA) (2012), fuel delivery for international maritime transport in 2010 was approximately 200 million tonnes of oil equivalent (Mtoe) and a smaller fraction of about 43 Mtoe was used for domestic maritime transport.

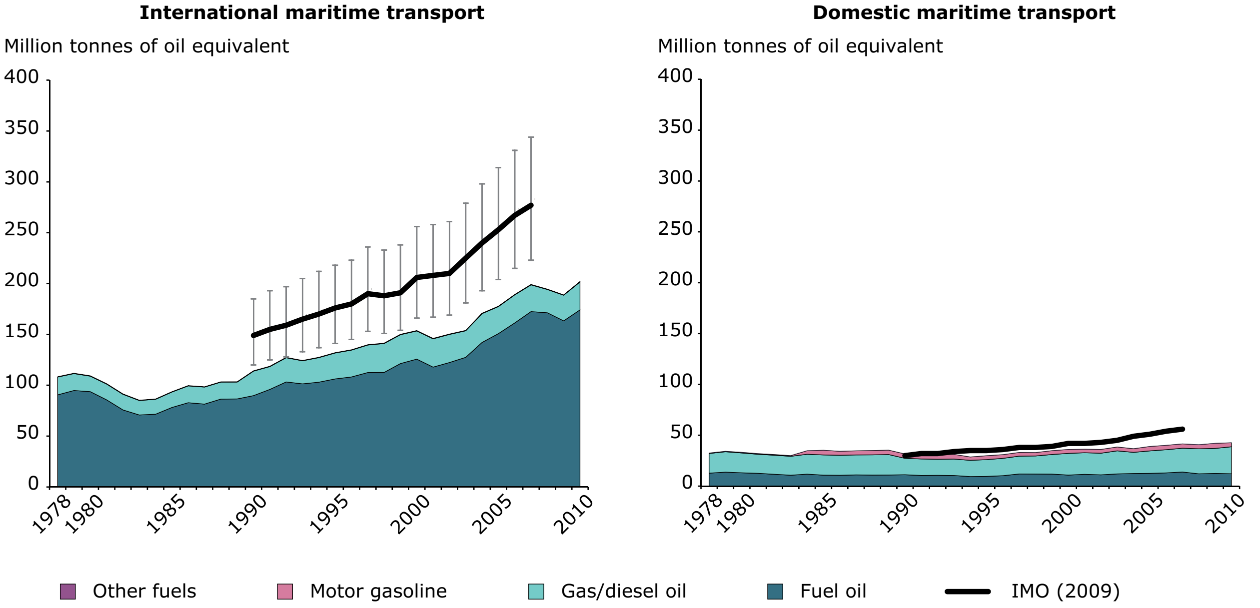
Box 2.1 Registration of ships under a flag of convenience

The concept of a flag of convenience refers to the practice of ship owners to register their ship(s) in a country (so-called flag state) other than their home country under a so-called foreign flag. Due to the fact that ships operate on a global scale, registration under a foreign flag is usually motivated for ensuring ship operations (e.g. hiring of foreign staff on board ships) and creating the best commercial conditions under which to operate a ship (e.g. taxation).

The registration of ships in other countries does not necessarily mean that a ship is brought out of the scope of environmental legislation. Compliance of a ship with international standards for safety and pollution prevention should be checked by the flag state and certificates issued based on inspection and surveys. In Europe, a total of 44 certificates and documents are checked to determine whether a ship is in accordance with EU and international legislation and conventions (see Directive 2009/16/EC).

In the past there have been cases where flag states have not implemented international standards. As a response, the shipping sector is advising ship owners to select only those countries that meet international obligations. This can be realised, for example, via annual surveys showing to what extent flag states have ratified maritime treaties/legislation and have a system in place that guarantees compliance checking (e.g. ICS/ISF, 2012). At the EU level, a so-called port state control system has been set up that ensures that all ships calling into EU ports are subject to inspection and ships that are found in non-complience with EU legislation or international conventions can be refused entry to EU ports or even be detained. Such a system was laid down in Directive 2009/16/EC. Further information on the law of the sea and jurisdiction of flag states and port states can be found in, for example, Miola and Ciuffo (2011).

Figure 2.1 Fuels delivered to international and domestic maritime transport



Note: Under IEA definitions, the statistics on international marine bunkers cover those quantities delivered to ships of all flags that are engaged in international navigation. Domestic navigation includes fuels delivered to vessels of all flags not engaged in international navigation. These amounts are used in inventory calculations as fuel consumed.

Source: EEA, based on IEA, 2012 and Buhaug et al., 2009.

The main fuels used in international shipping are HFO (87 % in 2010) and MGO/MDO (13 %). Domestic shipping shows a large variety of fuels with the most important being MGO/MDO (60 %), HFO (31 %) and motor gasoline 9 %). Whereas domestic shipping has increased slightly from 32 Mtoe in 1979 to 42 Mtoe in 2010, global international shipping has doubled from 100 Mtoe in 1978 to 202 Mtoe in 2010. There is uncertainty about the actual amount of marine bunker fuel being used. Buhaug et al. (2009) showed that when applying activity-based fuel consumption modelling (see Chapter 3), the actual amount of marine bunker fuel being used for international shipping is significantly larger, with 277 Mtoe in 2007.

The fuel quality and potential environmental impact due to, for example, sulphur and other components are dependent on the process of production of marine bunker fuels. Whereas MGO and MDO are the result of distillation processes in oil refineries, HFO is a residual product of the oil refinery process. For example, sulphur content is lower in distillate fuels than in residual fuels. In the latter, water and other sediments could also be components of the fuel. According to the EIA (2012), approximately 12 % of the world refinery output is residual fuel oil (RFO). The use of RFO is not limited to marine transport. A good overview of the refinery process, fuel types and characteristics can be found in US EPA (2008). To ensure safe application of fuels in ship engines and to confirm (inter)national environmental standards, international fuel standards have been developed. ISO 8217:2012 defines fuel requirements such as fuel density, ash content, water content and sulphur content (http://www.iso.org/iso/catalogue_detail.htm?csnumber=59479).

2.2 Environmental legislation on air pollutants and greenhouse gases from the maritime sector

Due to the characteristics of the shipping sector, global operations in trade, registration of ships in different countries — sometimes even in countries other than the owner company's country — and the fact that marine fuel can be bunkered in any location in the world makes environmental and other legislation a challenge. Especially in the field of climate change mitigation, the ambition level of the European Union (EU) to tackle GHG emissions from international shipping differs from that of the current progress under the International Maritime Organization (IMO). To date, no integrated air pollutant and GHG emissions legislation exists. The following sections present global and European developments in addressing emissions from shipping.

2.2.1 Air pollutants

At a global level, IMO is addressing air pollution through the International Convention for the Prevention of Pollution from Ships (MARPOL) and its Annex VI (²), which limits emissions from sulphur oxides (SO_X), nitrogen oxides (NO_X), ozone (O_3)-depleting substances and volatile organic compounds (VOC) from tankers. In addition (see Section 2.2.2), the improvement of ship efficiency could lead to reduction of fuel consumption by ships with an added co-benefit of a reduction in air pollutants.

IMO's Marine Environment Protection Committee (MEPC) revised the MARPOL Annex VI by reducing the global sulphur limit of marine fuels from 4.5 % to 3.5 % (in 2012), and stepwise to 0.5 % in 2020 (or 2025, pending review of fuel availability). Sulphur limits in so-called Emission Control Areas (ECAs) for SO_X and PM are set at 1.00 %, beginning on 1 July 2010 (from 1.50 %) and should be further reduced to 0.10 % (effective from 1 January 2015). One method to control these limits is via Port State Control by checking the so-called bunker delivery note (see Chapter 3). Reductions of NO_X emissions from marine diesel engines are also regulated, focusing on new ships where NO_X emissions limits for engines are defined as a function of speed and installation year. Ships built between 2000 and 2011 need to comply with NO_X emissions at maximum engine speed of about 9.8–17 gramme per kilowatt-hour (g/kWh) (Tier I), those built after 2011 need to comply with 7.7–14.4 g/kWh (Tier II), and ships operating after 2016 in so-called NO_X Emission Control Areas (NECAs) need to comply with emissions of 2.0–3.4 g/kWh (Tier III). To date there is no NECA in Europe, although assessments have been performed evaluating the potential impact of establishing, for example, a North Sea NECA (Danish EPA, 2012). Due to the lack of NECAs and the fact that the NO_X emissions limits refer to new ships, the impact of IMO NO_X regulations seems to be limited at present.

The EU Thematic Strategy on Air Pollution concluded in 2005 (³) the importance of reduction of emissions

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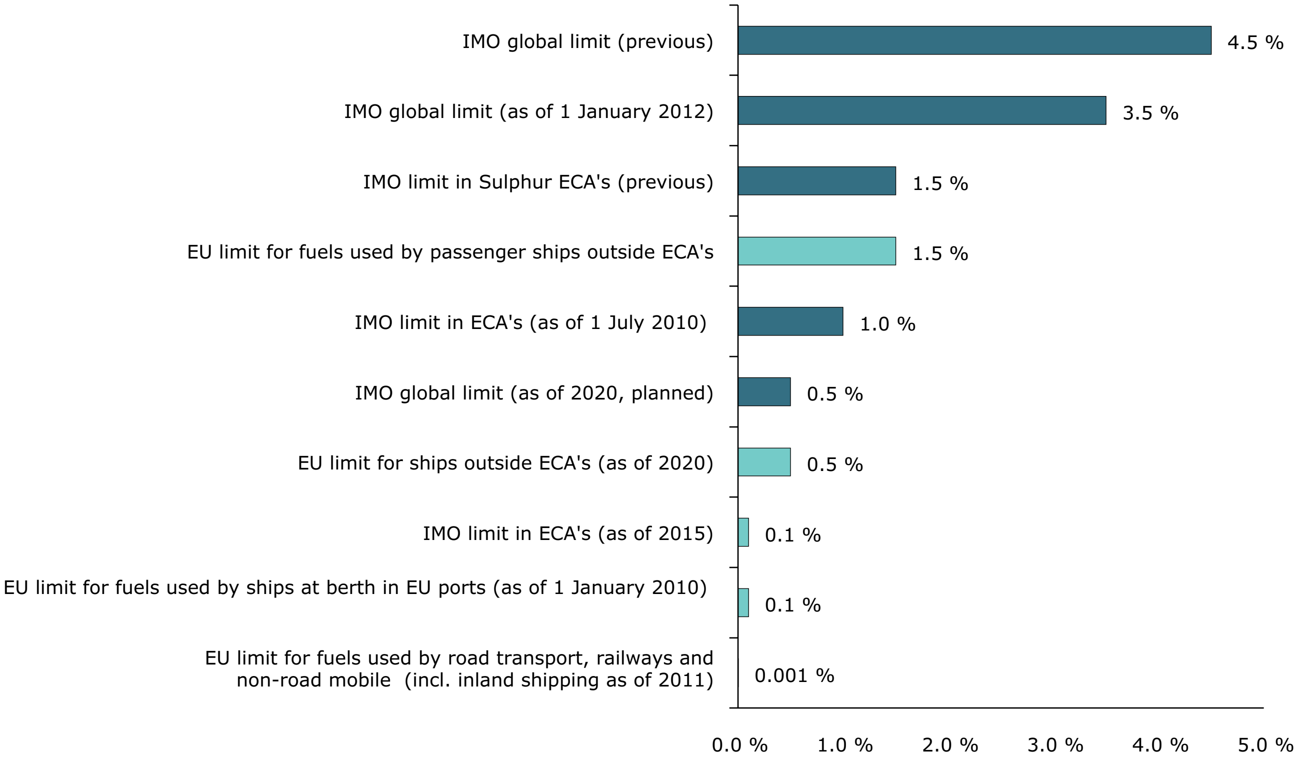
(²) First adopted in 1997 and entered into force in May 2005.

(³) To be reviewed in 2013.

of sulphur dioxide (SO_2), NO_X and PM from ships in order to improve health and the environment. Council Directive 1999/32/EC relating to a reduction in the sulphur content of certain liquid fuels limits the maximum sulphur content of marine fuel (EC, 2009). The Council Directive also contains some additional fuel-specific requirements for ships calling at EU ports, obligations related to the use of fuels covered by the directive, and the placing on the market of certain fuels. The directive does not contain provisions to regulate ship emissions of NO_X or PM. This directive was amended by Directive 2005/33/EC of the European Parliament and of the Countil (EC, 2005) that designated the Baltic Sea, the English Channel and the North Sea as Sulphur Emission Control Areas (SECAs) and limited the maximum sulphur content of the fuels used by ships operating in these sea areas to 1.5 % m (% by mass). This fuel standard applies also to passenger ships operating on regular service outside SECAs. In addition, it also introduced a 0.1 % m maximum sulphur requirement for fuels used by ships at berth in EU ports from 1 January 2010. Recently, Directive 2012/33/EU of the European Parliament and of the Council amending Directive 1999/32/EC was adopted (EU, 2012b). This amendment of Directive 1999/32/EC entered into force on 17 December 2012 and align this directive with the sulphur provisions of the 2008 IMO amendment of MARPOL Annex VI. It will also adapt this directive to IMO provisions on alternative compliance methods, and improve implementation of the directive by harmonising and strengthening provisions for monitoring of compliance and reporting. Furthermore, the directive fixes the introduction of the 0.5 % m fuel standard to 2020 irrespective of a possible postponement by IMO, and sets a 3.5 % m cap for the sulphur content of fuels for ships equipped with a scrubber except for scrubbers operating in closed mode.

To date, there are different requirements on the sulphur content of marine fuels, depending on location, type of ship and, in the case of NO_X, also the age of the ship. Figure 2.2 presents an overview of the different implemented and planned sulphur limits for marine fuels under IMO and EU legislation. Compared to other transport types, the sulphur content remains relatively high. For inland shipping ([4]), the fuel quality requirements as of 2012 are at the same level as for road transport.

Figure 2.2 IMO and EU implemented and planned sulphur limits for marine fuels in comparison to present-day EU limit vales for road transport, railways and inland shipping



Note: % by mass of the fuel.

Source: EEA, based on IMO and EU legislation.

Given the global dimension of sea transport and the fact that ships can bunker fuel of different qualities, it will be difficult to monitor present-day and future emissions reductions.

2.2.2 *Greenhouse gases*

At the global level, to date, no sector emissions reduction target has been established. Due to the global dimension of ship operations, the United Nations Framework Convention on Climate Change (UNFCCC) has recognised that IMO is the best organisation where GHG emissions from shipping should be addressed. IMO adopted in 2003 a resolution urging the IMO MEPC to evaluate and develop mechanisms to reduce GHG emissions from shipping.

In 2009 the MEPC put forward a package of technical/operational measures to address GHG emissions from ships. The key instruments in this package were the Energy Efficiency Design Index (EEDI (5)), the Energy Efficiency Operational Indicator (EEOI (6)) and the Ship Energy Efficiency Management Plan (SEEMP (7)). The EEOI and the SEEMP were finalised as voluntary measures, while the EEDI could possibly be adopted as a binding measure for ships built in the future. More recently, in 2011, the parties to Annex VI of MARPOL adopted mandatory measures to reduce emissions from new ships under a new Chapter 4 titled 'Regulations on energy efficiency for ships'. This regulation makes it mandatory to use the EEDI for new ships and ships that have undergone major revision from 1 January 2013. The regulation applies to ships over 400 GT so does not cover the whole vessel fleet (see Section 2.1). In addition, an amendment was made to MARPOL Annex VI that obliges each ship to have a SEEMP on board; however, it does not make it mandatory to implement the measures described in the SEEMP.

The EU has committed itself to reducing GHG emissions by at least 20 % by 2020 until a global and comprehensive post-2012 agreement is concluded. International shipping is the only sector not covered by an EU emissions reduction target. Under the EU 6th Environment Action Programme (EAP), a commitment was expressed to take EU action if GHG emissions targets where not agreed upon by IMO by 2003 (Art. 5, no 1600/2002/EC). This has been repeated in the Climate and Energy Package adopted in 2009, where the Commission indicated that if by 31 December 2011 no international agreement was made the EC should make a proposal to include international maritime emissions in the EC reduction commitment. Due to the lack of progress at the international level the EC has started to explore options for bringing shipping under the EC reduction commitment. In 2011, a working group was established in the framework of the European Climate Change Programme (ECCP) and reduction measures and instruments were assessed and discussed. At present, as stated in a joint statement by the Vice-President of the European Commission and the EU Commission for Climate Action, the next action by the EU is making a proposal to set up a system for MRV of maritime emissions in early 2013 (8).

2.3 Voluntary actions and other practices

Due to relatively high marine fuel prices and the economic downturn that caused a large overcapacity of available ships, some companies started the practice of so-called 'slow steaming'. According to Faber et al. (2012), based on ship engine power characteristics a speed reduction of 10 % would result in approximately 19 % energy reduction, taking into account reduced engine power and increased travel time. Assessment data on the amount of CO_2 emissions that might have been reduced due to this practice are not available. The option of making slow steaming compulsory under legislation has been proposed by several studies; however, it is currently not proposed or implemented in legislation. Chapter 4 discusses further the emissions and environmental implications of slow steaming.

Another approach aimed at reducing emissions from shipping is through awareness creation.

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(4) The navigation of inland waterways, i.e. navigable rivers, canals, sounds, lakes, inlets, etc.

(5) EEDI: The Energy Efficiency Design Index requires minimum energy efficiency levels (CO_2 emissions) per capacity mile (e.g. tonne mile) for different ship type and size segments. During Phase 1 (2015–2019) the efficiency improvement should be 0–10 % and increase up to 30 % in Phase 3 from 2025 onwards.

(6) EEOI: Energy Efficiency Operational Indicator. An information tool that allows ship operators to compare the fuel efficiency of ships against benchmark values.

(7) SEEMP: Under a Ship Energy Efficiency Management Plan, the operational measures that can be or are taken to enhance the energy efficiency of the ship against benchmark values are recorded (EEOI).

(8) See http://ec.europa.eu/clima/news/articles/news_2012100101_en.htm.

Organisations such as the Danish Eco Council (2012) have made a case for the introduction of so-called labelling of ships identifying the energy efficiency of individual vessels, helping the selection of energy-efficient ships when individual ships are chartered by companies. An example of an energy labelling system is the web application hosted by the Carbon War Room ([9]).

It is important to keep in mind that, currently, these labelling activities in most cases make use of information from ship design data as included in international ship registries and thus should be regarded as theoretical labels; the actual energy use of a ship and its efficiency during a particular voyage is also determined by ship operating procedures and external factors such as weather conditions.

([9]) See http://www.carbonwarroom.com/sectors/transport/shipping/operation-shippingefficiency#mission.

3 Monitoring and modelling of shipping activity and emissions

3.1 Introduction to monitoring and modelling

From different perspectives the need for reliable information on the consumption and combustion of bunker fuel and resulting emissions of air pollutants and GHGs is essential. Firstly, ship owners need to know the amount of fuel bunkered and consumed because fuel cost forms a large fraction of ship operating costs (up to 50 %). Secondly, in order to understand the present-day and potential future environmental impact of ships, the amount, type and location of the release of air pollutants and GHGs into the atmosphere need to be quantified. Thirdly, in order to propose environmental policies or to monitor progress or compliance with existing policies and legislation, the release of emissions from the sector over time periods (e.g. emissions inventories) or from individual ships (e.g. air emission limits, fuel quality requirements) needs to be known.

Recently, the EC announced that in 2013 legislation for the MRV of CO_2 emissions will be proposed. Other activities that already require MRV activities are the reporting of ship emissions under international conventions such as the Convention on Long-range Transboundary Air Pollution (CLRTAP) and the UNFCCC.

This chapter distinguishes between monitoring and modelling of ship activities and resulting fuel consumption (Section 3.2), as well as the monitoring and modelling of emissions of air pollutants and GHGs emitted during the combustion of these fuels (Section 3.3).

3.2 Monitoring of ship movements and fuel consumption

There is a large variety of different monitoring activities in use to establish information on ship movements and fuel consumption. The most important ones are presented here in alphabetical order: Automatic Identification System (AIS), Automated Mutual-Assistance Vessel Rescue System (AMVER), fuel sale statistics, information on board ships, International Comprehensive Ocean-Atmosphere Data Set (ICOADS), Long Range Identification and Tracking (LRIT), and port statistics.

Automatic Identification System (AIS)

The highest level of detail on ship movements can be obtained with AIS data. The AIS was developed to avoid collisions and to assist port authorities to control marine traffic. IMO adopted a regulation (footnote on Regulation 19 of SOLAS Chapter V) requiring AIS to be installed on all ships larger than 300 GT engaged in international voyages, cargo ships over 500 GT engaged in national voyages and all passenger ships. An AIS transponder as installed on vessels includes a GPS (Global Positioning Receiver), which collects position, speed and course. It also includes VHF transmitters, which periodically transmit GPS information and information on the ship (such as vessel name, IMO number, flag, length, draught, destination and expected time of arrival). Currently, approximately 72 000 vessels are equipped with AIS. With position data, speed can be instantaneously calculated, providing a good estimate of delivered engine power, which can be further processed in emissions calculations (see Section 3.4). In coastal areas, AIS messages are captured by ground stations, while messages sent on the oceans are captured by satellite.

The AIS data uses a frequency of 1 Hz. This is too much data for emissions modelling purposes and most studies use AIS data at one message per minute. The range of coastal AIS receivers is 15–20 nautical miles (nm)/28–37 km (at a height of 15 m) or up to 40–60 nm/74–111 km for receivers positioned at a higher altitude. This range is not sufficient to cover large areas so collaboration is needed for complete coverage of ship movements in European waters. For the EU, the European Maritime Safety Agency (EMSA) collects the AIS data for SafeSeaNet. For the Baltic Sea, the Helsinki Commission (HELCOM) collects the AIS data. Satellites have limited capacity for high frequency data and above busy shipping routes (e.g. English Channel) the signal gets saturated; however, due to high frequency, even with some missed messages shipping activity can be well monitored. Commercial ship-tracking initiatives exist, such as http://www.marinetraffic.com and http://www.aishub.com. The most extensive worldwide dataset is AISLive, offered by IHS Fairplay, which combines satellite and terrestrial AIS information. An example of the amount of detail available is shown in Figure 3.1, representing real-time ship traffic in the English Channel and over inland waters in Belgium and the Netherlands on 8 October 2012.

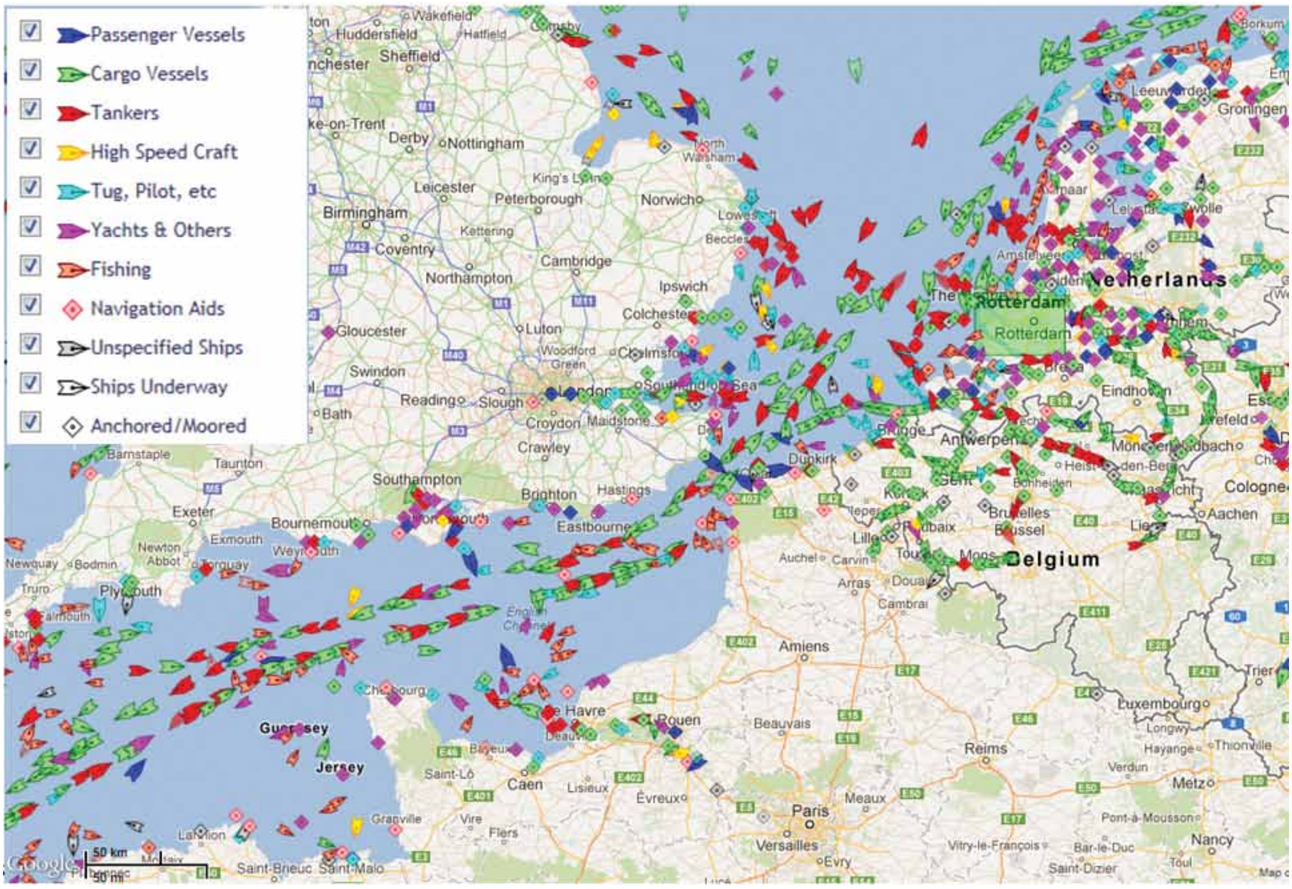
Automated Mutual-Assistance Vessel Rescue System (AMVER)

The Automated Mutual-Assistance Vessel Rescue System (AMVER) is a vessel reporting system with a global coverage to support search and rescue operations (http://www.amver.com). Due to the relatively low number of ships reporting (only ships > 1 000 GT) and the low temporal resolution (6 hours), AMVER data are less suited for activity and emissions monitoring. Global or regional emissions totals can be distributed proportionally with ICOADS or AMVER activity as proxy.

Fuel sale statistics

Countries report their sales of international bunker fuel and domestic bunker fuel to international institutions like the IEA and UNFCCC. See Figure 2.1 for an overview of global IEA data on fuel consumption and about the difference between international and domestic bunker fuel. 'The domestic/international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship' (http://www.iea.org/stats/defs/origins/marine.asp). However, in practice, sea-going vessels also use domestic fuel at sea and inland shipping can also be international. Corbett & Koehler (2003) compared bottom-up and top-down global fuel consumption of maritime shipping and estimated that the share of domestic bunker fuel in international shipping is about 31 %. The difference has even become bigger over the

Figure 3.1 Real-time ship traffic in the English Channel on 8 October 2012 at 10.40



Note: Graph represents the location of 1 236 vessels by different vessel types over international and inland waters. Ships in the Rotterdam area (green box) are not displayed in this graph. Graph includes the international waterway known as the English Channel and part of the North Sea and inland waters of Belgium, France, the Netherlands and the United Kingdom.

Source: See http://www.marinetraffic.com (accessed 8 October 2012 at 10.40).

years (Corbett and Winebrake, 2008). There are many reasons for misreporting. Some ships are not exclusively operating in domestic or international navigation. Some countries have taxes on domestic fuel but not on international fuel. The bottom line is that global international bunker sales are not very accurate for estimating the fuel consumption of international shipping. If fuel sales are used to estimate fuel consumption and emissions in a smaller area (e.g. Europe) there is an additional problem that not all fuel sold in an area is actually consumed there.

Information on board ships

Under IMO regulation, specific information on fuel sales and fuel consumption is recorded by individual ships and their owner companies. Under regulation 18 of MARPOL Annex VI, the preparing and making available of bunker fuel delivery notes (BDNs) is compulsory for ships over 400 GT. This means in practice, for example, that the sulphur content of bunkered fuel is specified in the BDN by the fuel supplier and that, for example, a so-called MARPOL sample of the delivered fuel is kept on the ship. Furthermore, under SOLAS Chapter V regulation 28, ships over 500 GT on international voyages longer than 48 hours have to provide a daily report to the owner company including information on ship position, course and speed.

Recently, several ship companies have started using flow meter information and frequent bunker tank readings to establish a monitoring system providing close to real-time information, and through the use of software tools the actual and prognosed fuel consumption during the voyage can be used to optimise shipping operations, resulting in the reduction of fuel consumption (10).

The operation and reliability of the different flow meters that are applied on board ships is a point of discussion in the sector (11) also because flow meters that monitor volume throughput might overestimate the amount of fuel actually being bunkered due to the fact that air is sometimes introduced during the pumping of bunker fuel, the so-called 'cappuccino-effect' (12).

International Comprehensive Ocean-Atmosphere Data Set (ICOADS)

ICOADS, or International Comprehensive Ocean-Atmosphere Data Set (http://icoads.noaa.gov/), is an extensive worldwide database with sea weather data. Data are collected with buoys, vessels and platforms and transmitted by satellite. The reports from vessels are a good proxy for shipping activity all around the world. About 4 000 ships worldwide reported to ICOADS in 2003; this is about 13.8 % of the world fleet of ships of 1 000 GT and greater, or about 4.4 % of the world fleet (Wang et al., 2008). Due to the relatively low number of ships reporting to ICOADS, the data are not suited for activity and emissions monitoring. Scientific studies have sometimes applied ICOADS combined with AMVER as proxy to spatially allocate emissions to a specific area (Wang et al., 2008; Eyring et al. 2005).

Long Range Identification and Tracking (LRIT)

LRIT is compulsory for all passenger ships, including high-speed craft, cargo ships of 300 GT and above, and mobile offshore drilling units (IMO regulation link). Every 6 hours the LRIT transmits the identity of the ship, the position report, and date and time of the position. The ship sends LRIT messages to communication satellites (Iridium and Inmarsat). This permits a worldwide coverage. For the EU, EMSA coordinates the data flow. The system was deployed for the purpose of maritime safety and security, search and rescue, and protection of the maritime environment.

The EU LRIT data centre provides information to the Member States (MS) about all ships within 1 000 nm. LRIT data are suited for calculation of emissions at sea, but less suited to monitoring harbour activities.

Port statistics

All ports keep track of the number of port calls and the cargo volumes shipped. These data are available for different ship types and sizes. Different levels of detail from shipped cargo to individual

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(10) There are several commercial software applications available under the name of vessel performance monitoring systems and a selection of European ship companies have installed these type of applications (e.g. Maersk, Norden).

(11) See for example, http://www.worldbunkering.com/news/winter-2010/0475-coriolis-the-new-black.html.

(12) See for example, http://www.westpandi.com/Documents/Loss%20Prevention/Loss%20Prevention%20Bulletins/120814%20Loss%20Prevention%20Bulletin%20-%20Bunkering%20-%20The%20Cappuccino%20Effect.pdf, http://www.standard-club.com/docs/AMaster'sGuidetoUsingFuelOilOnboardships.pdf and other in-sector information sources.

ship movements are available. The collection of port statistics is regulated in Directive 2009/42/EC. Information on the carriage of goods and passengers by sea-going vessels calling at ports as reported by MS is available at Eurostat. When information on the origin and destination is available, the movements can be attributed to shipping lanes and used in modelling of ship emissions (see for example, Chiffi et al., 2007; Campling et al., 2010).

3.3 Monitoring of ship emissions

There are different methods for monitoring emissions from shipping and the applied/required technique and frequency depends on the objective of the emissions monitoring. In the case of an emissions trading scheme, a continuous monitoring system or a system that is able to calculate the emissions budget is necessary. This can be achieved through emissions modelling using detailed activity data such as those provided by the AIS (see Section 3.2), continuous on-board measurements or a combination of both. In the case of CO_2 emissions only, verified fuel consumption data can be combined with certified fuel-specific emissions factors. In the case of control and enforcement of sulphur and NO_X regulations, once-only measurements such as on-board inspection or fuel sampling are sufficient to determine compliance. In order to control more ships at a higher frequency, remote sensing techniques might be more practical or continuous emissions measurement on board ships could be implemented.

Table 3.1 provides an overview of ship emissions monitoring techniques in relation to SO_X and NO_X measurements and spatial coverage. Details of the individual methodologies are described below.

Onboard emissions measurements

Monitoring equipment could be installed on board every ship to transmit measurements on a regular basis. There are different possible configurations. When only fuel consumption is measured, emissions factors have to be applied for NO_X and SO_2. As mentioned above, there is uncertainty about the fuel quality and the effective use of after-treatment equipment.

The latter problem can be solved with a direct measurement of CO_2, SO_2 and NO_X in the stack. This is the most accurate way to monitor the emissions of a ship. It allows controlling emissions anywhere and anytime. The drawback of this solution is its elevated cost. The advantage is that a continuous

Table 3.1 Ship emissions monitoring techniques in relation to SO_x and NO_x emissions

Technique	SO_2 measurement	NO_x measurement	Coverage	Remarks
Emissions modelling	Apply emissions model	Apply emissions model	Anywhere, anytime	E.g. with STEAM model combining AIS, Lloyds data
FC monitoring + modelling	Apply EF (gSO_2/kg_fuel)	Apply ef (gNO_X/kg_fuel)	Anywhere, anytime	Sulphur content and activation of after treatment system unknown
Emissions monitoring	Measured	Measured	Anywhere, anytime	Relatively high cost for CEM
Satellite monitoring	–	Concentration must be converted to emission	Anywhere, anytime	For large areas, not for individual ships
LIDAR	SO_2 flux (g/s) measured, estimate of fc needed	–	Local (e.g. port entrance)	Sensible to wind speed and direction, not all sulphur oxidises to SO_2
DOAS	SO_2 concentration + wind speed gives flux, estimate of FC needed	NO_X concentration + wind speed gives flux, estimate of FC needed	Local (e.g. port entrance)	Accurate enough to check sulphur content, accuracy for NO_X not sufficient
Ultraviolet (UV) camera	SO_2 flux (g/s) measured, estimate of FC needed	–	Local (e.g. port entrance)	Still experimental
Sniffer aeroplane or helicopter	Derive sulphur content from SO_X/CO_2 ratio	Derive NO_X emissions from NO_X/CO_2 ratio, assumption of SFC needed	Local	Reliable
Unmanned arial vehicle (UAV)	Derive sulphur content from SO_X/CO_2 ratio	Derive NO_X emissions from NO_X/CO_2 ratio, assumption of SFC needed	Local	Reliable

Note: FC=fuel consumption, EF=emission factor , CEM=continuous emissions monitoring, LIDAR=Light detection and ranging, DOAS= Differential optical absorption spectrometry, SFC=specific fuel consumption.

measurement, anywhere and anytime, is possible. This is necessary for the implementation of an emissions trading system or the control of a SECA or NECA. The on-going EU project Transphorm (http://www.transphorm.eu) is analysing the application of on-board measurements to improve estimates of shipping emissions.

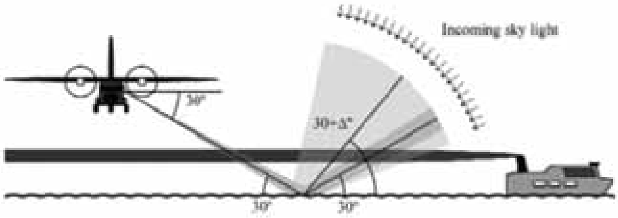
Sniffers

With an aeroplane, helicopter or unmanned arial vehicle (UAV) it is possible to measure the concentrations of CO_2, NO_X and SO_2 in the plume behind a ship. The ratio of SO_2 and CO_2 is proportional to the sulphur content in the fuel. The ratio between NO_X and CO_2 can be used to check if the ship complies with NO_X regulations. An assumption has to be made about the specific fuel consumption (SFC) of the engine. This technique is considered to be the most reliable, with an accuracy of 15 % regarding sulphur content (Balzany Lööv et al., 2011).

Differential Optical Absorption Spectrometry (DOAS)

The concentration of a pollutant in the plume can be measured by the absorption of certain frequencies in a light beam passing through the plume. The difference in attenuation between a passing and a non-passing light beam is proportional with the concentration. Berg et al. (2012) did airborne measurements on sea-scattered solar light. They measured nitrogen dioxide (NO_2) and SO_2 concentrations. The concentrations multiplied by the wind speed give the flux of NO_2 and SO_2. Together with an estimate of the fuel consumption, the sulphur content and specific NO_2 emission can be calculated. The accuracy is estimated to be 40 % for SO_2. This is sufficient to distinguish between fuel with 1 % mass sulphur content mS and 0.1 % mS. The accuracy on NO_X emissions is not good because NO_X is emitted as a mixture of NO and NO_2.

Figure 3.2 Illustration of the airborne optical measurement of ship emissions

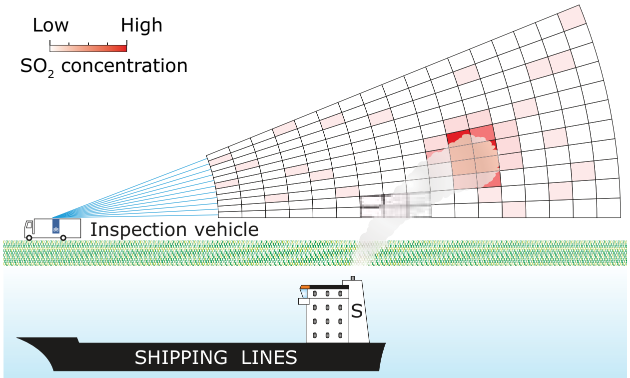


Source: Berg et al., 2012.

Light Detection and Ranging (LIDAR)

LIDAR is a remote sensing technique that uses pulses of two frequencies, one that is strongly absorbed by the species to be measured and one that is absorbed less. From an analysis of the reflected light it is possible to determine the concentration along the beam every 100–200 m up to 2.5 km from the light source. Berkhout et al. (2012) used a LIDAR to measure SO_2 emissions of ships sailing on the Western Scheldt, the Netherlands. They moved a light beam up and down to obtain the SO_2 concentration in a plane where the plume is passing through (see Figure 3.3). The measurement plane is chosen perpendicular to the wind speed. The product of wind speed and SO_2 concentration gives the flux of SO_2 (g/s) emitted by the ship. This flux has to be combined with an estimate of the fuel consumption to determine the sulphur content of the fuel. The fuel consumption can be calculated with the speed (from the AIS) and the installed power as explained in Section 3.4. With an extensive measurement campaign, Berkhout et al. (2012) demonstrated that the technique is fully operational and able to distinguish between ships using high-sulphur or low-sulphur fuel. The measurement uncertainty is about 20 %. The technique is cost effective because patrol vessels can be deployed more efficiently. The biggest drawback of this technique is the dependence on optimal wind direction and speed for good measurements.

Figure 3.3 Side view of the situation during a SO_2 emissions measurement by LIDAR



Source: Berkhout et al., 2012.

Satellite monitoring

With satellite measurements (e.g. the SCIAMACHY instrument, http://www.sciamachy.org), it is possible to determine NO_2 and SO_2 concentrations in the atmosphere. However, it is complicated to determine emissions from these concentrations. The SAMBA project (SAtellite Monitoring of ship emissions in the Baltic seA, http://iap.esa.int/projects/maritime/samba) currently investigates the possibility of determining shipping emissions from concentrations. SAMBA is an Integrated Applications Promotion (IAP) project of the European Space Agency (ESA). Some preliminary results were presented at a workshop in Noordwijk, the Netherlands on 9 May 2012. It seems that NO_2 emissions can be determined well in large areas but it is uncertain if this technique will allow monitoring of individual ships. One of the problems is background pollution from sources other than shipping in areas like the North Sea and the Baltic Sea.

3.4 Calculation of fuel consumption and resulting ship emissions

Emissions from shipping are calculated using two types of methodologies. The first is combining fuel sales data with emissions factors from, for example, emissions guidance documentation. The second is modelling of both fuel consumption and resulting emissions taking into account technical and operating conditions of ships.

Top-down: emissions factor calculations using fuel sale data

This method is applied by several countries preparing emissions from domestic and international shipping to LRTAP and UNFCCC. By combining bunker fuel statistics with default or technology-based emissions factors, the emissions — usually at country level — are calculated. Another example of top-down emissions calculations is the EDGAR database, for which results are presented in Chapter 4.

Bottom-up: (individual) ship emissions modelling

The consumption of fuel by the vessel fleet is generally modelled using equation 3.1 or similar formulas calculating the delivered engine power and resulting fuel consumption of main and auxiliary ship engines. Equation 3.1 is applied to individual ships or for specific ship types using averaged values.

$$\mathrm{FC} = \sum_{\mathrm{engine}} \mathrm{SFC[g/kWh]} \times \mathrm{P_{inst,engine}[kW]} \times \mathrm{LF[\%]} \times \mathrm{T[h]}$$

The power delivered by the main engines depends on the vessel speed in the first place, but also on weather conditions and sea currents. Emissions models differ in the degree of detail to estimate the engine power. The simplest method is to multiply the installed power with a load factor for each activity. More complex methods take into account the instantaneous speed. Engine power is proportional to the third power of the speed. An even higher accuracy can be obtained when the effects of wind, waves and currents are included. The power of the auxiliary engines (AE) is more difficult to estimate. The simplest method is to assume a load factor and multiply it by the installed power. More accurate methods use ship type-specific surveys. In harbour areas the auxiliary engines are the main source of emissions while the main engines are switched off or running at low load.

A constant SFC per engine type can be used. Emissions models distinguish between 2-stroke diesel, 4-stroke diesel, steam turbine and gas turbine. Two-stroke diesels are also referred to as slow-speed diesels (SSD) because they operate at about 100 rpm and are directly coupled to the propeller. Two-stroke diesels power 26 % of the vessels and consume 60 % of the fuel because of their higher power (Corbett and Koehler, 2003). Four-stroke engines can be medium speed or high speed diesel (MSD or HSD). Most auxiliary engines are HSDs. They provide 67 % of all vessels with electrical or hydraulic power. Only 1 % of all ships are powered with turbines. The SFC depends on the load factor, the fuel and the build year of the engine, but not all models take this into account.

Information on the total installed number and type of engine is taken from vessel datasets. The most detailed dataset is the commercially available Lloyd's Register (http://www.lr.org). Free-of-charge, but less detailed, data are available from the UNCTAD report 'Review of Maritime Transport' (UNCTAD, 2011). See Table 3.2 on the source of information and assumptions applied by the three models used in Europe.

Pollutant emissions are calculated using equation 3.2:

$$\mathrm{Emission} = \sum_{\mathrm{engine}} \mathrm{EF[g/kWh]} \times \mathrm{P_{inst,engine}[kW]} \times \mathrm{LF[\%]} \times \mathrm{T[h]}$$

Emissions factors for pollutants are generally expressed in mass per mechanical energy delivered

Table 3.2 Information and assumptions applied by three widely used emissions models to calculate fuel consumption from shipping activities

Fuel consumption		**ENTEC**	**TNO**	**STEAM2**
Main engine	Installed power	Lloyd's Register	Lloyd's Register	Lloyd's Register and ship owners
	Load factor	At sea: 80 % Manoeuvring: 20 % At berth: 20 %	Cruising (at sea): 85 % Reduced speed: 65 % Manoeuvring: 10–40 % At berth: 0 %	$\mathrm{LF} = 0.8\left(\frac{V_{\mathrm{transient}}}{V_{\mathrm{design}} + V_{\mathrm{safety}}}\right)^3$ $V_{transient}$: speed from AIS data V_{design}: design speed from Lloyds Register V_{safety}: 0.5 kilotonnes Correction for wave height and direction
	Delivered power	P[kW] = LF X $P_{installed}$	P[kW] = LF X $P_{installed}$	$\mathrm{P[kW]} = 0.8\mathrm{P}_{\mathrm{installed}}\left(\frac{V_{\mathrm{transient}}}{V_{\mathrm{design}} + V_{\mathrm{safety}}}\right)^3$
	SFC	SFC taking into account: engine type (SSD, MSD, HSD, ST, GT) fuel type (MDO, MGO, RO)	SFC taking into account: the engine type (2-stroke, 4-stroke, steam turbine, gas turbine) load factor fuel type (MDO, HFO/RO) build year	SFC from engine manufacturers Default SFC = 200 g/kWh
AE	Installed power	Lloyd's Register	Lloyd's Register	Lloyd's Register as upper limit for power estimate
	Load factor	At sea: 30 % (50 % of electric power from shaft generator) Manoeuvring: 50 % At berth: 40 %	n/a	n/a
	Power		For each ship type from port survey (GT)	Power depends on ship type and activity

Note: SFC = specific fuel consumption; SSD = slow-speed diesels; MSD = medium speed diesels; HSD = high speed diesels; ST = steam turbine***; GT = gas turbine***; AE = Auxiliary engine; MDO = marine diesel oil; MGO = marine gasoline oil; HFO = heavy fuel oil; RO = residuel oil.

Source: ENTEC (Whall et al., 2010); TNO (Denier van der Gon, Hulskotte, 2010); STEAM2 (Jalkanen et al., 2009, 2012).

by the engine (g/kWh). The power estimation is the same as for fuel consumption. All models calculate NO_X, SO_X, PM, CO, hydrocarbon (HC) (or VOC) and CO_2 emissions. NO_X emissions depend on the engine speed. NO_X formation is triggered by high temperatures but takes time to form. Hence, slow-turning 2-stroke engines produce more NO_X. CO and HC emissions increase strongly at low engine loads. Some models split HC into methane (CH_4) and NMVOC using fixed factors. The impact of ship operation and emissions is illustrated in Table 3.3 by highlighting differences in emissions factors for SSD engines of residual oil at sea or manoeuvring/at berth.

SO_X emissions are proportional to the sulphur content in the fuel (Table 3.4). Hence, they depend on the assumptions made about fuel quality. All emissions models assume that ships stick exactly to sulphur content limits in vigour in the area where they are sailing or when at berth. This means that at berth in EU ports a sulphur content of 0.1 % m is assumed since 1 January 2010 (EU, 2005). In the North Sea and Baltic SECA, the current (2012) sulphur limit is 1.0 % m. Models assume that ships switch to low sulphur fuel when they enter the SECA. However, the global limit is 4.5 % m and the real average sulphur content of 2.7 % m is used in all models. Obtaining accurate information on fuel quality is difficult (13). The SO_2 emissions do not only depend on the fuel quality but also on exhaust gas after treatment. Due to more stringent emissions regulations on SO_2, the use of a sea water scrubber (SWS) is an alternative for using low sulphur fuel. PM emissions depend strongly on the sulphur content.

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(13) A source of accurate fuel information could be the World Ports Climate Initiative (WPCI) (http://wpci.iaphworldports.org/). This is a voluntary cooperation between ports and ship owners. Ship owners submit their bunker certificates which contain information on sulphur content. With this information an Environmental Ship Index (ESI) is calculated, which evaluates NOX and SOX emissions. Participating ports reward ships with tax reductions based on their ESI.

Table 3.3 Difference in emission factors for slow-speed diesel engines using residual oil at sea or manoeuvring/at berth (Unit g/kWh)

	NO_x pre-2000	NO_x post-2000	NO_x average	SO_2	CO_2	VOC	PM	SFC
At sea	18.1	15	17	10.5	620	0.6	1.7	195
Manoeuvring and at berth	14.5	12	13.6	11.6	682	1.8	2.4	215

Note: Emissions factors from ENTEC study.

Source: Whall et al., 2010.

Table 3.4 Illustration of present-day sulphur contents by fuel type in 2007 and as required in Emission Control Areas

Fuel	Assumed sulphur content		
	2007	2010–2020 non-SECA	2010–2020 SECA
Marine Gasoline Oil (MGO)	0.2 %	0.1 %	0.1 %
Marine Diesel Oil (MDO)	1.5 %	1.5 %	1.0 %
Residual Oil (RO)	2.7 %	2.7 %	n/a

Note: % by mass.

Source: Whall et al., 2010.

Black carbon (BC), a fraction of PM, is not a standard output of most emissions models. According to Lack & Corbett (2012), BC emissions depend on engine load, fuel quality and installation of scrubbers, and that BC emissions per fuel mass increase when the engine load decreases. The consequence is that BC emissions might rise when the concept of slow steaming is applied to save fuel, especially residual fuel. The BC emissions of high quality distillate fuels are on average 30 % lower and potentially 80 % lower than for residual fuel. Scrubbers reduce BC emissions by 25–75 %.

CO_2 emissions are proportional to the fuel consumption and the carbon content of the fuel. There are no important differences in the carbon content values used by different models.

The methods, data and assumptions applied by three widely used emission models in Europe are presented in Table 3.5. The ENTEC model was used in European and worldwide studies, and the Netherlands Organisation for Applied Scientific Research (TNO) and STEAM2 models have been applied at the European and more local scale. Details about the models and data used are provided in Annex I.

Spatial allocation of emissions

In order to support regional and local air quality modelling studies, ship emissions data need to be available with a spatial allocation of emissions at a specific location at a specific point in time. Local/national air quality modelling studies require high resolution ship emissions inventories in the range of 1–5 km grid resolution; regional air quality modelling often uses higher resolution ranging from approximately 10 x 10 km resolution up to 50 x 50 km grid resolution.

Several model-based studies such as ENTEC or STEAM make use of the ship movement data to provide high resolution ship emissions datasets. Emissions inventory datasets that support large-scale atmospheric modelling sometimes also apply aggregated ship emissions data derived from aggregated annual data using the AIS, ICOADS or AMVER as proxy to distribute emissions in space and time. An illustration on method and result of allocation ship emissions on grid can be found in the diffuse emissions data prepared as part of the European Pollutant Release and Transfer Register (E-PRTR) (14).

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(14) See http://prtr.ec.europa.eu/DiffuseSourcesAir.aspx.

Table 3.5 Information and assumption applied by three widely used emissions models to calculate emissions factors from shipping activities

Emissions factors	ENTEC	TNO	STEAM2
NO_x	Depends on 5 engine types, 3 fuel types and activity (at sea, at berth) Post-2000: IMO NO_x Technical Code	Depends on engine type, build year and load	Engine manufacturer information Default: IMO Tier I Curve
SO_x	Depends on sulphur content and eventual exhaust gas after treatment (scrubber)	Depends on sulphur content and eventual exhaust gas after treatment (scrubber)	Depends on sulphur content and eventual exhaust gas after treatment (scrubber)
PM	Depends on engine type, fuel type and activity (at sea, at berth) and sulphur content: $PM_{2.5}$: 90 % of PM PM_{10}: 95 % of PM	Sulphur content, fuel type, engine type EFs for PM_1, $PM_{2.5}$ and PM_{10}	Depends on engine type, sulphur content and engine load EF for organic carbon (OC)
HC (VOC)	Depends on 5 engine types, 3 fuel types and activity (at sea, at berth)	Depends on engine type, build year and load	Not available
CO	-	Depends on engine type, build year and load	Base emissions factor of CO as a function of engine load
NMVOC	99 % of HC	Not available	Not available
CH_4	1 % of HC	Not available	Not available

Source: ENTEC (Whall et al., 2010); TNO (Denier van der Gon and Hulskotte, 2010); STEAM2 (Jalkanen et al., 2009, 2012).

4 European maritime emissions inventories and projections

A variety of inventories and projections representing present-day and future shipping emissions on the European seas exists. During the preparation of writing this EEA report, a large selection of these studies were reviewed by ETC/ACM. A detailed description and overview is provided in Annex I. The different emissions estimates resulting from these studies are presented and discussed in this chapter (inventory data in Section 4.1 and projection data in Section 4.2). Furthermore, an assessment is made on the importance of European shipping emissions on a global scale (Section 4.3).

4.1 Emissions inventories

4.1.1 Comparison of European ship emissions inventories

Figure 4.1 compares the present-day emissions of emissions inventories reviewed for this report, both in absolute number per year (right panel) as well as an indication of the technology assumptions in the inventories by providing an indication on how much air pollutant is released together with CO_2 (left panel). To illustrate the fact that different geographic areas are included, the graphs are marked with different colours, grouping the different studies. Most studies have been found to focus on CO_2, NO_X and SO_2 emissions; a smaller amount of studies is available on emissions of $PM_{2.5}$, NMVOC and CO. A more detailed description of the studies and an overview of regional studies (e.g. North Sea area) is provided in Annex I. Often, the inventory and scenario studies use different definitions of European seas or only focus on a specific part of European seas (e.g. North Sea). Box 4.1 presents a selection of geographic areas often considered in shipping emissions inventories.

Large ranges in emissions estimates between various studies can be found, sometimes up to a factor of 3. This is due to the fact that emissions represent different years and differ in coverage of specific geographic areas in which they occur. Also, the applied method and source of emissions included (national vs. international shipping) contributes to the visible differences. For example, a comparison of those studies that report emissions from international shipping within the EMEP domain (marked in blue in Figure 4.1) shows sometimes large differences by compound that — although sometimes estimated for different years — cannot be explained by growth in fuel consumption/shipping activity alone: CO_2 (71–141 Tg)), NO_X (1 674–3 365 Gg), SO_2 (1 015–2 251 Gg), $PM_{2.5}$ (191–254 Gg), NMVOC (114–143 Gg), CO (332–345 Gg).

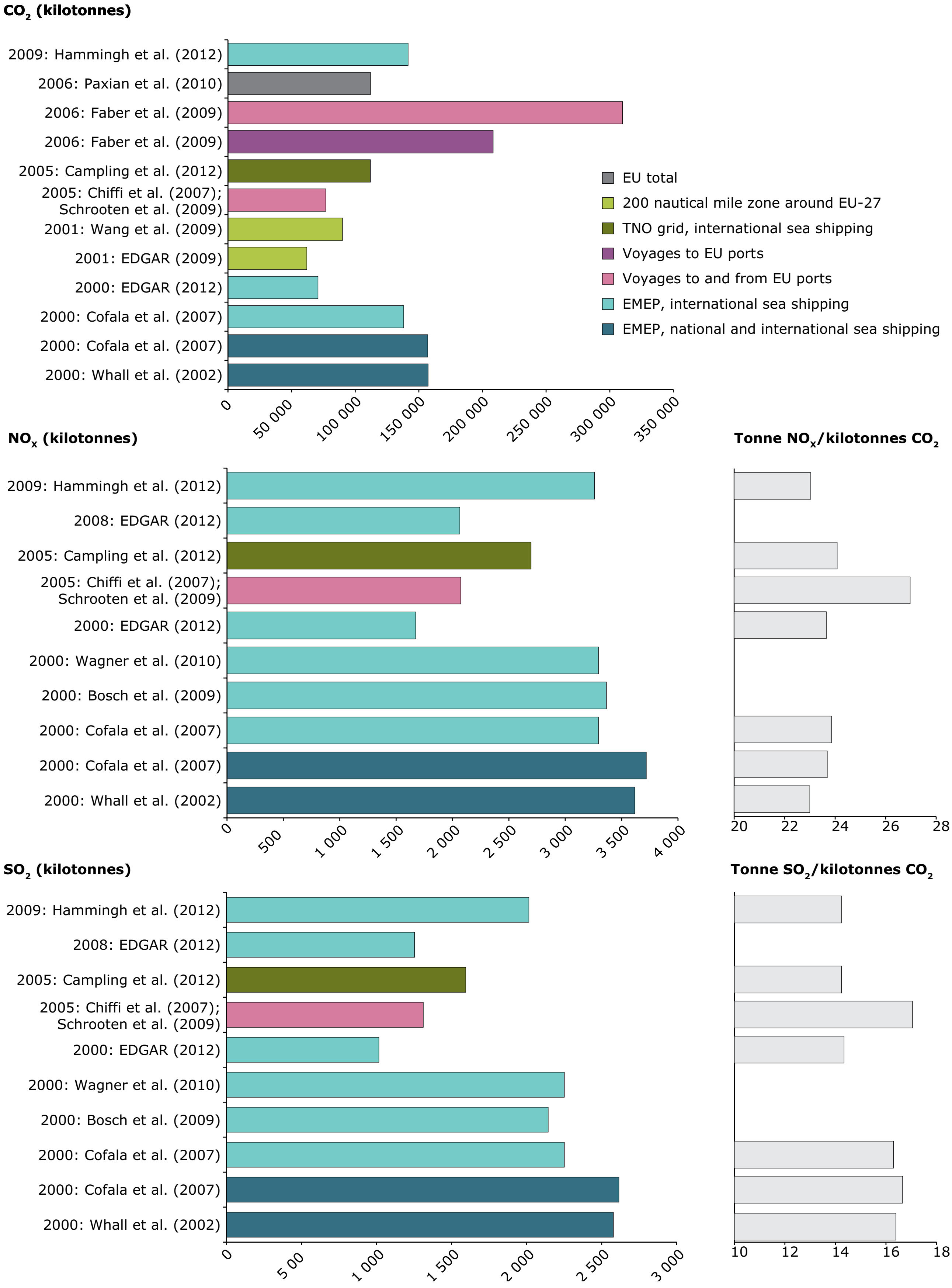
The relatively low emissions reported by the EDGAR inventory compared to other studies covering the early 2000 period are most likely due to the use of fuel statistics from the IEA (top-down) versus a bottom-up emissions inventory method. Buhaug et al. (2009) and other studies (see for example, Dalsøren et al., 2008; Endresen, 2003) have shown that nationally reported maritime fuel statistics underestimate the real fuel use by international sea shipping. Although this issue has been known for several years, several national inventories (e.g. UNFCCC/LRTAP) still use fuel statistics as a basis for inventory calculations. This is an area where the quality of shipping inventories should be evaluated and, if needed, improved on.

As will be discussed in more detail in Chapter 5, the impact on air quality from shipping is to some extent related to the fact that most shipping emissions occur close to the coastal areas. This can be illustrated by looking at emissions within the 200-mile zone around the EU-27 (EDGAR, 2009) and those occurring within the whole EMEP domain from international shipping (EDGAR, 2012). The larger domain contains only 14 % more emissions than the 200-mile zone.

The high estimates by Faber et al. (2009) are partly explained by the difference between bottom-up and top-down emissions calculations due to marine-fuel statistics. Another aspect is that emissions in the Faber et al. study were calculated for the whole voyage between the port of departure (worldwide) and the part of arrival in the EU-27 and vice versa. Not shown in Figure 4.1 are CO_2 emissions from voyages between EU ports, which are estimated at 112 Tg (see discussion domestic intra-EU shipping versus reported under UNFCCC below).

The Extremis inventory by Chiffi et al. (2007) and Schrooten et al. (2009) estimates emissions for 2005 and the methodology uses trade data. Faber et al. (2009) note that trade-based emissions inventories

Figure 4.1 Present-day emissions of greenhouse gases and air pollutants according to recent studies focusing on shipping in Europe and European seas



CO_2 (kilotonnes)

NO_x (kilotonnes)

Tonne NO_x/kilotonnes CO_2

SO_2 (kilotonnes)

Tonne SO_2/kilotonnes CO_2

Figure 4.1 Present-day emissions of greenhouse gases and air pollutants according to recent studies focusing on shipping in Europe and European seas (cont.)

Note: The right panel presents emissions inventories reviewed for this report, both in absolute number per year. The left panel gives an indication of the technology assumptions in the inventories by linking the amount of air pollutant emitted together with carbon dioxide (CO_2).

Source: EEA and ETC/ACM, based on studies referenced in graphs.

Box 4.1 Relevant geographic areas to consider in shipping emissions inventories

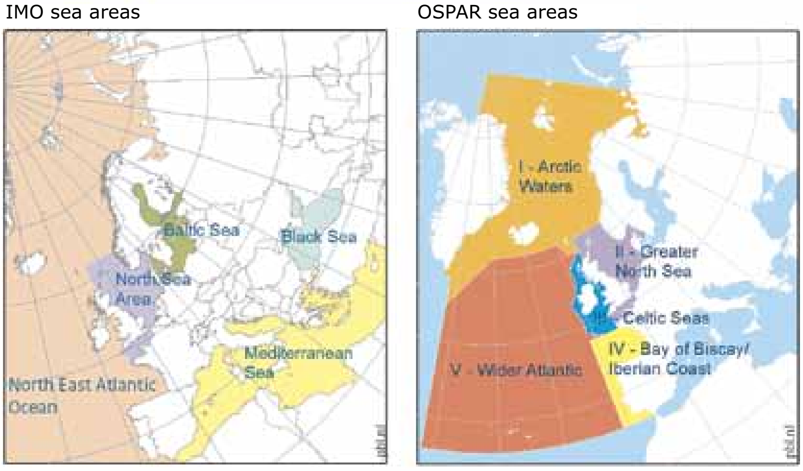
There are different geographic areas where the EU or some of its MS have interests or responsibilities. These range from large maritime areas such as the Atlantic Ocean, the Mediterranean Sea and the Black Sea, to smaller national areas like the 200- and 12-mile zones.

EMEP area: A number of emissions inventories for European marine sources have been using the EMEP area as their geographical domain. Figure 4.2 (top left) represents most of the EMEP domain. It is a wider European area used in the Emission Monitoring and Evaluation Programme (EMEP) under the Convention on LRTAP (CLRTAP) of the United Nations Economic Commission for Europe (UNECE).

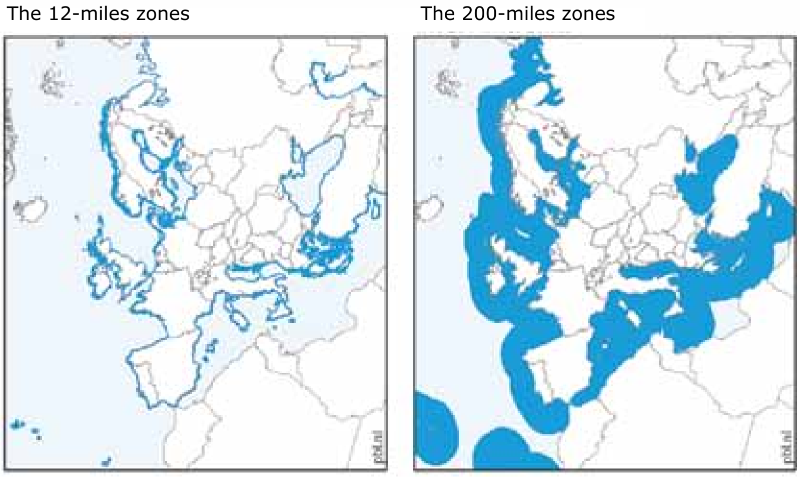
Sea areas defined by IMO: IMO has defined the borders of a number of European sea areas in Annex V of the International Convention for the Prevention of Pollution from Ships (MARPOL); see Figure 4.2 (top left). The so-called ECAs are the North Sea and the Baltic Sea. The North-East Atlantic as presented in the figure represents only the part of the Atlantic that is within the EMEP domain and does not belong to any of the defined European seas.

The OSPAR sea regions: The OSPAR Commission is an organisation grouping 15 governments of the western coasts and catchments of Europe and the European Community. Its objective is to protect the marine environment of the North-East Atlantic. The North East Atlantic is subdivided into five OSPAR regions: 1) Arctic Waters, 2) the Greater North Sea, 3) the Celtic Seas, 4) Bay of Biscay and Iberian Coast, and 5) the Wider Atlantic. Figure 4.2 (top right) shows the OSPAR sea areas.

Figure 4.2 Boundaries of international sea areas around Europe


IMO sea areas

OSPAR sea areas


The 12-miles zones

The 200-miles zones

Source: ETC/ACM, 2012.

Territorial waters or 12-mile zone: The 12-mile zone of a state is a belt which extends 12 nm or 22 km from the mean low-water mark. This area is regarded as sovereign territory of the state. Figure 4.2 (bottom left) shows the 12-mile zone of the EU MS. Greece currently has a 6 nm zone but has declared to reserve the right to establish a 12 nm territorial sea at a time deemed appropriate.

Exclusive Economic Zones of the EU and Member States: The Exclusive Economic Zone (EEZ) is an area which stretches 200 nm or 370 km from the coast line of a state. In this zone the state has special rights over exploration and exploitation of marine resources. Figure 4.2 (bottom right) shows the EEZ for EU members and non-members.

generally generate consistently lower estimates than inventories based on ship movements; this is visible in Figure 4.1 (purple bars). Trade-based estimates do not account for the non-cargo ships (passenger, fishing, offshore, tugboats and 'other' or miscellaneous ships) and may underestimate the use of smaller, less efficient ships, which are more numerous in European waters. In addition, intra-EU voyages by ships arriving from outside the EU are not adequately taken into account by this methodology.

As discussed in Chapter 3, whereas CO_2 can be directly related to fuel consumption, other information is needed to calculate air pollutant emissions (engine types, fuel quality, abatement measures). This is reflected in the figures for air pollutants; where CO_2 emissions estimated for the same domain are relatively close, the air pollutant emissions from the same studies show larger variations. For example, while the CO_2 emissions from Whall et al. (2010) and Cofala et al. (2007) from national and international shipping (dark blue bars) are rather close, the emissions from NO_X, SO_2 and NMVOC are different. Another example is found when comparing the Wagner, Bosch and Cofala studies for year 2000; the difference between the studies depends on the type of pollutant, with a relatively large difference for $PM_{2.5}$.

By comparing the amount of air pollutant emitted per mass of CO_2 emitted, an indication can be given of the importance of technology information (combustion technology, emission abatement equipment on the calculation of shipping emissions (right panel of Figure 4.2). This technology indication could not be calculated for all studies because some studies did not report CO_2 emissions or specific air pollutants. In the case of NO_X, the average implied emissions factors range mainly between 23 and 24 Mg/NO_X per Gg CO_2. Only the studies by Chiffi et al. (2007) and Schrooten et al. (2009) estimate a somewhat higher emissions factor. More information can be found in Annex I. In the case of SO_2, it is known that the applied sulphur content of marine fuels strongly determines the SO_2 emissions. The implied emissions factor ranges from 14 to 17, highlighting that the sulphur content in marine fuels is rather similar between studies. Emissions from PM are more difficult to estimate because the emissions depend on fuel type, sulphur and ash content. Normally, higher quality marine fuels (and thus more expensive) have lower PM emissions. The range in implied emissions factors is relatively large with values of 1.5–2.1 Mg $PM_{2.5}$ per Gg of CO_2 emitted. For NMVOC the differences are relatively large but this can be caused by the fact that some studies included emissions from fuel evaporation and other studies did not. The number of different studies presenting CO emissions is too small to discuss differences in implied emissions factors.

4.1.2 *Emissions data reported to UNFCCC and CLRTAP*

Under the UNECE CLRTAP the aim is to limit and prevent air pollution. Under the LRTAP Convention, countries have agreed to report their emissions of air pollutants specified under the convention, such as NO_X and SO_2. Emissions from maritime activities are included in the national emission totals reported to LRTAP. This includes emissions from inland and domestic maritime shipping on international waters but excludes emission from international maritime shipping. The fuels sold within the country for the purpose of international shipping activities and resulting emissions based on an emissions factor approach (see Chapter 3) are reported as a memo item.

National emissions inventories reported to the UNFCCC follow a similar approach when it comes to reporting emissions from shipping activities. Only inland shipping emissions are reported whereas emissions from international shipping are reported as a memo based on international bunker fuel sales data and emissions are calculated using an emissions factor approach.

Table 4.1 presents the emissions from CO_2 and main air pollutants as reported as a memo item in the LRTAP and UNFCCC inventories. The emissions calculated using international bunker fuel data do not reveal to what extent the bunkered fuel is used within European seas, for example used for travel between EU Member States or for voyages going beyond the European seas. According to Faber et al. (2009) the CO_2 emissions from intra-EU voyages is estimated to be 112 Tg in 2006. This number includes both domestic (EU country) and international shipping between EU ports. CO_2 emissions from domestic navigation based on the sum of MS reported data is approximately 18 Tg in 2006. This means that based on fuel sales, summing up domestic (18) and international (174) bunker fuel sales, theoretically 192 Mtonne of CO_2 emissions could have been released within Europe if all bunker fuel sold is consumed on Europen seas.

This information shows that currently a potentially large fraction of GHG and air pollutant emissions is not accounted for in inventories supporting the LRTAP and UNFCCC conventions. Especially when

Table 4.1 Emissions in the EU-27 from CO_2 and air pollutants as reported under UNFCCC and LRTAP in 1990, 2006 and 2010 representing emissions from international voyages departing from EU-27 ports

Inventory	Year	Emissions (Gg)					
		CO_2	NO_X	SO_2	$PM_{2.5}$	NMVOC	CO
UNFCCC	1990	111 844	1 331	1 002	-	52	145
UNFCCC	2006	174 593	1 954	1 581	-	79	187
UNFCCC	2010	150 862	1 873	1 429	-	80	196
LRTAP	1990	-	1 416	1 056	95	53	152
LRTAP	2006	-	2 051	1 647	161	77	176
LRTAP	2010	-	1 916	1 460	148	72	159

Source: EEA, 2012a and EEA, 2012b.

it comes to assessment of the environmental impact of air pollutant emissions, this type of information is needed. As shown in Section 4.1.1, emissions inventories that calculate, for example, the emissions from international shipping show a large range of NO_X and SO_2 emissions and that the LRTAP data on marine bunker fuel sales is at the lower end of this range.

4.1.3 *Contribution of European ship emissions to global total emissions from shipping*

To place the European maritime emissions in a worldwide perspective, some studies with a global scope were included in the overview. In 2007 global international shipping emitted 870 Tg CO_2, which is 2.7 % of the total global CO_2 emissions. Global national and international shipping emitted 1 050 Tg in 2007, which is 3.3 % of total global CO_2 emissions (Buhaug et al., 2009). The study by Buhaug et al. compared bottom-up fuel consumption based on the AIS data with fuel sales. Their best estimate for global fuel consumption of maritime shipping in 2007 is 333 Tg Mtonne and for international shipping it is 277 Tg. The IEA total marine sales for 2007 were estimated on 234 Tg. They are lower due to incomplete reporting. The contribution from international shipping in European waters (Table 4.2) to CO_2 emissions from international shipping worldwide ranges roughly from 10–30 %. Based on the inclusion of all ship traffic from national and international shipping arriving or departing from EU-27 ports, the contribution is estimated to be 31 % (Faber et al., 2009). The contributions to global NO_X, SO_2 and $PM_{2.5}$ emissions from international shipping are approximately: 10–20 % (NO_X), 10–25 % (SO_2) and 15–25 % ($PM_{2.5}$).

The types of ships that contribute to European and global emissions of CO_2 are presented in Table 4.3. The data has been taken from Faber et al. (2009) who presented a breakdown in CO_2 emissions by ship type for total global shipping, ships arriving in European ports and intra-European shipping. Container carriers and tankers are the main contributors to global and European CO_2 shipping emissions. Within Europe the role of bulk carriers is smaller compared to global shipping, especially within intra-EU transport. In comparison to the

Table 4.2 Emissions from international shipping in European and global seas

	Year	CO_2	NO_X	SO_2	$PM_{2.5}$
		Gg			
European seas: international shipping (^{a})	Different base years between 2000 and 2009	70 778–208 400	1 674–3 259	1 015–2 251	161–254
Global seas international shipping (^{b})	2000	647 000	16 000	9 000	1 100
	2007	870 000	20 000	12 000	1 500
Global seas: national and international shipping (^{b})	2000	778 000	19 000	11 000	1 300
	2007	1 050 000	25 000	15 000	1 800

Note: (^{a}) See Figure 4.1 and references therein; (^{b}) Buhaug et al., 2009.

Table 4.3 Contribution of various ship types to global and European maritime CO_2 emissions

Ship type	Ship type contribution to CO_2 emissions (%)		
	Global shipping	Voyages to EU ports	Intra-EU
Container	33.3	24.3	18.4
Tanker	20.8	16.5	15.1
General cargo	7	10.7	12.9
Bulk carrier	15.1	10.6	5.9
Reefer	2	2.5	1.4
Ro-ro	5.1	6.8	8
Passenger	10.7	22	29.6
Fishing	1.1	1.4	2
Rest	4.9	5.2	6.7
Total	100	100	100

Source: Faber et al., 2009.

global total, the role of passenger ships is relatively large in Europe. Especially for intra-EU traffic, the contribution is close to 30 %.

4.2 Emissions scenarios

Most of the presented publications include emissions projections by international shipping in European seas up to 2020 or 2030. Only Campling et al. (2012) present projections up to 2050. These so-called baseline scenarios take into account expected socio-economic trends and the effect of policies currently implemented or foreseen to be implemented in the near future. The key assumptions on developments in transported cargo or fuel use, efficiency improvements, and fuel and emission standards are summarised for those publications in Annex I. Most of the projections on maritime emissions only make assumptions on the growth in transported cargo, shipping activities and marine fuel use in the forthcoming decades. Few of the presented studies made explicit baseline assumptions on improvements in fuel efficiency through ship design and operation, slow steaming or an increased share of LNG (Buhaug et al., 2009; Hammingh et al., 2012). Recent work published too late to be included in this report evaluated energy efficiency improvements (see for example, DNV, 2012).

The assumed growth rates in fuel use (and thus CO_2 emissions, see Figure 4.3, top left panel) for future years in the selected studies show a wide range from about 1–4 % for transported cargo or fuel use. Most of these assumptions were based on historic relationships between growth in gross domestic product (GDP) and marine transport (in a pre-crisis economic situation) which were extrapolated. A study into sea transport in the EU after the economic crisis (Schade and Krail, 2010) expects that growth in seaborne trade in the short term (2011–2015) may catch up with pre-crisis levels (around 2 % for GDP), reflecting an economic recovery after the 2008–2009 crisis. For subsequent years (> 2015/2020), the growth rates are expected to decline due to the dampening effects of the high public debts, the ageing of the EU population and the resulting reduction in the labour force. Such arguments may support the use of lower growth rates for new emissions projection studies compared to a number of pre-crisis scenario studies that use annual growth rates up to 4 %. Moreover, the inclusion of recently adopted energy efficiency improvements by IMO leads to smaller future growth rates for fuel use by international shipping.

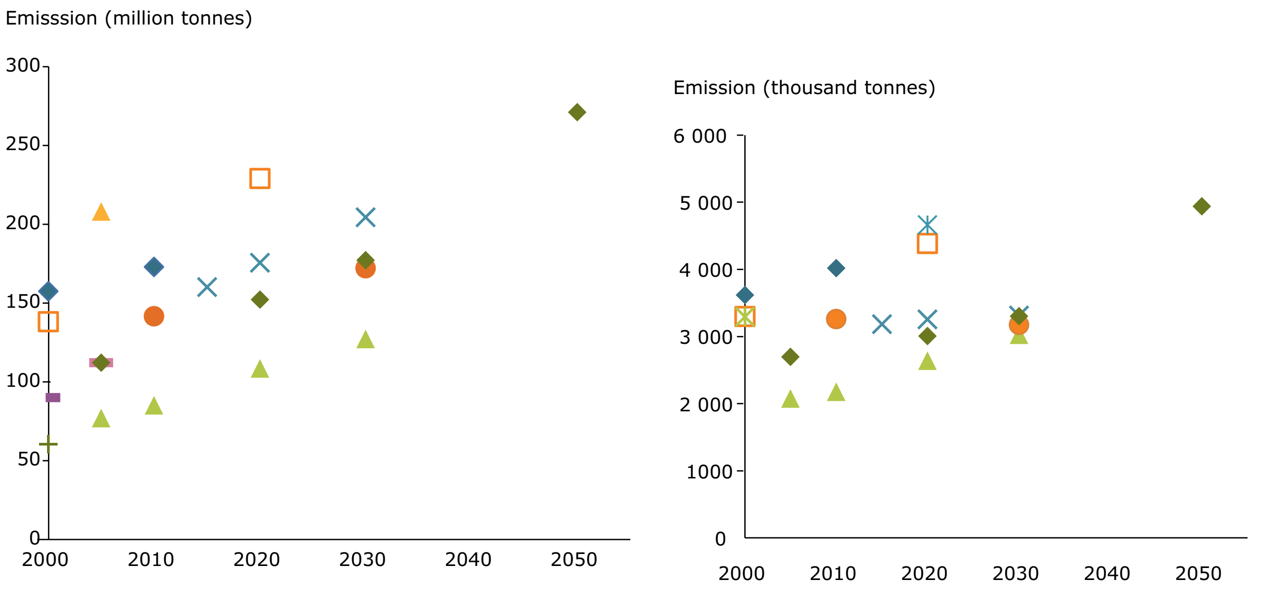
The difference in fuel use development and CO_2 emissions is shown in Figure 4.3, top left panel. Those studies that have applied higher growth rates, especially those conducted up to 2009, could not foresee the economic downturn influencing marine transport demand. As a result, those studies show higher CO_2 emissions both in present day (then scenario year, e.g. 2010) and future years. For example, the range of emissions estimates for the year 2020 is between approximately 100 and 225 Tg of CO_2, and between 125 and 200 for the year 2030. The study covering the period up to 2050 shows emissions increasing up to 270 Tg of CO_2. The air pollutant scenarios as shown in Figure 4.3 reflect the assumption on growth and fuel demand as well as assumptions on emissions abatement technology development and emissions limit values.

NO_X emission scenarios (Figure 4.3, top right panel) in the year 2020 show a similar difference as for CO_2, but in the year 2030 the studies seem to merge into an estimate of about 3 000 Gg of NO_X. The different studies reach this point despite different assumptions. For example, the projection for 2030 by Campling et al. (2010) represents a small increase of NO_X emissions, which is the result of an assumed growth rate in fuel use (2 % annually) and the application of IMO Tier I and Tier II regulations [15]. According to Hammingh et al. (2012), a minor decrease in NO_X emissions is foreseen in 2030,

Figure 4.3 Emissions projections for CO_2, NO_X, SO_2 and $PM_{2.5}$ from international shipping in European seas

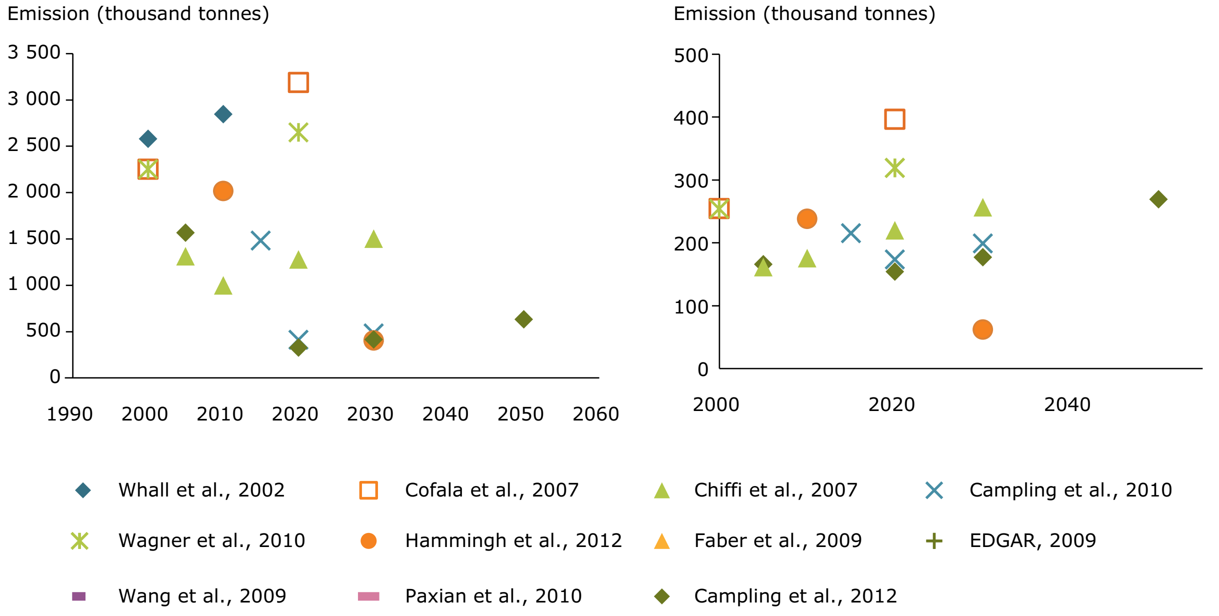
CO_2 emissions from international sea shipping in European seas

NO_X emissions from international sea shipping in European seas



SO_2 emissions from international sea shipping in European seas

$PM_{2.5}$ emissions from international sea shipping in European seas



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[15] In an updated study, released recently but too late to be used in the analysis, Campling et al. (2012) revised earlier estimates. For example, NO_X emissions are estimated to increase by 25 % in 2050 and 2020 emissions are expected to be lower than 2005 levels due to the economic downturn and internationally agreed fuel efficiency standards (EEDI).

compared to 2009, which is explained by the lower assumed growth rate (1 % annually), the applied IMO Tier I and TIER II regulations in all EU seas, an increase in LNG use and the assumed NECA in the Baltic Sea. According to Hammingh et al., such a control area in the Baltic Sea would see a 30 % emissions reduction. Another effective measure seems to be the use of LNG as marine fuel. According to Hammingh et al., the use of LNG would reduce NO_X emissions in the 2030 baseline for the North Sea by about 8 %.

The baseline emission scenarios for SO_2 are strongly determined by the applied sulphur content in marine fuels and assumed growth rate of the sector. As can be seen in Figure 4.3 (lower left panel) the impact of sulphur content assumptions result in higher emissions in the scenarios published before 2008, when IMO adopted the low sulphur requirements for 2020. One study, by Cofala et al. (2007), explored the impacts of various low sulphur requirements via alternative scenarios (only baseline scenarios are shown). The decrease in SO_2 emissions between 2005 and 2010 (Chiffi et al., 2007) is explained by the introduction of the two sulphur ECAs (with 1.5 % sulphur) in the Baltic Sea and North Sea from 2007 onwards. Wagner et al. (2010) assumed in the baseline for 2020 that the 0.5 % sulphur content requirement in non-SECAs would be postponed from 2020 to 2025, following the planned review of the sulphur requirements by IMO in 2018. That explains the relatively high estimates in 2020. The baseline projections by Campling et al. (2010) and Hammingh et al. (2012) took into account the stringent IMO sulphur requirements adopted in 2008 for marine fuels that will enter into force between 2015 and 2020. Both inventories show that SO_2 emissions are expected to decrease dramatically after 2015 and 2020. After 2020, SO_2 emissions may rise again due to the assumed growth in fuel use and the absence of new policies (Campling et al., 2010, 2012).

The baseline projections for $PM_{2.5}$ emissions (Figure 4.3, lower right panel) are strongly determined by the fuel quality (RFOs or distillate fuel oils) and fuel sulphur content. Several studies show that $PM_{2.5}$ from large marine diesels depend on the fuel type and its sulphur and ash content (Kurok et al., 2007; Duyzer et al., 2007; Whall et al., 2010). In residual or HFO, constituents, such as ash, asphalt, metals, oxides and sulphur, and its high viscosity contribute to the formation of $PM_{2.5}$. Other constituents of the emitted PM include unburned compounds such as carbon soot and HCs from fuel and lubricating oil. The more expensive distillate fuels generally have a much lower sulphur and ash content, and lower viscosity. As a result, the quantity of the PM formation is much lower. Buhaug et al. (2009) showed that PM emissions are reduced by over 70 % if marine fuel is changed from HFO with 2.7 % sulphur to distilled MDO with 0.5 % sulphur (based on Kurok et al., 2007). PM emissions are reduced by over 80 % if the sulphur content is reduced from 2.7 % S in HFO to 0.1 % in MDO (the IMO requirement for SECAs). The impacts by the low sulphur fuel requirements on PM emissions in European seas are best seen in the baseline projections by Campling et al. (2010, 2012) and Hammingh et al. (2012). As explained before, a number of other baseline projections did not include, or only partly included, the use of such low sulphur fuels in their baselines (Whall et al., 2002; Cofala et al., 2007; Chiffi et al., 2007; Bosch et al., 2009; Wagner et al., 2010). The baseline projection by Hammingh et al. (2012) estimates relatively low PM emissions. This is based on an optimistic estimate for the reduction of PM emissions by using low sulphur fuels in the Atlantic Ocean, the Mediterranean Sea and the Black Sea.

With the exception of SO_2 emissions, the currently implemented and the scheduled emissions and energy policies within international shipping are not expected to decrease CO_2 and other pollutant emissions in Europe. The rate of growth will to some extent be reduced but future emissions will remain above present-day emissions.

Box 4.2 Measures to reduce air pollutants and greenhouse gas emissions from shipping

Scenarios discussed in Section 4.2 assume different technologies and practices that are applied already or will be applied in the near (2020) and distant future (post-2030). Three types of measures can be considered in a scenario study: (i) fuel quality/fuel switch, (ii) emissions reduction technologies, (iii) ship operating measures. Information on the costs associated with installing/operating different abatement measures is not discussed here; more information can be found in recent work by Miola et al. (2010) and Campling et al. (2012).

(i) Fuel quality/fuel switch

SO_2 emissions are proportional to sulphur content in the fuel. Most scenario studies assume that the shipping sector will follow the sulphur content limits over time and most emissions model studies assume that ships will switch to low sulphur fuel when entering, for example, SECAs. LNG is an alternative fuel that, although not visible in international fuel statistics (see Figure 2.1), is entering the shipping sector, especially in short-distance shipping and ferries. Although it requires technical modifications to ship engines, the advantage is that LNG does not emit SO_2 and about 90 % less NO_X compared to bunker fuel oil. CO_2 emissions are also reduced; LNG emits about 20 % less CO_2 (Buhaug et al., 2009).

(ii) Emissions reduction technologies

Sea water scrubbing is an established technology to reduce sulphur and PM concentrations in exhaust gases. According to Cofola et al. (2007), SO_2 can be reduced up to 75 % and PM up to 25 %. According to Campling et al. (2012), the most efficient method to reduce NO_X emissions is the installation of selective catalytic reduction (SCR) technology which could reduce NO_X emissions by 80 %. Alternative measures are, for example, the use of slide valves instead of conventional fuel valves (Corbett et al., 2010) reducing both NO_X and PM and diesel particulate filters (DPFs). Regarding PM emissions, slide valves can reduce PM emissions by 25–50 % and DPFs can achieve 70–95 % PM reduction and 95–99 % of BC emissions reduction. Further examples of emissions reduction technologies can be found in, for example, Cofala et al. (2007), Corbett et al. (2010) and Miola et al.(2010).

(iii) Ship operating procedures

Due to relatively high bunker fuel oil prices and the economic downturn and the resulting large overcapacity of available ships, some companies started the practice of 'slow steaming'. Faber et al. (2012) estimated that a speed reduction of 10 % would result in approximately 19 % energy reduction and thus lower emissions. The practice of slow steaming means that the engine load is decreasing and this could lead to an increase of BC emissions (see Section 3.4). Another practice that could lead to reduction of emissions is to operate the ship against the EEIO, an instrument developed by IMO in relation to the EEDI. Another operating procedure that can reduce emissions is so-called shore power. This is the practice of switching off the main and auxiliary engines of a ship while at berth and connecting to the electricity grid. Oil tankers and passenger vessels do not always use shore power. Oil tankers use main engines to power discharge and loading pumps, and passenger vessels use extra power to ventilate and keep general electrical services running while passengers and cargo are embarking/disembarking (De Meyer et al., 2008).

Environmental Kuznets theory

When scenario studies focus on distant future emissions, for example post-2030, it will be difficult to include non-existing technological measures that are expected to be developed over time when technology advances. Most scenarios studies (see for example, Riahi et al., 2012) assume a further reduction in emissions assuming that higher environmental quality can be associated with increasing welfare through the so-called environmental Kuznets theory. See, for example, ETC/ACM (2012) for a discussion of methods applied by emissions scenarios with a time frame up to 2050.

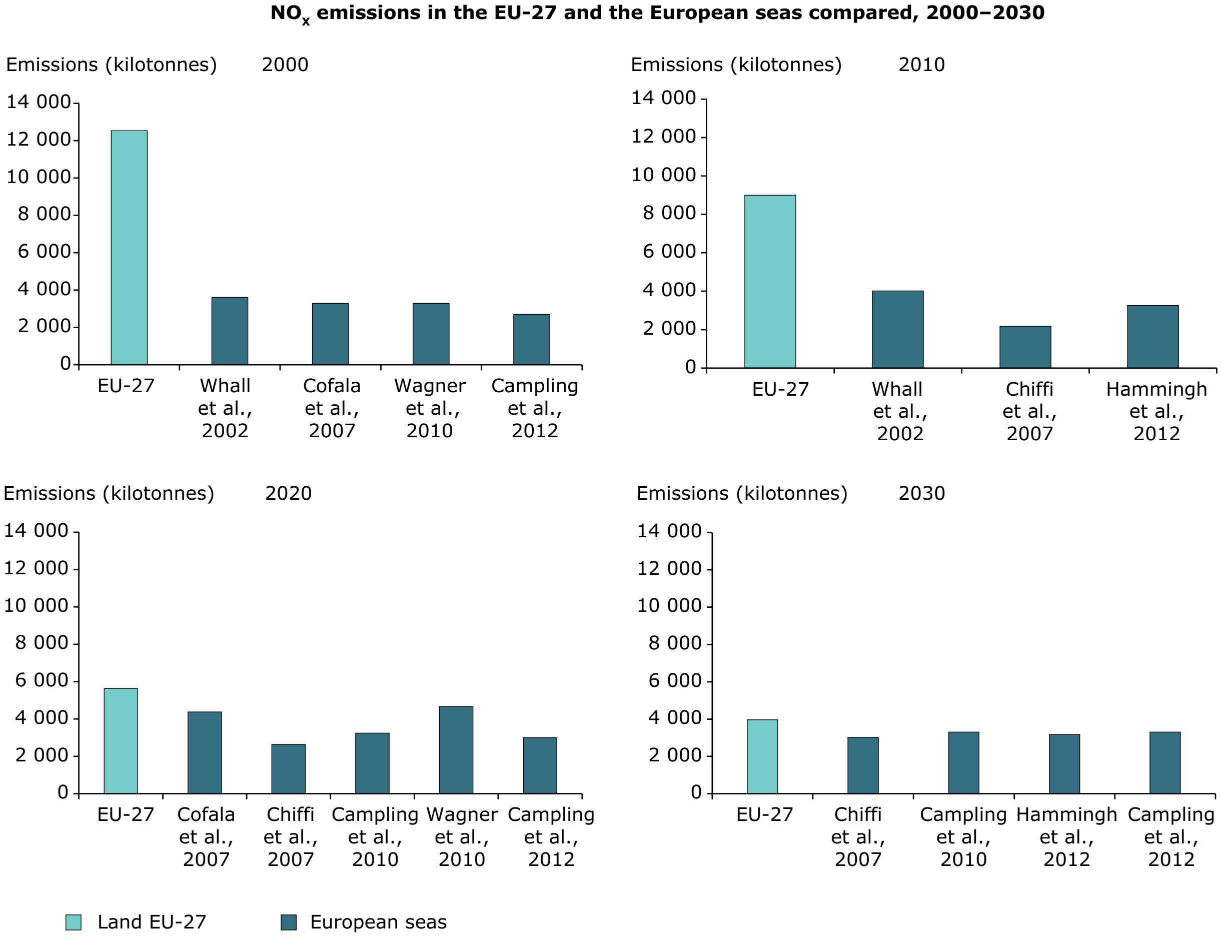
4.3 Shipping emissions in comparison to land-based sources in Europe

As shown in the previous section, most scenario studies show that with the exception of SO_2 emissions, strong reductions from shipping emissions in European seas are not to be expected based on current and foreseen future policies. With land-based sources expected to be reduced in the coming years, the importance of shipping emissions will grow in the future. This has been assessed by comparing shipping scenarios with all land-based emissions sources, thus not limited to land transport emissions, in the EU-27 Member States. Land-based emissions were taken from the TSAP_REF2050 baseline available through the GAINS model (IIASA, 2012). This recent baseline scenario has been prepared for the revision of the EU Thematic Strategy on Air Pollution (TSAP) in 2013 and takes the PRIMES 2010 Reference scenario (and associated control strategies) as a starting point, including feedback from MS (IIASA, 2012). Figures 4.4 to 4.6 present the trends of NO_X, SO_2 and PM emissions.

The comparison for NO_X emissions (Figure 4.4) clearly shows the increasing contribution of shipping emissions to land-based sources since the year 2000. NO_X emissions in the EU-27 are expected to decrease by nearly 70 % between 2000 and 2030. Up to 2030, the land-based emissions probably exceed the NO_X emissions from international shipping in the seas surrounding Europe (see baselines by Campling et al., 2010, 2012 and Hammingh et al., 2012). The baselines by Cofala et al. (2007) and Wagner et al. (2010) do take into account the already agreed emissions limit values by IMO (TIER I and II) in combination with a relatively high growth factor for fuel use (about 2.5 % per year).

SO_2 emissions in the EU-27 are expected to decrease by almost 80 % between 2000 and 2030

Figure 4.4 Comparison of NO_X emission trends between EU-27 land-based sources and emissions from international shipping within European seas



with current air policies in the EU (Figure 4.5). SO_2 emissions in European seas are also expected to decrease dramatically between 2000 and 2020. This is explained by the legislation on sulphur content requirements for future marine fuels. After 2015 the maximum allowed sulphur content in the SECAs Baltic Sea and the North Sea is 0.1 % (compared to 2.7 % in 2000). The maximum sulphur content in other European waters (outside SECAs) may not exceed 0.5 % by 2020 (compared to 2.7 % in 2000). The impacts of these stringent sulphur requirements in 2020 are best shown by Campling et al. (2010). For 2030, both Campling et al. (2010, 2012) and Hammingh et al. (2012) estimate similar total SO_2 emissions from European waters that take the stringent sulphur requirements (i.e. current legislation) into account. The baseline estimate by Cofala et al. (2007) for 2020 is relatively high, which is explained by the fact that they included a sulphur content of only 1.5 % in the SECAs (Baltic Sea and North Sea) and 2.7 % in the other European sea areas. Based on the above estimates it can be expected that the land-based emissions probably exceed the SO_2 emissions from international shipping in European waters up to 2030.

In 2000, $PM_{2.5}$ emissions from land-based sources outweighed the emissions from international shipping in European waters by far (Figure 4.6). Both emissions from land-based sources (EU-27) and sea-based sources are expected to decrease. The emissions in the EU-27 are expected to decrease by more than 40 % between 2000 and 2030 with current air policies in the EU. $PM_{2.5}$ emissions in European seas may also decrease substantially between 2000 and 2020. This is explained by the introduction of low sulphur marine fuels in European waters in the period up to 2020. The impacts by the low sulphur fuel requirements on $PM_{2.5}$ emissions in European seas (a reduction of about 80 %) are best seen in the baseline projection for 2030 by Campling et al. (2010, 2012) and Hammingh et al. (2012).

Figure 4.5 Comparison of SO_2 emission trends between EU-27 land-based sources and emissions from international shipping within European seas

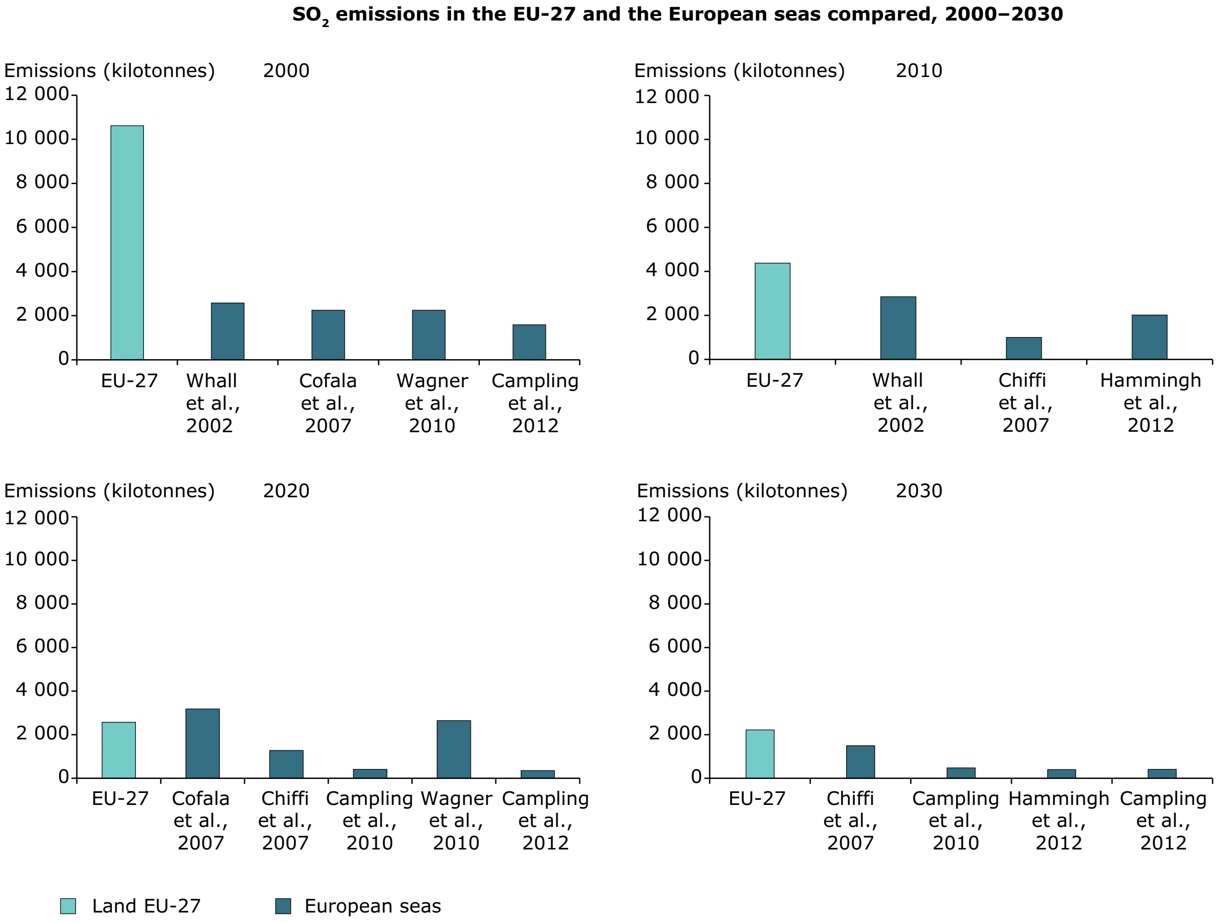
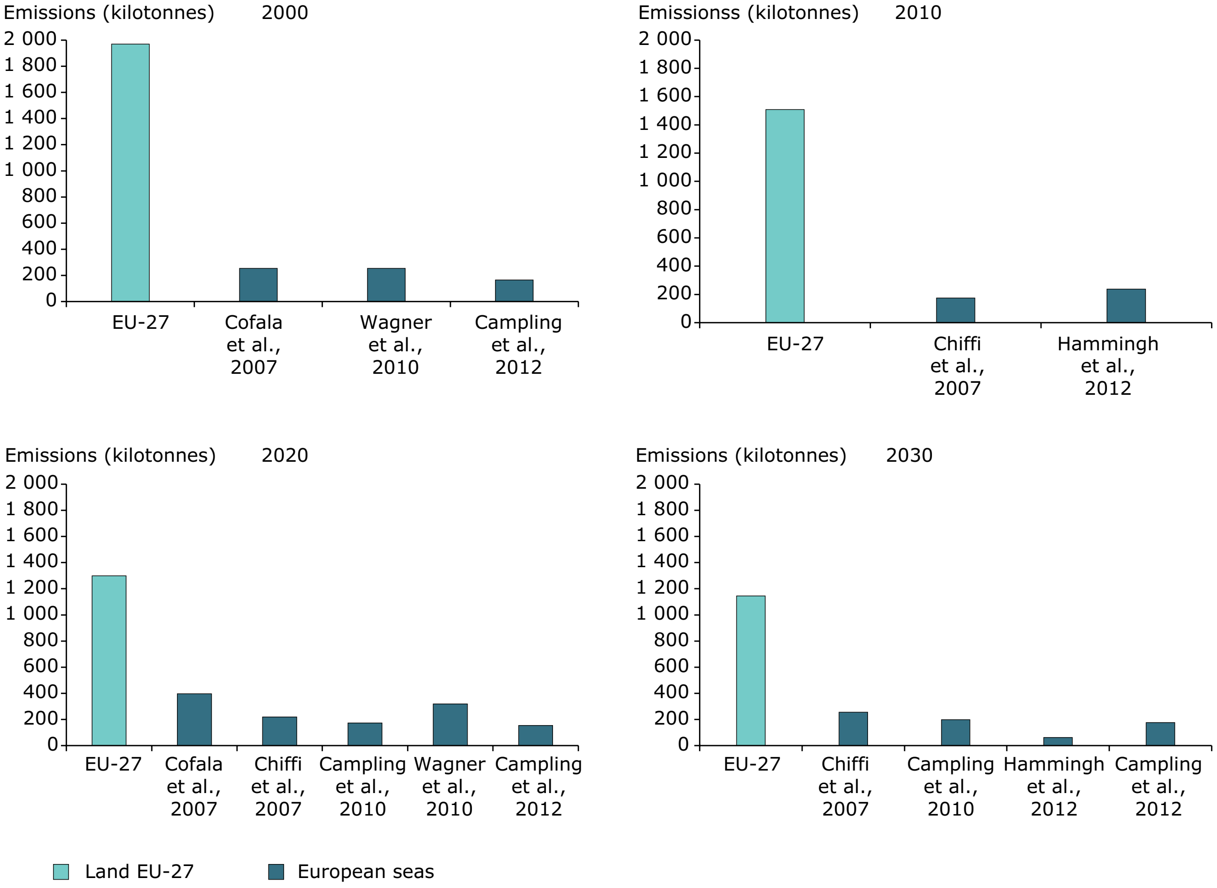


Figure 4.6 Comparison of $PM_{2.5}$ emission trends between EU-27 land-based sources and emissions from international shipping within European seas

$PM_{2.5}$ emissions in the EU-27 and the European seas compared, 2000–2030



5 Emissions from maritime transport and air quality

5.1 The various potential impacts of shipping emissions on air quality

With nearly 70 % of global shipping emissions estimated to occur within 400 km from land (Endresen et al., 2003), ships have the potential to contribute significantly to air quality problems in coastal areas. In EU waters, a larger share of emissions takes place closer to the shoreline — according to Hammingh et al. (2012), 89 % of North Sea ship emissions are within 50 nm and 97 % within 100 nm from shore. The increased flow of commercial ships into and out of ports does not only affect major ports, but also medium- and small-scale ones (Viana et al., 2009). Ship emissions are known to have impacts on human health, ecosystems and air quality (see also TERM 2012 report (EEA, 2012c)).

Human health

Ambient concentrations of PM have been associated with a range of health impacts (see for example, EEA, 2012d, Olesen et al, 2009). The extent to which these health impacts are caused by shipping emissions remains unknown. Vanadium (V) and nickel (Ni), as well as BC and polycyclic aromatic hydrocarbons (PAHs) are typically emitted by shipping activities and they are well known to be hazardous to human health. Keuken et al. (2011) showed that the reduction of combustion aerosols (from industry, energy production, shipping and road traffic, for example) is important for the reduction in health impacts. Corbett et al. (2007) evidenced that shipping-related PM emissions are responsible for approximately 60 000 cardiopulmonary and lung cancer deaths annually, with most deaths occurring near coastlines in East Asia, Europe and South Asia. Under current regulations and with the expected growth in shipping activity, Corbett et al. (2007) estimated that annual mortalities could increase by 40 % by 2012 compared to the situation in 2002. Based on previous estimates of global $PM_{2.5}$-related mortalities (Cohen et al., 2005), 3–8 % of these mortalities may be attributable to marine shipping (Corbett et al., 2007). Thus, mortality and health benefits in multiple regions globally could be realised from policy action to mitigate ship emissions of primary $PM_{2.5}$ formed during engine combustion and secondary $PM_{2.5}$ aerosols formed from gaseous exhaust pollutants. In a recent publication by Andersson et al. (2009), international shipping is estimated to contribute 5 % to the total primary $PM_{2.5}$ population-weighted concentration in Europe and 9 % to the secondary inorganic aerosol population-weighted concentration. This study indicated that it might be more efficient, for the health of the European population, to decrease primary PM emissions (especially in western EU) than to decrease precursors of secondary species.

Ecosystems

Recent studies investigate the impact of gases and particles emitted by ships on acidification and eutrophication of water and soil in coastal regions due to deposition of sulphur and nitrogen compounds (Derwent at al., 2005; Kalli et al., 2010; Sutton et al., 2011). Maritime transport also poses negative externalities to natural habitats and economic losses to coastal areas in the form of shipping disasters, notably large-scale accidental oil spills (Ng & Song, 2010).

An illustration of the potential importance of ship emissions on acidification and eutrophication in Europe can be provided by using source-receptor matrices for deposition of sulphur and nitrogen compounds as calculated by the EMEP model (EMEP, 2012). Figure 5.1 presents the relative contribution of different sea areas in Europe to the deposition of oxidised sulphur (top figure) and deposition of oxidised nitrogen (bottom figure) in EEA countries in the year 2010. Although the relative contribution depends on many factors such as location of a country close to major shipping lanes, meteorology and importance of land-based sources, the contribution of different European sea areas is rather clear. According to the EMEP source-receptor data, emissions from within the North Sea area are contributing to more than10 % of sulphur deposition in Denmark (13 %) and the Netherlands (25 %), and more than 10 % of nitrogen deposition in Belgium (13 %), Denmark (17 %), the Netherlands (17 %), Norway (17 %), Sweden (11 %) and the United Kingdom (11 %). Emissions from shipping in the Mediterranean sea can contribute to more than 10 % of sulphur deposition in Cyprus (14 %), Italy (15 %) and

Malta (56 %) and to more than 10 % of nitrogen deposition in Cyprus (30 %), Greece (21 %), Italy (15 %), Malta (51 %), Spain (10 %) and Turkey (12 %). Emissions from within the Atlantic Ocean contribute to 19 % of sulphur deposition in Ireland and 15 % in Portugal. Nitrogen deposition due to emissions from within the Atlantic Ocean can be contributing significantly to deposition in Iceland (10 %), Ireland (16 %) and Portugal (19 %). The combined impact is rather large for countries like Cyprus (N deposition), Denmark (S and N deposition), Greece (N), Ireland (S and N), Malta (S and N), the Netherlands (S and N), Norway (N), Portugal (N), Sweden (N) and United Kingdom (S and N).

Air quality

As stated above, nearly 70 % of ship emissions occur within 400 km of coastlines. These emissions cause air quality problems through the formation of ground-level ozone, sulphur emissions and PM in coastal areas and harbours with heavy traffic. However, O_3 and aerosol precursor emissions as well as their derivative species from ships may be transported in the atmosphere over several hundreds of kilometres, and thus contribute to air quality problems further inland, even though they are emitted at sea (Eyring et al., 2010). These emissions refer not only to those produced through the stack, but also by routine shipping operations on ports such as loading and unloading of goods and their transport by means of trucks and/or rail. Detailed knowledge on the latter emissions is even scarcer than for the former (Ng & Song, 2010). It is important to bear in mind that the major impact of air quality degradation is on human health, even if other aspects such as visibility or degradation of building materials may be affected by it.

5.2 The contribution of shipping emissions to present-day air quality in coastal areas

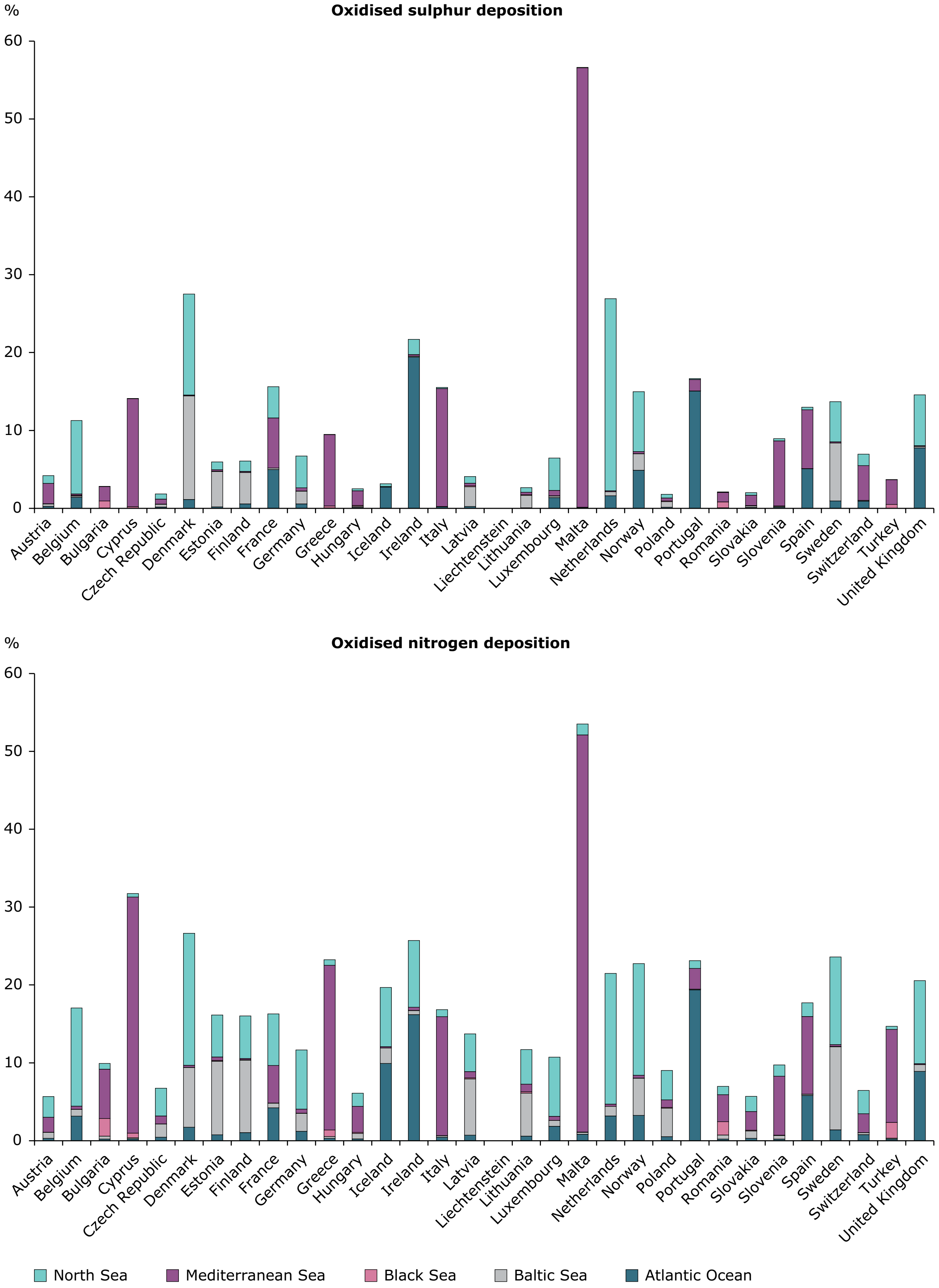
An in-depth literature review was carried out to identify what studies have been carried out recently to assess the impacts of shipping emissions and related harbour activities (loading/unloading) on urban air quality in coastal areas. The total number of studies is relatively small and, specifically, studies that provide a quantitative assessment are relatively scarce. This section presents results of the literature review; a detailed description of the studies included is presented in Annex II. In addition, through analysis of atmospheric measurements and the performance sensitivity runs with atmospheric chemistry models, the contribution of shipping activities to air quality have been identified and quantified.

5.2.1 *Observations*

Vanadium (V), thorium (Th) and nickel (Ni) are known to be tracers of shipping combustion emissions and therefore the presence of these compounds in the composition of plumes and concentrations measurements can be used to identify and quantify the contribution of shipping to observed concentrations of PM and gaseous compounds (see for example, Querol et al., 1996, Viana et al., 2003 and other studies described in more detail in Annex II).

Table 5.1 presents the present-day contribution from shipping to air quality based on observation data at specific locations (harbour areas) for PM. Based on the studies reviewed, shipping emissions contribute to ambient PM levels in European coastal areas with 1–7 % (PM_{10}), 1–14 % ($PM_{2.5}$) and at least 11 % for PM_1. From these results, it is evident that the impact of shipping activities increases with decreasing particle size. For comparison, contribution reported for non-European harbours (United States of America) were in the range of 4–6 % for $PM_{2.5}$. The observation data available to attribute the role of shipping to gaseous pollutant concentrations is even scarcer than for PM. Except for Isakson et al. (2001), who observed that shipping caused a significant increase in concentrations compared to background concentrations (106 % for NO_2 and 281 % for SO_2), other studies were not able to directly identify the contribution of shipping to gaseous pollutant concentration (see for example, Reche et al. 2011). Some studies were able to use trend analysis and time-line of implementation of specific shipping sector policies, such as sulphur content of shipping fuel, or socio-economic trends, such as the economic crisis starting from 2009, to identify the importance of shipping to air quality (Velders et al., 2011; Schembari et al., 2012). Box 5.1 presents an analysis of decreasing trends in SO_2 observations in European harbours. Future work could expand on this type of assessment by utilising information available for harbour areas in AirBase, although the classification of measurement stations in the European Air Quality Database (AirBase) does not identify harbour or coastal stations.

Figure 5.1 The percentage contribution of emissions released from ships in various European seas to the national oxidised sulphur and nitrogen deposition in EEA countries



Source: EEA, based on EMEP, 2012.

Table 5.1 Summary of present-day contribution from shipping to air quality at specific locations across Europe focusing on airborne particles based on observations data

Reference	Contribution	Size fraction/PM component	Location
Mazzei et al. (2008)	20 % ([a])	PM_1	Genoa (Italy)
Viana et al. (2008)	10–30 %	PM_{10} and $PM_{2.5}$	European cities
Viana et al. (2009)	2–4 % 14 %	PM_{10} $PM_{2.5}$	Mellia (Spain)
Hellebust et al. (2010)	< 1 %	$PM_{2.5\text{-}10}$ and $PM_{0.1\text{Stud-}2.5}$	Cork (Ireland)
Pandolfi et al. (2011)	3–7 % 5–10 %	PM_{10} $PM_{2.5}$	Algeciras (Spain)
Becagli et al. (2012)	30 % 3.9 % 8 % 11 %	Nss SO_4^{2-} PM_{10} $PM_{2.5}$ PM_1	Lampedusa (Italy)
For comparison, information from non-EU areas:			
Kim and Hopke (2008)	4–6 %	$PM_{2.5}$	Seattle (USA)
Minguillón et al. (2008)	< 5 %	OC	Los Angeles (USA)

Note: ([a]) Source of particles is heavy oil combustion; study identified this mainly coming from ship emissions and not from land-based sources in the study area.

5.2.2 *Model studies*

The performance of atmospheric chemistry model runs with and without shipping emissions (so-called sensitivity runs) allows isolating the contribution of ship emissions to modelled concentration of air pollution. For example, Marmer and Langmann (2005) have performed sensitivity runs for the Mediterranean Sea area by switching off NO_X emissions and SO_2 emissions from shipping. The model results showed that this led to a 15 % reduction of surface O_3 concentration and 46 % reduction of mean sulphate aerosol concentrations. Andersen et al. (2009) modelled the population-weighted exposure to air pollutants from different emission sources (including shipping) and found that on average across Europe the exposure to shipping emissions was lower compared to exposure from other sources. The averaged found contributions were, for $PM_{2.5}$ (8 %), NO_X (16.5 %) and SO_2 (11 %). More information on these and other model studies can be found in Annex II. Besides the contribution to air pollutant concentrations and human exposure, other studies modelled deposition of sulphur and nitrogen compounds to assess the shipping sector contribution to acidification and eutrophication of water and soil in coastal areas (Sutton et al., 2011).

One should be aware of the limitation of this type of model study with a relatively large spatial resolution (e.g. 50 x 50 km). Emissions inventories used in these model studies do not capture the detail of local emissions in port and coastal towns, and the relatively coarse model resolution does not allow quantifying the local air quality at sub-grid scale. There are studies that provide local/regional assessments at a higher resolution (see for example, Whall et al., 2010; Hammingh et al., 2012), but these do not allow a European-wide assessment of the importance of the shipping sector.

The advantage of model simulations is that information is provided for larger areas than is possible with observations. Results will differ due to differences in approach and methodologies. For example, the findings of Andersen et al. (2009) focus on Europe as a whole region, whereas other studies focus on specific harbour or coastal areas. It is important to realise that model simulations are accompanied with uncertainty, both in the emissions inventory data included in the model runs (see Chapter 4), meteorological data, model setup and methodology (the annihilation experiment consisting of switching off all emissions of a given activity sector, yielding important uncertainties because of the non-linearity of atmospheric chemistry). To support the analysis of the impact of the shipping sector on air quality, two additional model studies are presented in more detail. The first offers results from a LOTOS-EUROS model calculation (Schaap et al., 2012) and the second presents results from ETC/ACM work in direct support of this assessment using the Chimere model.

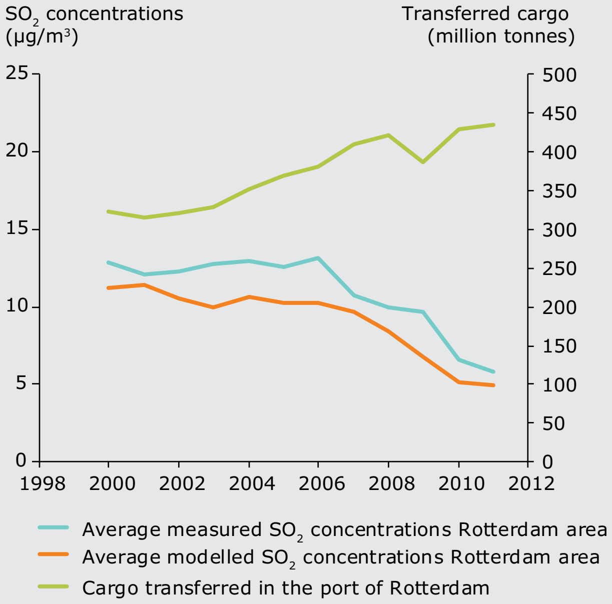
Box 5.1 The impact of European sulphur policies and economic trends on SO_2 concentrations in harbour areas

Recently, a decrease in SO_2 concentrations in the Rotterdam area and in Mediterranean harbours has been observed (Velders et al., 2011; Schembari et al.; 2012).

Rotterdam

Figure 5.2 presents the trend in monitored and modelled SO_2 concentrations as well as data on cargo transferred in the port of Rotterdam area in the period 2000–2011. The trends clearly shows a decoupling of trends in cargo transported in the port of Rotterdam and averaged measured and modelled SO_2 concentrations, as well as the temporary effect of the global economic downturn on transport of cargo in the Rotterdam area. Concentration levels were more or less constant between 2000 and 2006, and decreased rapidly between 2007 and 2010 with 2010 levels about 50 % below the 2000–2006 average. Concentrations in the Netherlands decrease gradually from 2000 to 2010 with 2010 levels also about 50 % below the 2000–2006 average. The behaviour of both the monitored and the modelled SO_2 concentrations is in line with the change in emissions over time from the sectors that contribute the most to SO_2, such as refineries, sea shipping and inland shipping (both on waterways and sea lanes and within port, and emissions from other countries. The SO_2 emissions from shipping decreased after 2006 as result of the use of fuel with a lower sulphur content due to the introduction of the SECA in the North Sea in 2007). The SO_2 emissions from refineries decreased prior to 2010 because of a regulatory switch from HFO to natural gas. An additional decrease in 2010 compared to 2009 originated from the EU directive to use fuel with a sulphur content of maximally 0.1 % for sea ships at berth in ports (see Section 2.2).

Figure 5.2 Trends in air quality (SO_2) and cargo transfer in the port of Rotterdam, the Netherlands



Source: Updated and adjusted results from Velders et al., 2011.

Mediterranean

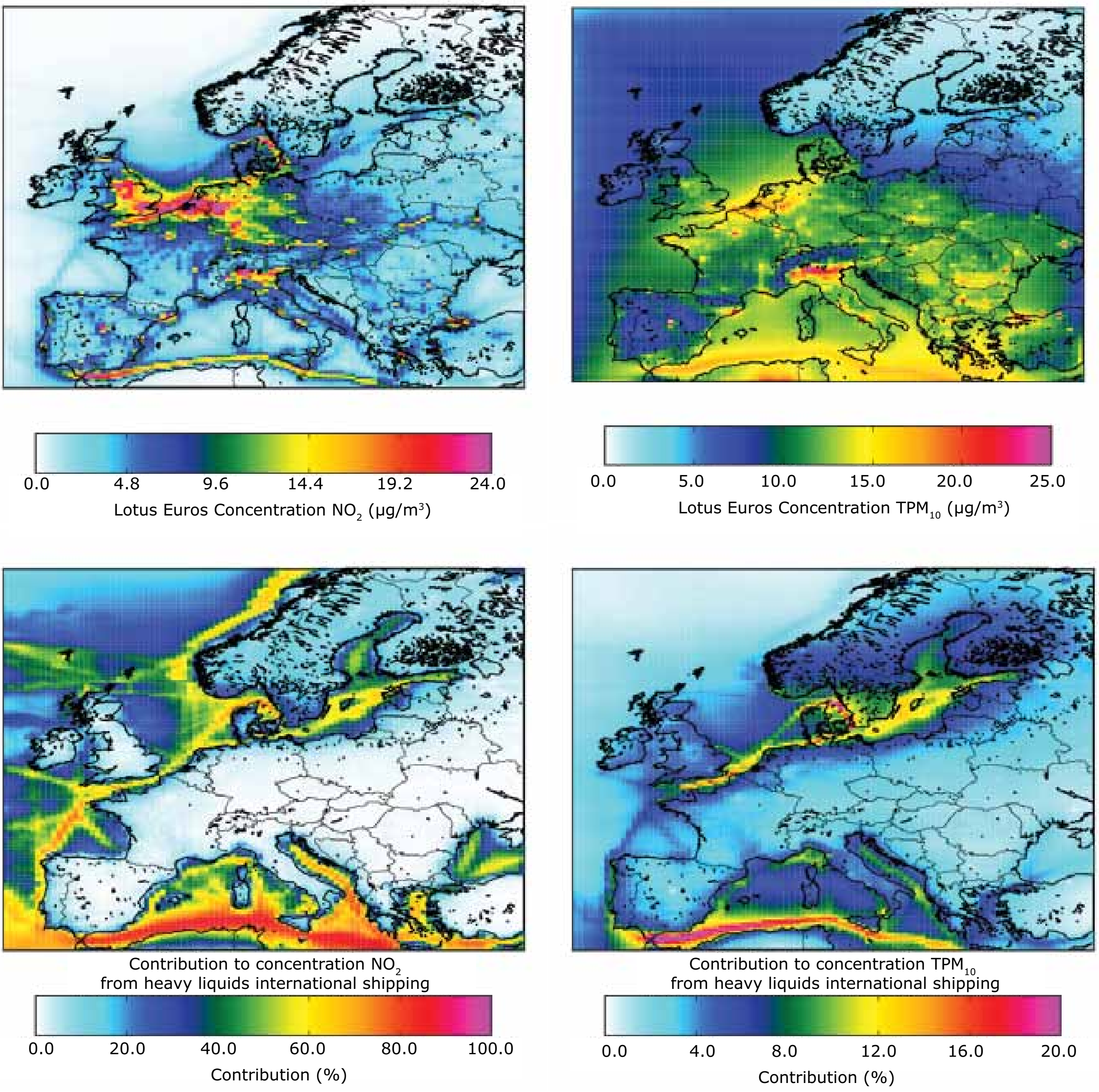
Similar results have been found by Schembari et al. (2012) who analysed the impact of EU Directive 2005/33/EC requiring the use of low sulphur fuel in some Mediterranean harbours. The concentrations of SO_2 were found to decrease significantly from 2009 to 2010 in three out of four EU harbours, with the average decrease of the daily mean concentrations in the different harbours at 66 %. No decrease was observed in the non-EU harbour of Tunis or in NO_x or BC concentrations. The effect on PM contributions was not evaluated.

LOTOS-EUROS model (TNO)

The LOTOS-EUROS model (Schaap et al., 2008; Hendriks et al., 2013) has been applied to estimate the contribution of international shipping to NO_2 and PM_{10} concentrations across Europe. Within the Seventh Framework Programme (FP7) project EnerGeo, a source apportionment module for LOTOS-EUROS was developed to track the origin of the components of PM and their precursors (Kranenburg et al., 2012). For anthropogenic emissions, the TNO-MACC emissions database for 2005 has been applied (Pouliot et al., 2012), which retains the information on fuel types used. One of the available source categories is heavy fuel combustion in international shipping, thus enabling tracking of the contribution of this emission source throughout the model simulations. The result of the model study is presented in Figure 5.3.

On an annual basis, international shipping causes high NO_2 concentrations in the busiest shipping routes (Figure 5.3, top right panel). Ship tracks are clearly visible in the relative contribution of shipping

Figure 5.3 Modelled NO_2 and PM_{10} concentration and contribution from heavy fuel oil from international shipping



Source: Schaap et al., 2012.

to surface NO_2 concentrations (Figure 5.3, bottom left panel), with values between 50 and 90 % depending on distance to shore and the amount of NO_X outflow from adjacent land masses. Due to the short lifetime of NO_X, the contribution to concentrations over the continent is relatively small in non-coastal areas.

For PM_{10} (Figure 5.3, top right panel), a large part of the modelled PM_{10} across the sea consists of sea salt (and also dust in southern Europe) — thus the contribution of shipping to PM_{10} is less visible over shipping lanes (Figure 5.3, bottom right panel). Due to the longer lifetime of PM compared to NO_X, the contribution of shipping PM_{10} in non-coastal areas is more important than for NO_X. In general, shipping emissions cause between 4 and 8 % of the modelled mass concentration up to about 200 km from the coast — in particular, the Gibraltar Strait, the English Channel, the Kattegat and the Baltic Sea area.

Chimere model (ETC/ACM)

Model simulations supporting this EEA report have been performed by ETC/ACM to quantify the impact of shipping activities on air quality using the Chimere Chemistry Transport Model (Bessagnet et al., 2008) developed by INERIS and CNRS in France. The Chimere model is being used for operational air quality forecasting within the MACC pre-operational air quality forecasting service (Rouïl et al., 2009; Menut and Bessagnet, 2010). Emissions representing present-day activity have been taken from the Global Energy Assessment (GEA) dataset (Riahi et al., 2012) for the year 2005. A comparison of the GEA emissions inventory with other studies is described in Annex III.

Model simulations have been performed with or without air pollutant emissions from the shipping sector included. The modelling domain covers greater Europe at a resolution of about 50 km. The choices of a relatively coarse resolution (50 km) and relying on global-scale emissions datasets (GEA) is motivated by the scope of exploring a range of future scenarios and the need to optimise computing resources. These choices can explain the limited differences with the LOTOS-EUROS results introduced above. The modelling setup is described in further detail and validated against measurements in Colette et al. (2011) and Colette et al. (2012a). Result of the model simulations have been used in the TERM 2012 report (EEA, 2012c) to highlight the importance of the shipping sector on air quality.

Figure 5.4 presents the annual mean concentration of NO_2, SO_2, SO_4, $PM_{2.5}$ and the average of summer daily maximum for O_3 (left panels) and the relative contribution of shipping emissions (right panels). The model results clearly show the geographical variability of the impact of shipping emissions on air quality, although the patterns differ from those obtained with the LOTOS-EUROS model because the models rely on different emissions datasets (GEA versus TNO-MACC). Switching off shipping emissions has a very strong impact over sea surfaces, but the magnitude of the response varies depending on the pollutant. Figure 5.4 shows the maps for the control (2005) simulation (left panels) and relative contribution (in %) of shipping emissions at each grid point, computed by comparison of the control and the simulation where shipping emissions are set to zero. The response is very strong for NO_2 and SO_2 with shipping emissions responsible locally for up to almost 100 % of these species. The contribution to secondary formed particulate sulphates (SO_4) is also high (up to 50 %) but the impact on total $PM_{2.5}$ or O_3 is less sensible with at most 25 %. These numbers are in line with those reported in the TNO modelling experiments.

Table 5.2 presents average concentration over sea surface and coastal areas. Based on these results

Table 5.2 Average concentration of the main atmospheric pollutants over sea surfaces and coastal areas

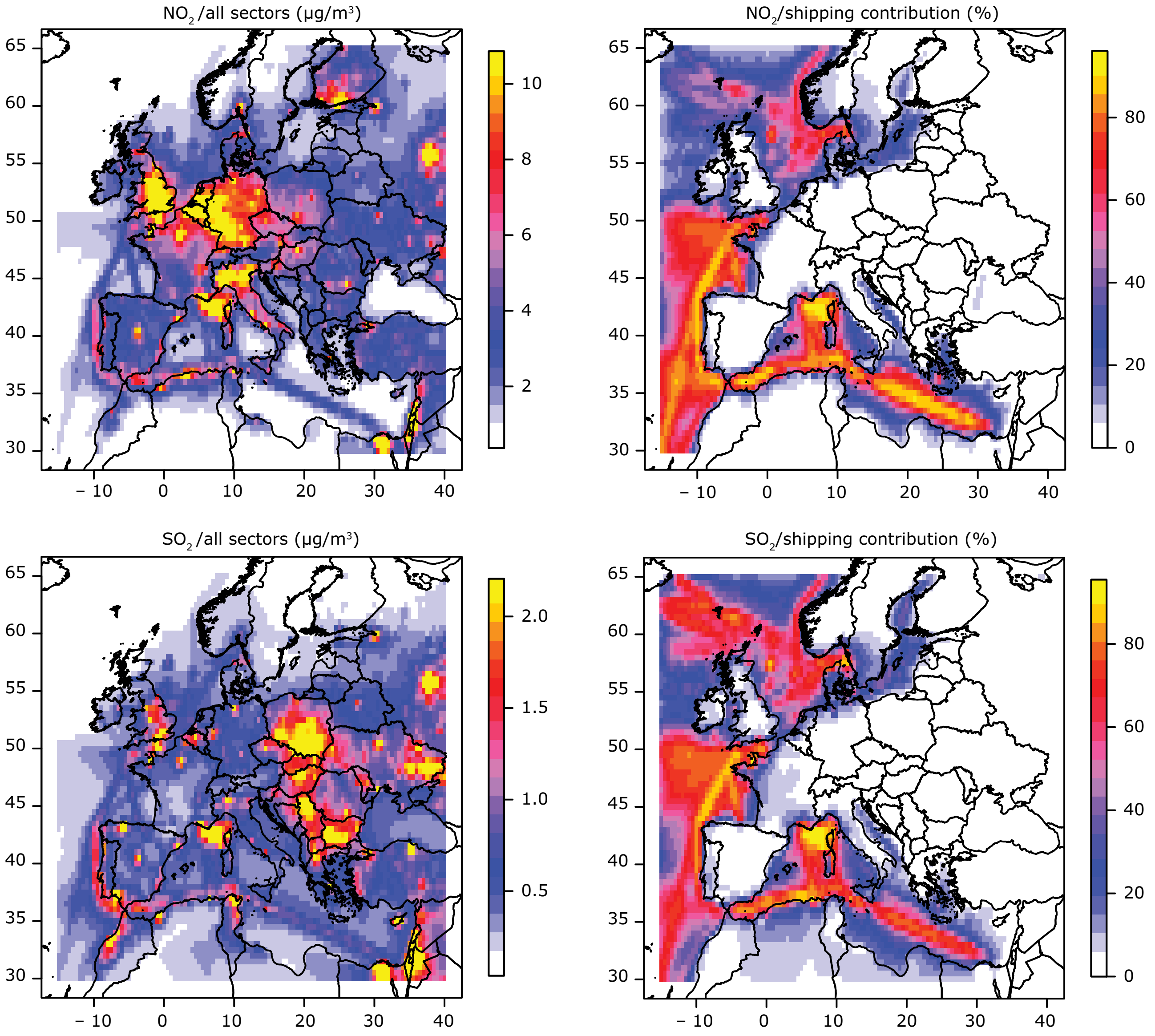
	Sea surfaces		Coastal areas	
	Annual mean (µg/m³)	% contribution from shipping sector	Annual mean (µg/m³)	% contribution from shipping sector
NO_2	1.99	42	3.98	14
SO_2	0.41	44	0.66	16
SO_4	1.42	15	1.51	10
BC	0.18	8.6	0.30	3.4
OC	0.43	6.1	0.84	2.1
$PM_{2.5}$	6.52	6.3	6.92	4.9
O_3	96.8	5.4	99.8	3.5

Note: Values represent annual mean in µg/m³, except for ozone where the averages of the daily summer maxima are presented. The contribution to these concentrations from shipping is expressed as %.

it becomes clear that, to date, ship emissions are responsible for about half of the NO_2 and SO_2 concentrations found over sea surfaces and of lesser importance for particulates and O_3 (this is due to other sources of particulates and O_3). In order to assess the impact of shipping on exposure of the European population to air pollution, the contribution of shipping over coastal areas has been calculated. Coastal areas in the Chimere model setup has been defined as 50 km-wide grid cells having at least one neighbouring cell identified as sea surface. These results show that ship emissions are on average responsible for about 10 % of the exposure to particulate sulphate and about 4–5 % for $PM_{2.5}$ and O_3 peak values, and that for NO_2, SO_2 and particulate sulphur and $PM_{2.5}$, western France, southern England, the Netherlands and northern Denmark are especially vulnerable to ship emissions. For O_3, the strongest contribution of shipping is found in the Mediterranean domain and less for the other coastal areas. To what extent future policies will influence the contribution of ship emissions to air quality has been explored via scenario analyses, which are described in Section 5.3.

Based on observation data and model studies, it has been shown that in several areas the emissions from shipping can have a significant contribution to air quality. The numbers of observation datasets evaluating the contribution of shipping are relatively

Figure 5.4 Maps (from top to bottom) of annual mean NO_2, SO_2, $PM_{2.5}$, SO_4 and average of the summer daily max O_3 (all in µg/m³) in the 2005 control scenarios (left) and relative contribution of shipping emissions (right), in %



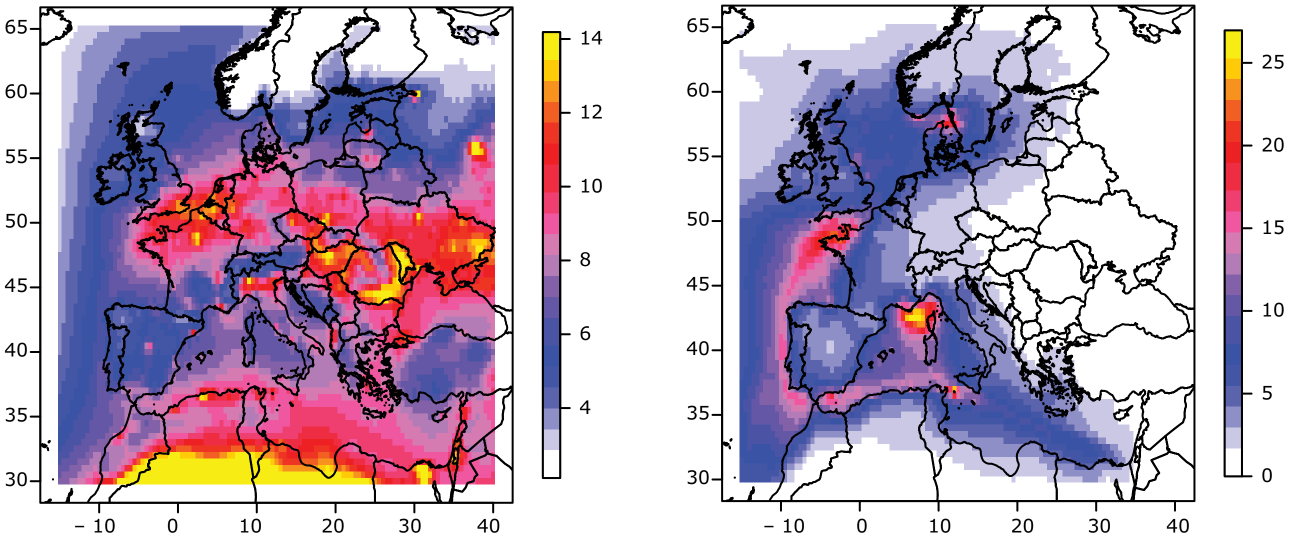
NO_2/all sectors (µg/m³)

NO_2/shipping contribution (%)

SO_2/all sectors (µg/m³)

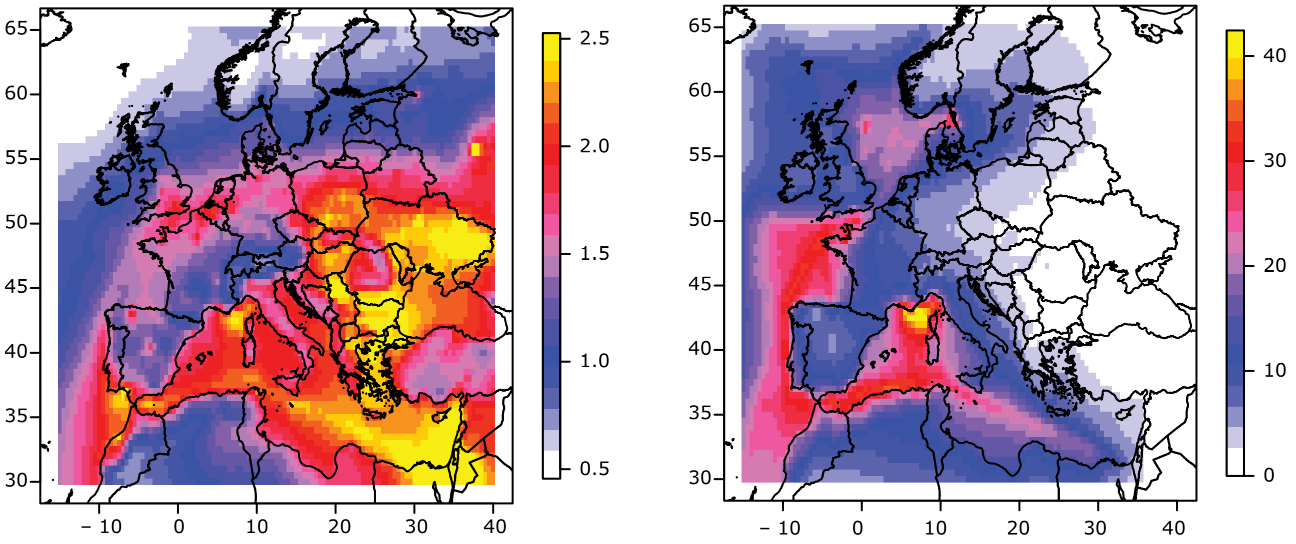
SO_2/shipping contribution (%)

Figure 5.4 Maps (from top to bottom) of annual mean NO_2, SO_2, $PM_{2.5}$, SO_4 and average of the summer daily max O_3 (all in µg/m³) in the 2005 control scenarios (left) and relative contribution of shipping emissions (right), in % (cont.)



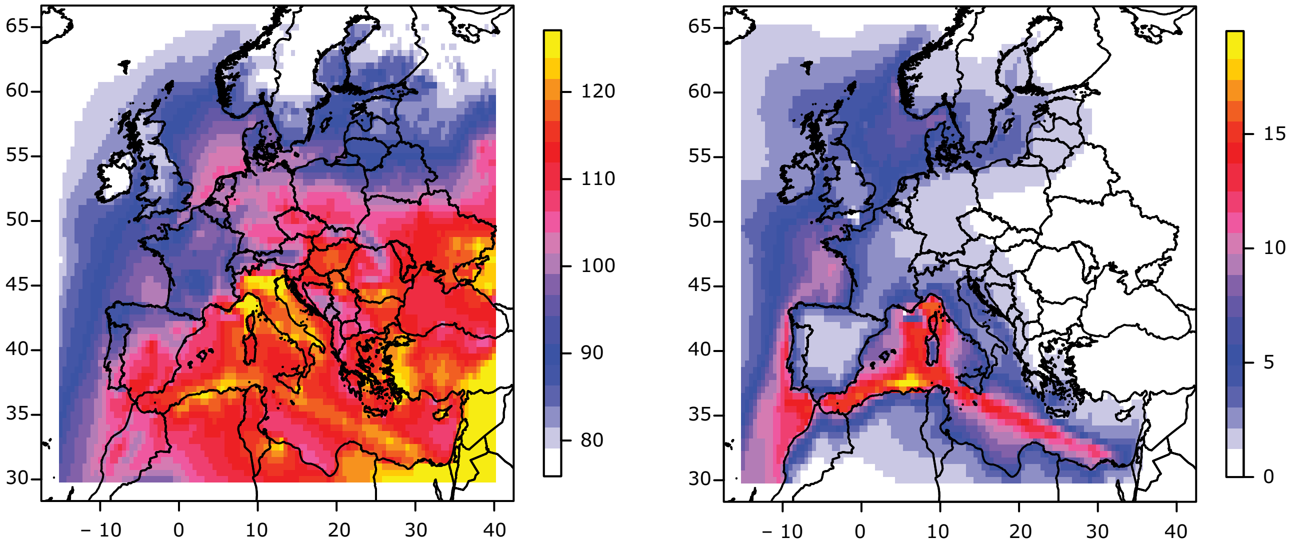
$PM_{2.5}$/all sectors (µg/m³)

$PM_{2.5}$/shipping contribution (%)



SO_4/all sectors (µg/m³)

SO_4/shipping contribution (%)



O_3/all sectors (µg/m³)

O_3/shipping contribution (%)

scarce and make it difficult to evaluate to what extent current exceedances of air quality levels are caused by shipping activities. This is an area for future activity.

The studies that are available have shown that implementing sulphur legislation in Europe has improved the air quality in the Rotterdam and Mediterranean areas.

Results from the model studies show that the effect on air quality is dependent on the lifetime of pollutants and the importance of other emissions sources and other causes. In particular, the direct impact of NO_2 and SO_2 emissions are more of a local nature, whereas the contribution of air pollutant releases due to PM emissions and emissions of O_3 and aerosol precursors is found over larger areas in Europe. The contributions of PM_{10} and $PM_{2.5}$ are consistent with the results from observation that the contribution from shipping increases for smaller particles. To what extent that is directly caused by combustion emissions or through the handling/loading at harbours cannot be determined based on the available data.

5.3 Assessment of the future contribution of shipping activities to the quality of air in Europe

Based on the application of emissions scenarios developed under the GEA (Riahi et al., 2012), the potential future contribution of shipping activities to air quality in Europe has been evaluated by ETC/ACM using the Chimere model. The two global scenarios applied differ with respect to future air quality legislation and policies addressing climate change and energy efficiency (see also Annex III). The so-called reference scenario includes all current implemented and planned air quality policies but no further climate policies than currently implemented. The so-called mitigation scenario also includes all current implemented and planned air quality policies and in addition includes further climate policies leading to a stabilisation of global warming to not more than 2 °C in 2100. Concerning shipping emissions, both scenarios include mitigation measures that correspond to MARPOL Annex VI regulations for NO_X and SO_2.

Using the same model setup as used to analyse present-day contribution of shipping to air quality, the present-day emissions (2005) and the two scenarios have been included in the model simulations. As an example, the annual average concentration of $PM_{2.5}$ as modelled with Chimere is presented in Figure 5.5. The results show that compared to the year 2005 situation (top panel), emissions of land-based sources will be reduced significantly under both the reference and mitigation scenarios. The additional climate measures in the mitigation scenario lead to stronger reductions of $PM_{2.5}$, indicating a strong co-benefit of additional climate measures. Figure 5.5 clearly shows that with reduced land-based emissions, the contribution of shipping to air pollution is expected to increase. This is comparable with studies evaluated in the literature review (see above and Annex II). The result for the mitigation scenario clearly highlights the co-benefit of a strong climate change mitigation policy.

For each case (present-day and two scenarios) the model runs have been complimented with a sensitivity run where shipping emissions where set to zero. The results are shown in Table 5.3. The average load of primary pollutants over sea surfaces decreases strongly when switching off shipping emissions. Table 5.3 provides the average concentration over sea surfaces and the relative contribution (in %) of shipping emissions for each scenario. Shipping emissions are found to be responsible for 42 % of the NO_2 found over sea surfaces for the control (2005) simulation. Very similar numbers are found in the projection: 43 % and 45 % (over sea surfaces) for the reference and mitigation scenarios, respectively.

For SO_2, the contribution is also important (44 % for the control), but it decreases with time: the current legislation regarding shipping emissions will lead to a decrease of the contribution of ships to SO_X by 2020 down to 27 % for both the reference and mitigation scenarios. As a consequence, a similar behaviour is simulated for particulate sulphate. On the contrary, the relative contribution to black and organic carbon is found to increase in 2020 compared to the current situation, for both scenarios. The change in BC and OC also highlights the contribution of shipping to the burden of the compounds, in addition to sulphates. Shipping activities are found to be responsible for only 6.3 % and 5.4 % of the total mass of $PM_{2.5}$ and daily maxima O_3 simulated over sea surfaces because of the contribution of other sources. Shipping emissions are responsible for up to 10 % of the exposure to sulphates in the present situation; this figure will decrease in the future, but ships will remain responsible for about 3–4 % of the exposure to $PM_{2.5}$ and daily maximum O_3.

It is important to realise that the results presented here reflect European averages or data on a 50 x 50 km grid. In order to better assess the impact on urban/coastal air quality in particular locations, regional and local air quality model studies are needed.

Figure 5.5 Annual average maps of $PM_{2.5}$ (µg/m³) modelled with Chimere: 2005 control, 2020 reference and 2020 mitigation

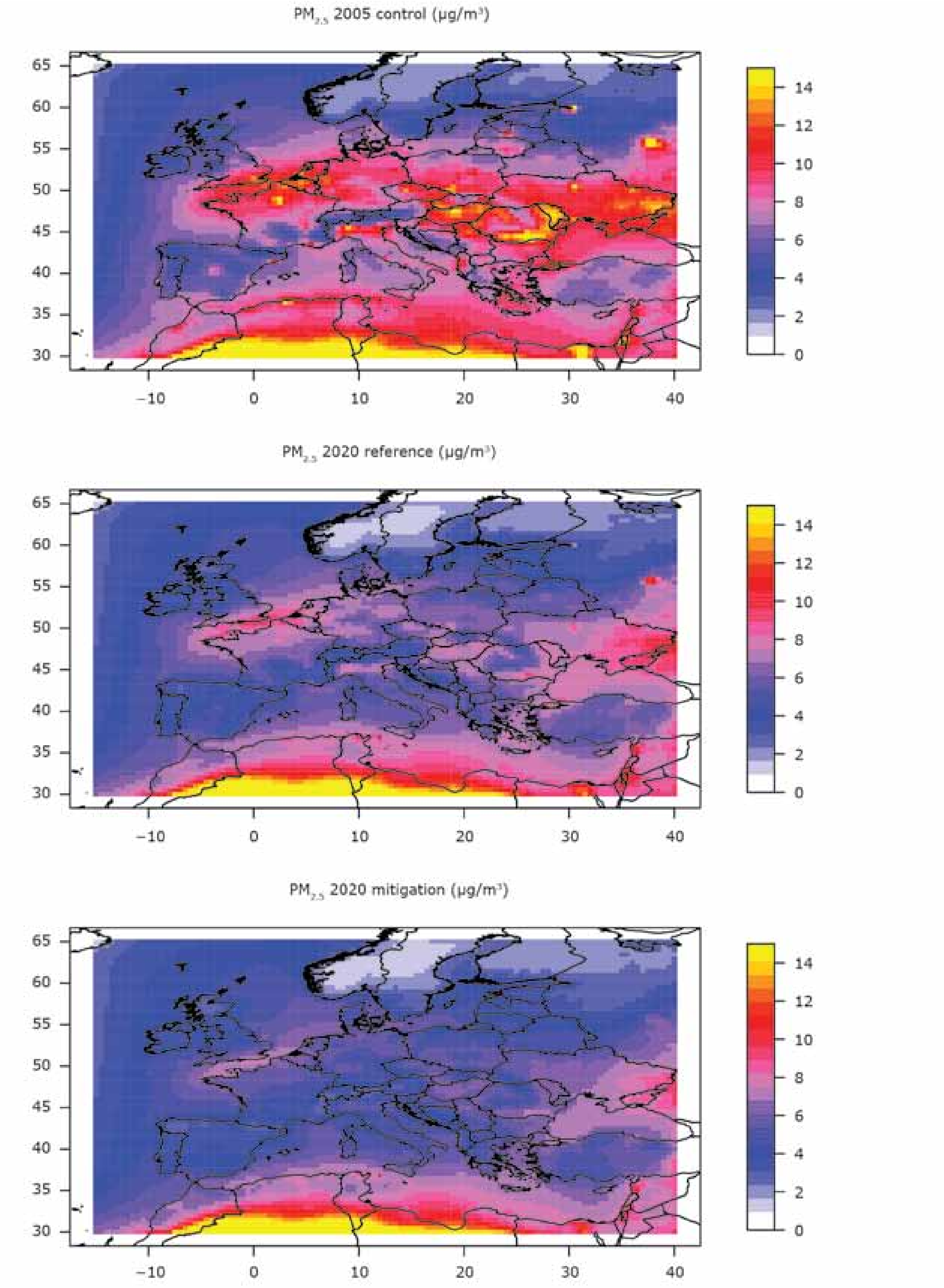


Table 5.3 Average concentration (µg/m³) of the main atmospheric pollutants and the contribution of shipping emissions (in %) over sea surfaces and coastal areas

	Sea surfaces			Coastal areas		
	2005	2020 reference	2020 mitigation	2005	2020 reference	2020 mitigation
NO_2	1.99 (42 %)	1.82 (43)	1.44 (45)	3.98 (14)	3.7 (15)	2.72 (17)
SO_2	0.41 (44)	0.20 (27)	0.16 (27)	0.66 (16)	0.46 (6.9)	0.35 (7.2)
SO_4	1.42 (15)	0.89 (7.8)	0.79 (7.4)	1.51 (10)	0.99 (5.1)	0.85 (4.9)
BC	0.18 (8.6)	0.11 (17)	0.085 (18)	0.30 (3.4)	0.17 (7.2)	0.13 (8)
OC	0.43 (6.1)	0.14 (22)	0.12 (22)	0.84 (2.1)	0.24 (8.7)	0.19 (8.9)
$PM_{2.5}$	6.52 (6.3)	5.52 (4.7)	5.14 (4.2)	6.92 (4.9)	5.5 (4.1)	4.9 (3.9)
O_3	96.8 (5.4)	94.2 (5.6)	90.8 (5.6)	99.8 (3.5)	96.9 (3.7)	92.5 (3.8)

Note: Values represent annual mean, except for O_3 which are summer averages of daily maxima.

Source: ETC/ACM, 2012.

6 Climate change

6.1 The complex contribution of ship emissions to climate change

The modification of the balance between incoming solar and outgoing terrestrial radiation is referred to as RF. Emissions of GHGs and air pollutants from shipping contribute to RF in a rather complex manner through direct and indirect RF (Fuglestedt et al., 2010; Eyring et al., 2010; Lund et al., 2012).

Direct RF refers to the change of fraction of light being absorbed and/or scattered by direct contact with atmospheric components (GHGs or aerosols). The effect can be warming (absorbing, also known as positive RF) or cooling (scattering, also known as negative RF).

Indirect RF refers to the contribution of aerosol emissions to altering cloud properties (such as their lifetime and the size distribution of droplets), resulting in influencing the interference of incoming solar radiation with clouds. The role of shipping is very important here because a significant fraction of ship emissions occur over oceans with pristine areas prone to the formation of low-level cloud formation. Another indirect effect of aerosol emissions is the deposition of BC on ice and snow areas, thus altering the albedo of these surfaces in such a way that less solar radiation is reflected by these surfaces so that these snow and ice masses are melting faster because of the increased absorption of solar radiation.

Present-day situation

When looking at GHG and aerosol emissions from shipping, different RF impacts are found (see Figure 6.1). Emissions from CO_2 are estimated to have a positive RF and recent work (Eyring et al., 2010) estimated this to be 0.037 W/m^2 with an uncertainty range of 0.028 to 0.047. NO_X emissions result both in warming and cooling. NO_X emissions contributing to O_3 production result in positive RF of 0.026 W/m^2 (0.010 to 0.050)[2] but also reduce the lifetime of CH_4 resulting in a negative RF of – 0.033 W/m^2 (– 0.069 to – 0.014)[2]. Sulphate aerosols have a negative RF of – 0.031 W/m^2 (– 0.058 to – 0.015)[2], soot (BC) aerosols a positive RF of 0.002 W/m^2 (0.001 to 0.004)[2] and organic aerosol emissions result in a negative RF of – 0.0004 W/m^2 (- 0.0006 to - 0.0001)[2]. The role of ship emissions due to the indirect aerosol effect is estimated to be having a strong negative RF of – 0.409 W/m^2 (– 0.737 to – 0.047). The role interaction of shipping soot aerosol with snow is a relatively new area of study and based on work by the AMAP (2011); a positive RF of 0.0056 W/m^2 is estimated with a relatively high uncertainty (no range provided).

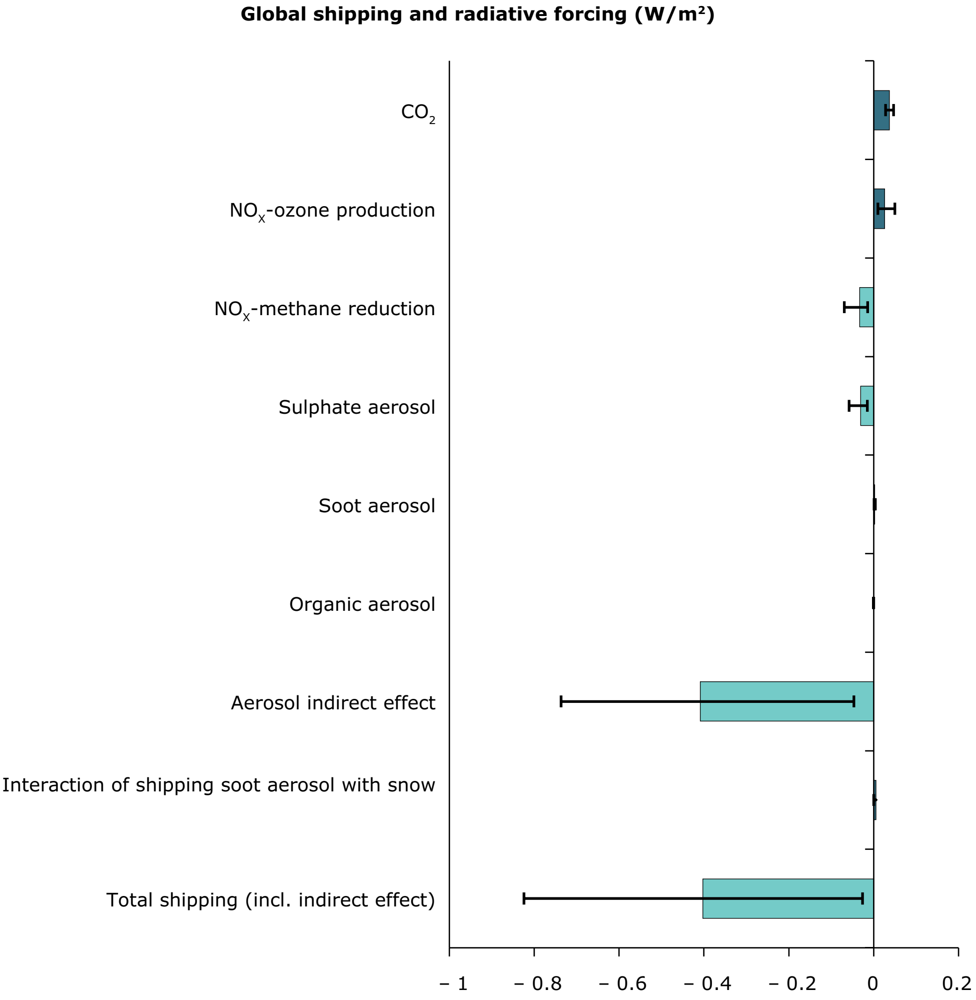
The net effect of these RF estimates is that the present-day ship emissions have a net negative RF of approximately – 0.40 W/m^2 with a large uncertainty range of – 0.824 to 0.026, including both a net negative RF and net positive RF. The results of Eyring et al. (2010) for the present-day situation are confirmed by other work.

Future emissions and impact on radiative forcing

As indicated in Chapter 4, different scenario studies show that within Europe (but same trends are occurring in global scenario studies), emissions of especially CO_2, but also NO_X, are expected to further increase over time (see Figure 4.3). SO_2 and $PM_{2.5}$ emissions are expected to decrease in the period up to 2030 and afterwards; these are expected to increase again up to 2050. As a result of these emissions trends, the net RF effect is expected to change. Until recently, most studies estimated that due to the reduction of aerosol emissions the negative RF of both SO_2 and the indirect aerosol effect would result in the emissions from shipping shifting from having a net cooling effect to having a net warming effect (see for example, Fuglestvedt et al., 2009; Eyring et al., 2010). Recently however, new studies based on other emissions scenario studies (RCP) and different model runs conclude that the emissions from the shipping sector would also in the future (up to 2050) result in a net negative RF (cooling) (Lund et al., 2012).

Due to the longer lifetime of CO_2, the reduction of GHGs remains an essential mitigation measure for tackling climate change. Even more, due to the strong linkage between air pollution and impact on human health and ecosystems, a trade-off game between refraining from air pollutant mitigation in the shipping sector to favour a (potential) net cooling effect of the shipping sector is wrong from a health and environmental perspective and risky

Figure 6.1 Global radiative forcing impact of global shipping emissions expressed in W/m²



Note: Dark blue bars represent a positive RF (warming), light blue bars represent a negative RF (cooling). Please note the relatively large uncertainty ranges. RF from shipping soot aerosol on Arctic snow does not have an uncertainty bar due to lack of data.

Source: EEA, based on Eyring et al., 2010 and Arctic Council, 2012.

given the large uncertainty in the RF values in the literature.

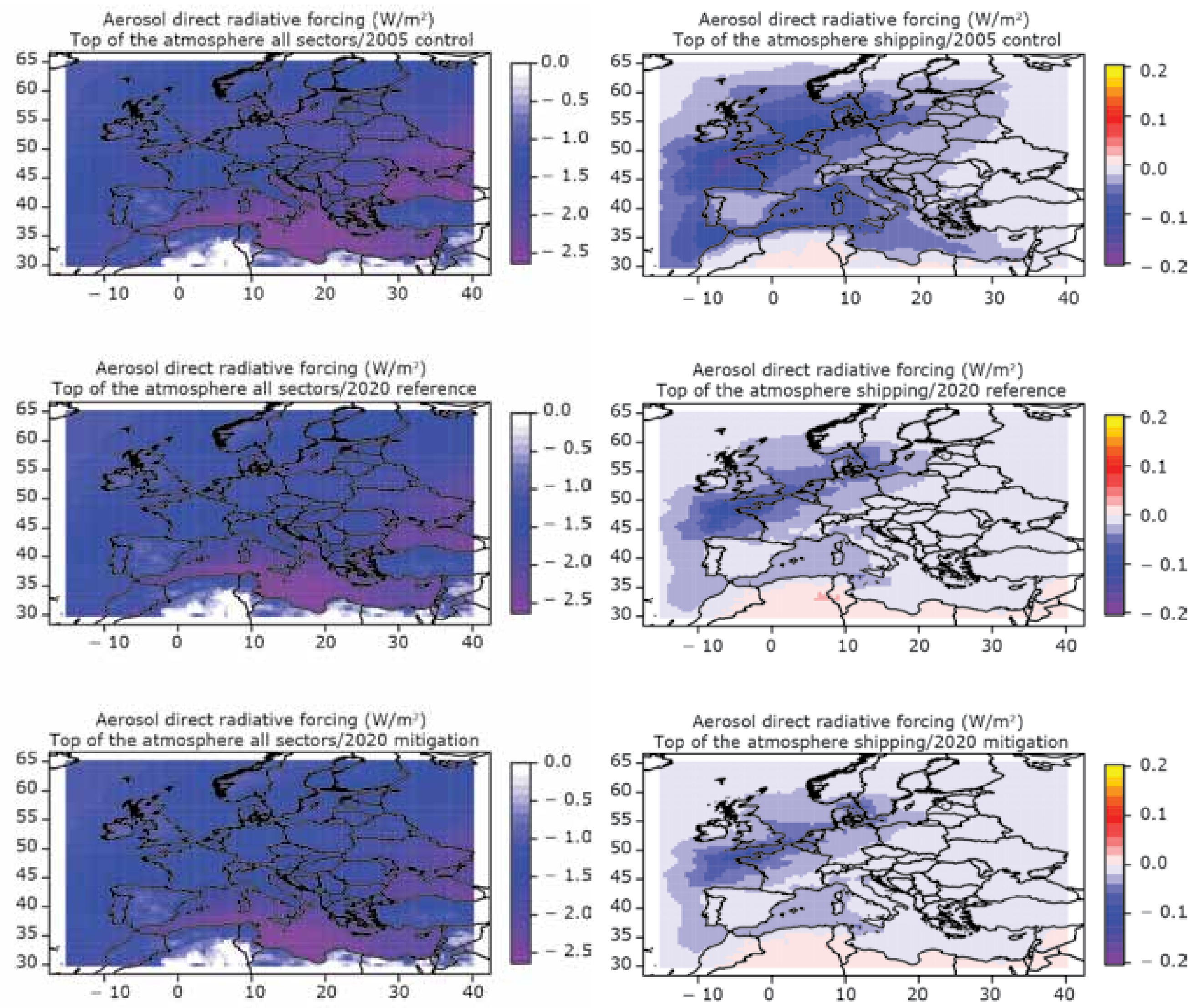
6.2 The impact on direct radiative forcing of aerosol emissions from shipping in Europe

Using the same scenario information and model setup as done for the air quality assessment in Chapter 5, the contribution of aerosol emissions from shipping activities in European seas to direct RF has been evaluated by the ETC/ACM. This model run takes into account explicitly the impact of the whole range of aerosol compounds on direct RF. However, it does not evaluate the other factors such as direct RF from GHGs (including O_3) and indirect RF effects such as those related to cloud-aerosol interactions.

The impact of shipping emissions on direct RF is assessed from the Chimere projections using an offline post-processing tool. Using the aerosol concentration, size and chemical composition, an optical model (Péré et al., 2010) is used to derive the aerosol optical thickness (AOT), single-scattering albedo (SSA) and asymmetry parameter. These quantities are then provided to a radiative transfer code (GAME) (Dubuisson et al., 2006) to obtain the total atmospheric direct RF. One of the strengths of the present approach is to rely on a physical representation of the chemical mix constituting the aerosols parcels, whereas RF obtained by investigating each constituent of the aerosol independently are often reported in the literature. The so called 'core-shell model' allows capturing the radiative properties of a parcel with a core of primary species (BC, OC and dust) surrounded by a coating of secondary species (sulphates, nitrates, ammonium, secondary organics), sea salt and water.

The direct RF at the top of the atmosphere as well as the relative contribution (in %) of shipping emissions is displayed in Figure 6.2 for the control case and the two projections (reference and mitigation 2020 scenarios). For all scenarios it is found that aerosols induce a negative direct RF. The well documented latitudinal gradient (related to the gradient of incoming solar radiation) as well as the patterns over sea surfaces (related to the impact of surface albedo) appears clearly on all maps. But the maximum over the Mediterranean is also largely influenced by the desert dust influx. In the projections, the RF over populated and polluted places decrease as a result of the reduced emission of PM precursors given that all the scenarios include the same air quality legislation.

Figure 6.2 Left: aerosol-induced direct radiative forcing (in W/m²) at the top of the atmosphere in the control (2005) and the two projections: reference (2020) and mitigation (2020); right: the contribution (W/m²) attributed to shipping activities



Note: The negative sign of which illustrates that ships contribute to an even larger negative forcing at the top of the atmosphere.

The highest RF values are found over the Atlantic offshore western France and in the golf of Genoa where ships are found to be responsible for about 10 % of the RF. On average, over sea surfaces the contribution of ships to the direct RF is found to be 2.8 %. This number is in line with the magnitude of the contribution of ships to SO_X emissions: 4.26 % in the present-day scenario (see Chapter 5). By 2020 we find that the contribution of ships to the direct RF at the top of the atmosphere will decrease down to only 1.4–1.2 % for the reference and mitigation scenarios, respectively.

The results show that in the time period up to 2020, the emissions scenario representing currently implemented policies, the direct RF due to ship emissions is not expected to shift from cooling to warming as such; however, the amount of negative RF will show a reduction over time. This means that in particular the strong SO_2 emissions reduction foreseen in the shipping sector will not result in a positive direct RF, at least up to the year 2020. Future work might be initiated to also address the issue of indirect RF.

7 Discussion

Although this report does not address all questions in relation to shipping and air quality and climate change, it does however provide a comprehensive source of information by collating a wide variety of information into one specific volume. Furthermore, the report has attempted to consider air pollution and climate change impact from the shipping sector in an integrated manner. With EU policies focusing on the shipping sector from a more thematic perspective such as implementing stricter sulphur regulations in 2012, the review of air quality legislation in 2013, and the forthcoming proposal on MRV of maritime CO_2 emissions in 2013, this report is timely in providing important insights from an integrated perspective.

As shown in the previous chapters, understanding and addressing international shipping and its impact on European air quality and climate forcing requires insight into a large variety of themes, ranging from registration of ships to countries, international maritime law, international environmental legislation, MRV of emissions (whether for individual ships, the sector or specific regions), atmospheric observation data and air quality and climate modelling.

As shown in Chapter 2, seaborne trade is an important component of the European economy. When looking at the number of ships registered within EU countries or ships owned by EU companies but registered in third countries, the European contribution to the global shipping fleet can be up to 30 %. By presenting international fuel sales data, it has been made clear that at present marine bunker fuel remains an important fuel source in maritime shipping and that alternative fuels such as LNG are not visible yet in international energy statistics. When looking at environmental legislation addressing international shipping, it has been made clear that there is a different pace in ambition levels between the EU and IMO.

The overview on methods and instruments for monitoring and modelling shipping activities and resulting emissions (Chapter 3) shows that there is a large variety of methods and tools available. Due to the potential different applications of these to individual ships, sectoral totals or specific geographic areas and the presence of limitations and uncertainty in the various methods and instruments, further analysis is required on the suitability of particular methods to support a European MRV system on CO_2 emissions or enforcement of specific fuel/emissions limit values. Of the available methods, modelling of ship emissions using so-called bottom-up methodologies is the current state of the art. The evaluation performed in this study to identify the methods and data applied by three commonly used models (ENTEC, TNO, STEAM2) showed that there are sometimes significant differences in model parameters, model structure and source of input data used. How these differences will be reflected when comparing the model results has not been assessed, but Chapter 4 clearly highlighted sometimes large differences between emission calculations.

The review of European maritime emissions inventories (Chapter 4) has revealed that relatively large emissions ranges have been found between emissions calculations covering shipping in European sea areas. These differences are a result of applying different models, statistical data and, moreover, coverage of different geographic domains or shipping activities. This result clearly shows that harmonisation and improved transparency, such as that established in the national emissions inventory activities in Europe, is needed for maritime emissions inventories. The comparison of ship emissions inventory studies with official national inventories shows that currently a relative large fraction of GHG and air pollutants from international shipping within Europe is not accounted for in inventories supporting the LRTAP and UNFCCC conventions. The analysis presented in Chapter 4 further highlights that the contribution from international shipping occurring in European waters is contributing to a relatively large fraction of worldwide shipping emissions. With 10–30 % of global CO_2, 10–20 % of NO_X, 10–25 % of SO_2 and 15–25 % of global $PM_{2.5}$, the effective reduction of ship emissions in European waters, either through international or EU environmental legislation, could have a significant impact at the global scale. The range in percentage contribution to the global emissions total further highlights the uncertainty that exists in ship emissions inventories.

Information is provided in Chapter 4 as to what extent fuel quality requirements, fuel switching, emissions reduction technologies and ship operating procedures can contribute to emissions reductions.

Based on a review of recently developed scenario studies, insight is given into which emissions abatement options are included, how these are included in the scenario studies, and what differences are occurring between scenario studies because of this. The review of recently developed scenario studies on ship emissions shows that except for SO_2 and $PM_{2.5}$, emissions are expected to further increase in the future. Especially for NO_X emissions, an important problem of present air quality problems, these could be equal to or even larger than land-based emissions sources as of 2020 and onwards.

Chapter 5 provides — based on existing studies — an overview of the various (potential) impact of shipping emissions on air quality and, as such, influences on human health and ecosystems. For some countries close to shipping lanes, the contribution of sulphur and nitrogen deposition, for example, can be significant (10–30 %). The review of available observation data shows that there are relatively few measurement data available to actually attribute the contribution of ship emissions to local air pollution. The results of the review show that based on available measurement data the contribution of PM from shipping to local PM concentrations can be up to 20–30 %, with the relative importance of ship emissions increasing with decreasing PM size. Due to the limited availability of observation data, the attribution of ship emissions to air quality can only be assessed performing sensitivity studies using atmospheric chemistry models.

Based on model studies provided and performed to support this report, it is shown that shipping can be responsible for up to 90 % of concentrations in pristine areas (e.g. NO_X). The impact to concentrations over coastal areas is relatively smaller and they do not exceed 5 % for $PM_{2.5}$ and O_3 on average over European coastal areas. The graphical respresentation of the relative contribution shows that there are several hotspot areas in Europe where the contribution of shipping can be up to 80 % for NO_X and SO_2 concentrations, up to 25 % for $PM_{2.5}$, up to 40 % for secondary sulphur aerosol and up to 15 % for O_3. Due to the large scale of the study domain and the available model setup, further studies are necessary with regional and local air quality models at a more local scale. Examples of such studies are mentioned in Chapter 5, but a European assessment of contribution of ship emissions to local air quality requires a significant amount of effort that goes beyond what an EEA study can establish. An example of what more local studies can highlight has been reflected upon by showing the impact of sulphur legislation and economic trends on air quality levels in the port of Rotterdam.

The assessment of future air quality up to 2020 shows that when considering all emissions sources, the implementation of a climate policy on top of current air quality legislation will result in significant co-benefits in particular in north-west Europe and parts of eastern Europe. The model results further highlight that due to the relative size of ship emissions in 2020 compared to reducing land-based sources, the contribution from ship emissions to air quality will increase in the future. The results in Chapter 5 directly or indirectly show the need for further reduction of emissions from international shipping in European seas — a topic which is being considerd in the 2013 air quality review.

In Chapter 6, based on the scientific literature, it has been shown that emissions from shipping (both air pollutants and GHGs) contribute to direct and indirect RF. The overall warming or cooling effect of the sector is rather uncertain but studies show that at the global level, at present, the indirect aerosol effect (cooling) is larger than the direct GHG effect (mainly warming). The future effect (after 2030) is rather uncertain and the scientific literature is not conclusive as to whether it is an additional warming or cooling effect. Based on model studies performed to support this report, it has been shown that present-day shipping emissions have a negative RF (cooling) at the top of the atmosphere over Europe. Model simulations presented in Chapter 6 show that shipping emissions scenarios including current agreed and implemented policies will not change the direct GHG effect from cooling to warming over Europe by 2020, although the net effect of cooling is reduced. The change in indirect RF over Europe due to ship emissions changes has not been assessed. Besides changes in ship emissions, the net effect will also be dependent on other parameters such as meteorological conditions. The work performed by the ETC/ACM supporting this report shows that the model setup is available to calculate potential co-benefits or trade-offs of air pollution and climate policies. This will be reflected in forthcoming work evaluating the effect of low-carbon mitigation policies on air quality in the near and distant future.

Based on the insights obtained from the review of available information and the performance of model simulations, the following recommendations are made to improve relevant knowledge and to support further discussion on the development of integrated air pollution and GHG mitigation policies in the international shipping sector.

- Due to the strong linkage between air pollution from shipping and its impact on human health and ecosystems, and given the large uncertainty of the RF effect of the potential change in ship emissions, it is important that both health and climate impacts of a change in ship emissions are integrated in environmental policymaking. This means that if in the distant future, for example, market-based measures are introduced to reduce CO_2 emissions from the shipping sector, the co-benefits or trade-offs on air pollutant emissions and their impact need to be taken into account.

- As highlighted in different chapters of this report, marine fuel statistics appear to be lower on fuel consumption compared to bottom-up model approaches using fleet-specific information. This has been a recurring issue for several years. With national inventories making use of fuel consumption statistics, this could be taken as an indication to improve emissions inventory information on national and international shipping. The information base, in particular on fuel consumption, can be improved with the introduction of an MRV system.

- Although the potential impact of ship emissions on air quality is known from model studies at a more aggregated level, the knowledge base on attribution of local air quality problems to ship emissions in areas close to shipping lanes is rather limited and there is a clear need to improve the observation-based knowledge.

- Setting up a European MRV system on CO_2 emissions from ships requires a suitable toolbox of monitoring and modelling techniques. This report has focused on presenting the relatively large number of methods for monitoring and modelling fuel consumption and ship emissions. A next step could be to start comparing detailed data such as bunker delivery notes, and continuing fuel consumption measurement with results from bottom-up and top down calculations.

- The review and model studies performed in this work showed that it is important to take into account the links between the emissions from international shipping and their impact on air quality and climate forcing. Due to the fact that a relatively large variation has been found between emissions calculations (both for air pollutants and GHGs), it would be beneficial to extend the proposal for a European MRV system to cover both air pollutants and GHG emissions. In this way, the emissions trends of both air pollutants and GHG can be monitored in a consistent manner over time, allowing for better highlighting and evaluating co-benefits and trade-offs of mitigation policies.

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Acronyms, units and terms

AE	Auxiliary engine
AirBase	European Air Quality Database
AIS	Automatic Identification System
AMVER	Automated Mutual-Assistance Vessel Rescue System
AOT	Aerosol optical thickness
BC	Black carbon
BDN	Bunker delivery note
CLRTAP	Convention on Long-range Transboundary Air Pollution
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DOAS	Differential Optical Absorption Spectrometry
EC	European Commission
ECA	Emission Control Area
EEA	European Environment Agency
EEA-32	32 member countries of the European Environment Agency
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EIA	U.S. Energy Information Administration
EMEP	Emission Monitoring and Evaluation Programme
ETC/ACM	European Topic Centre on Air Pollution and Climate Change Mitigation. The ETC/ACM is a consortium of European institutes contracted by the EEA to carry out specific tasks in the field of air pollution and climate change
EU	European Union
EU-27	Belgium, Bulgaria, Czech Republic, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland, Sweden, United Kingdom
GDP	Gross domestic product
Gg	1 gigagram = 1 kilotonne (kt)
GHG(s)	Greenhouse gas(es)
GT	Gross tonnage. The expression of a ship's overall internal volume
HFO	Heavy fuel oil
IEA	International Energy Agency
EEZ	Exclusive Economic Zone
EMSA	European Maritime Safety Agency
E-PRTR	European Pollutant Release and Transfer Register

HSD	High speed diesel
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
LRIT	Long Range Identification and Tracking
ME	Main engine
MDO	Marine diesel oil
Mg	1 megagram = 1 tonne (t)
MGO	Marine gasoline oil
MMD	EU Monitoring Mechanism Decision
MRV	Monitoring, Reporting, Verification
MSD	Medium speed diesel
Mtoe	Million tonnes of oil equivalent
MS	Member State
Ni	Nickel
NMVOC	Non-methane volatile organic compound
nm	Nautical mile
NO_2	Nitrogen dioxide
NO_X	Oxides of nitrogen
LNG	Liquefied natural gas
OC	Organic carbon
PAH	Polycyclic aromatic hydrocarbons
PM	Particulate matter
RF	Radiative forcing
RFO	Residual fuel oil
SCR	Selective catalytic reduction
SSD	Slow speed diesel
SEEMP	Ship Energy Efficiency Management Plan
SFC	Specific fuel consumption
SO_2	Sulphur dioxide
SO_4	Secondary formed particulate sulphates
SO_X	Oxides of sulphur
SWS	Seawater scrubber
Tg	1 teragram = 1 megatonne (Mt)
Th	Thorium
tkm	Tonne-kilometre
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
V	Vanadium
% m	Percentage expressed as mass of the fuel

Annex I Overview of available studies on maritime emissions in Europe

This annex presents a selection of important studies on maritime emissions inventories and projections. The information is based on a literature review performed by the ETC/ACM covering studies available until summer 2012. Table AI.1 and Table AI.2 provide an overview of key elements of the studies separated in presenting details of the inventory methods (AI.1) and details of the projection and scenario methods and assumptions (AI.2). The text below provides information on background and application of the studies in chronological order. This information can be used for further assessment studies and as reference for the emissions data and trends described in the report.

Description of relevant studies on maritime emissions in European seas

The study 'Quantification of emissions from ships associated with ship movements between ports in the European Community' carried out by ENTEC covers the whole EMEP area (Whall et al., 2002). This area includes the North Pole and the whole European continent. It is the first attempt in Europe to assess the importance of maritime emissions compared to land-based emissions. The activity data comes from four months of Lloyds Marine Intelligence Unit (LMIU) data from the year 2000 (bottom-up). Fishing vessels, not included in LMIU, were included separately. Port emissions were also included to some extent. The emissions model is the first version of the ENTEC model.

In the ENTEC study 'Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments', the focus is on assigning emissions to EU MS with nine different assignment methods (Stavrakaki et al., 2005). The study is based on work in the previous ENTEC study from 2002. The projections are extended in this new 2005 study from 2010 to 2020. Moreover, the impacts and costs of emissions reduction measures are determined for SO_2 and NO_X.

Maritime emissions were also covered in the Tremove transport and emissions simulation model developed for the European Commission (De Ceuster et al., 2006). It is designed to study the effects of different transport and environment policies on emissions of the transport sector. All relevant transport modes are modelled, including air transport. Maritime transport is treated in a separate model. Tremove covers the 1995–2020 periods with yearly intervals. Tremove based its maritime emissions module on the work of Whall et al. (2002). Hence, the geographical domain was also the EMEP domain. The ENTEC forecasts were, however, not adopted in Tremove. Instead, growth rates up to 2020 were derived from the Scenes maritime transport model and applied to the 2000 ENTEC figures. This resulted in an annual growth of 2.5 % for freight and 3.9 % for passengers. These growth rates were also taken by Cofala et al. in 2007.

The IIASA study 'Analysis of Policy Measures to Reduce Ship Emissions in the Context of the Revision of the National Emissions Ceilings Directive' focuses on the impact of maritime emissions on air quality, especially in Europe and the coastal regions (Cofala et al., 2007). The previous two emission inventories by ENTEC were refined distinguishing national and international emissions, emissions by flag state and emissions within the 12-mile territorial waters. Emissions are presented per European sea area (i.e. the Baltic Sea, the North Sea, the Mediterranean Sea, the Black sea, and the Atlantic Ocean) within the EMEP model domain. In addition, the study contains a number of scenarios with increasing reductions especially in SO_2 and NO_X emissions. This inventory was later adjusted and used by IIASA during their analysis in the framework of the revision of the Gothenburg Protocol during the 2010–2012 periods (Wagner et al., 2010). Part of the work by Cofala et al. (2007) is also used in Bosch et al. (2009) and Hammingh et al. (2012).

While the previous studies used a bottom-up approach, the Extremis study 'EXploring non road TRansport EMISsions in Europe Development of a Reference System on Emissions Factors for Rail, Maritime and Air Transport' used a mixture of a bottom-up and a top-down approach (Chiffi et al., 2007; Schrooten et al., 2009). The model correlates both national and international shipping activities to the partners of each single EU reporting country. Detailed maritime statistics and inventories with information about cargo type shipments, partner countries and ship features are the relevant sources. The model does not use direct observations of actual trips, but empirically derives the equivalent number of ships needed to trade by sea the total volume of a certain cargo type to and from each origin-destination harbour. Hence, no emissions per geographical area were calculated. Also transit traffic between non-EU countries was ignored. The emissions factors of the TNO model were used.

In the study 'Cost Benefit Analysis to Support the Impact Assessment accompanying the revision of Directive 1999/32/EC on the Sulphur Content of certain Liquid Fuels', Bosch et al. (2009) compare the effects of various options for SECAs (Baltic Sea, North Sea, Black Sea and Mediterranean Sea) with land-based measures (Bosch et al., 2009). The emissions calculations for shipping are based mainly on Cofala et al. (2007), i.e. the ENTEC model. But the PM emissions factors were based on the work of Cooper & Gustafson (2004). Bosch et al. (2009) used the same assumptions as Chiffi et al. (2007) for the growth rate of future shipping activities. The assumed sulphur content in SECAs in the baseline for 2020 is 1.45 % m instead of the 0.1 % m limit valid after 2015. Moreover, the baseline by Bosch et al. (2009) did not include the TIER I and II NO_X standards. The baseline by Bosch was not meant to represent a realistic baseline for 2020 including envisaged policies, rather it was meant as a reference point to show the impacts of additional NO_X (and sulphur) policies.

The study 'Technical support for European action to reducing Greenhouse Gas Emissions from international maritime transport' focused on CO_2 emissions (Bosch et al., 2009; Faber et al., 2009). For shipping activities, mainly LMIU data were used, which were allocated to shipping routes with an adjusted SeaKLIM algorithm (Paxian et al., 2010). This algorithm is designed to find the most probable shipping route between origin and destination. Fuel consumption factors of Corbett and Koehler (2003) were used. They assume a CO_2 emissions factor (ECF) for transport vessels (passenger and freight) of 206 g/kWh and for non-transport vessels (fishing and factory vessels, research and supply ships, tugboats) of 221 g/kWh. Load factors of 80 % and 50 % were used for main and auxiliary engines, respectively. Faber et al. (2009) derive estimates for CO_2 emissions for voyages arriving or departing in the various world regions. For Europe, Faber et al. (2009) show estimates for the CO_2 emissions from voyages arriving or departing in EU-27 ports, and for voyages between EU ports. Results are also available for the various ship types and ship sizes. The report by Faber et al. (2009) does not include data on emissions within a defined geographical area such as the EMEP area or the EEZ.

In the study 'Market-based instruments for reducing air pollution Lot2: Assessment of Policy Options to reduce Air Pollution from shipping' (Campling et al., 2010), the activities from the EX-TREMIS study by Chiffi et al. (2007) were taken. The activities were assigned to shipping routes to make air quality calculations possible. Because in EX-TREMIS the origin and destination zones were large (e.g. France Atlantic), trips were distributed over the possible routes according to their importance. The emissions factors are similar to the TNO model. However, the load factor of main engines was set to 75 % based on an analysis of shipping speeds in the LMIU database.

Miola and Ciuffo (2011): This paper provides a critical analysis of the ship emissions modelling approaches and data sources available, identifying their limits and constraints. It classifies the main methodologies on the basis of the approach followed (bottom-up or top-down) for the evaluation and geographic characterisation of emissions. The analysis highlights the uncertainty of results from the different methods. This paper presents an alternative methodology based on this approach.

The study 'Specific evaluation of emissions from shipping including assessment for the establishment of possible new emission control areas in European seas' (Campling et al., 2012) builds on a previous study (Campling et al., 2010). The emission inventory for 2005 is based on the Extremis/Eurostat dataset which was further developed and integrated with a digital European shipping routes map. Additionally, BC emissions were calculated as a fixed fraction of the fuel consumption (5 mg/MJ) independent of the sulphur content. Emissions are given for European sea areas within the EMEP area and also for shipping emissions released outside the EMEP area but within the TNO grid area (see Figure 4.2). The study includes a baseline projection up to 2050 and various scenarios describing the impacts of further sulphur and/or nitrogen ECAs in addition to the existing sulphur control areas in the North Sea and the Baltic Sea. Other scenarios describe the impact of slow steaming, soot filters and maximum feasible reductions on air polluting emissions from shipping. Cost calculations give estimates for the cost effectiveness for stringent nitrogen, sulphur and PM controls and for cost savings by slow steaming. The emissions will be used to calculated the impact on public health and ecosystems of the different scenarios. The calculated costs of measures then need to be compared with the calculated benefits.

Description of relevant regional studies on maritime emissions in Europe (Table AI.1)

Emissions from international shipping in the Belgium part of the North Sea and the Belgium seaports are described for the one-year period April 2003 to March 2004 in De Meyer et al. (2008). The study covers CO_2, NO_X and SO_2 emissions but does not contain emissions projections. The study follows a bottom-up, activity-based methodology (partly based on radar registration) that is estimated to cover 90 % of shipping activities in the area. The remaining activities (mainly dredgers and tugboats) were estimated using a top-down method based on fuel sales. De Meyer et al. (2008) estimated CO_2 emissions at 1.88 Tg, SO_2 emissions at 31 Gg, and 39 Gg of NO_X. Compared to national inventories (2003 data), this accounts to 1.5 % for CO_2, 30 % for SO_2 and 22 % for NO_X of total emissions of these gases in Belgium. When the CO_2 figure is compared with the current estimate of CO_2 emissions from international shipping, based on sold bunker fuels (22 754 Gg CO_2), the relevance of a detailed and precise emissions inventory becomes clear. In the end, the Belgian estimates are validated by comparing them with Dutch, EU and international emissions estimates.

Deniz & Durmusoglu (2008): Another example of emissions estimates. As an inland sea, the Sea of Marmara is an area that has too much ship traffic. Since the region of the Marmara is highly urbanised, emissions from ships affect human health and the overall environment. In this paper, exhaust gas emissions from ships in the Sea of Marmara and the Turkish Straits are calculated by utilising the data acquired in 2003. Main engine types, fuel types, operations types, navigation times and speeds of vessels are taken into consideration in the study. Total annual emissions from ships in the study area were estimated as 5.4 Tg y− 1 for CO_2, 111 Gg for NO_X, 87 Gg for SO_2, 20 Gg for CO, 5 Gg for VOC and 4.7 Gg for PM. The shipping emissions in the region are equivalent to 11 % of NO_X, 0.1 % of CO and 0.12 % of PM of the corresponding total emissions in Turkey. The shipping emissions in the area are 46 % of NO_X, 25 % of PM and 1.5 % of CO of road traffic emissions in Turkey. Schrooten et al. (2009): In this paper we present Mopsea, an activity-based emissions model to determine emissions from sea-going vessels. The model considers shipping activities of sea-going vessels in Belgian territory, combined with individual vessel characteristics. We apply this model to study the effects of recent international efforts to reduce emissions from sea-going vessels in Belgian territorial waters for the current fleet and for two scenarios up to 2010.

A new national emissions inventory for national and international shipping in Danish waters is presented by Winther (2008). Emissions from international shipping and fishing are based on a top-down method using national fuel sales data. Emissions from national shipping (regional and local ferries and national sea transport) is determined by using partly activity-based methodologies and partly fuel sales data. Fuel consumption for 2005 is estimated at 46 PJ, SO_2 emissions at 38 000 tonnes, and NO_X emissions at 78 000 tonnes. Winther also presents projections that assume that fuel consumption is constant, but emissions factors are adjusted over time in order to meet IMO emissions standards. He concludes that his forecasts demonstrate a need for stricter fuel quality and NO_X emissions standards in order to gain emissions improvements in line with those achieved for other mobile sources.

Marmer et al. (2009): Examined six different ship emissions inventories focusing on the Mediterranean Sea. All inventories include the emissions of NO_X, SO_2, CO and NMVOC. The global emissions inventories EDGAR FT 2000 (Olivier et al., 2005, with OC and BC emissions based on Bond et al., 2004), and Eyring et al., 2005), both compiled for the year 2000, are available on a 1 × 1 horizontal resolution and their spatial distribution is based on AMVER data (Endresen et al., 2003). In EDGAR, a top-down approach is applied, which is based on bunker fuel statistics from the IEA. Eyring et al. (2005) have applied the so-called activity-based, top-down approach, which is based on the information on ships and engine types (Lloyd's Register of Shipping, 2002). This activity-based, top-down approach results in higher emissions estimates for SO_2 and NO_X. The regional European inventories ENTEC (Whall et al., 2002), EMEP (Vestreng et al., 2007), CONCAWE (2007) and IIASA (Cofala et al., 2007) all share the same spatial distribution and methodology and hence deliver comparable emissions estimates for all compounds. Marmer and Langmann (2005) selected the EMEP inventory for the Mediterranean Sea and two global inventories based on AMVER data as input for global air quality calculations and the results were compared with concentration measurements.

Andersson et al. (2009): Contribution to emissions: The table AI.1 gives the total model domain emissions for the year 2001 and the distribution between source regions. The emissions in Eastern European Union (EEU) countries exceed those of Western European Union (WEU) for primary particles and SO_X. For nitrogen emissions (NO_X and ammonia (NH_3)) and carbon species (CO, NMVOC), the emissions in WEU exceed those of EEU. The emissions inventory used is less complete for some eastern European countries (Vestreng et al., 2007a). The same study raised raise concerns regarding comparisons between eastern and western Europe due to unresolved problems in some of the emissions data. Different countries may have different procedures on how and what they report and to which sector they attribute emissions. This might bias the comparison between eastern and western European emissions. Therefore, comparisons of sector distributions for the different regions are uncertain. The Swedish contributions to European emissions are 1–2 %. The contributions of international shipping to the total European emissions are relatively large: 8 % ($PM_{2.5}$), 16.5 % (NO_X) and 11 % (SO_X). Natural emissions of sulphur (di-methyl sulphide and volcanoes) contribute with a relatively large fraction of SO_X. EC and OM mainly originate from non-industrial combustion plants, road transport and shipping. Primary inorganic matter (IM) is mainly from stationary sources, with the largest contribution from production processes. The total emission of $PM_{2.5}$ is 3.02 Tg/yr (EC: 666 Gg/yr, OM: 933 Gg/yr and IM: 1.42 Tg/yr). Agriculture is the (single) largest contributor to NH_3. The largest sources of NO_X are road transport and other mobile sources and machinery, though there is contribution also from combustion. SO_X mainly originates from combustion and international shipping.

ENTEC UK Ltd. developed a gridded emissions inventory from ship movements within waters surrounding the United Kingdom, including the North Sea, English Channel, the Irish Sea and North-East Atlantic (Whall et al., 2010). The inventory uses 2007 ship movements and characteristics data from LMIU and supplementary AIS data. The ship movements were spatially distributed and emissions were calculated using information on engine types, installed power, fuel type, engine load factors and CO_2 and air polluting emissions factors. Projections were developed using a growth rate for ship movements of 2–4 % per year. However, in a later phase, a 1 % growth rate was added to the projections to account for the changing (worsening) global economic situation at that time. The latest version of the UK inventory includes the revised MARPOL Annex VI regulations by 2008. Their 2020 emissions estimates show increases in NO_2, CO_2 and NMVOC, which are due to growth. The significant sulphur and PM emissions decreases are due to the sulphur content reductions.

Tzannatos (2010a): This paper presents the contribution of Greece to ship exhaust emissions of CO_2, NO_X, SO_2 and PM from domestic and international shipping over the last 25 years (1984-2008), utilising the fuel-based (fuel sales) emissions methodology. Furthermore, ship exhaust emissions generated on the Greek seas and their externalities are estimated for the year 2008 utilising the fuel-based (fuel sales) approach for domestic shipping and the activity-based (ship traffic) approach for international shipping. Greece was found to be a major and growing contributor of exhaust emissions from domestic and international shipping. From 1984 to 2008 the ship emissions inventory for Greece had an almost four-fold increase.

Tzannatos (2010b): An in-port, ship activity-based methodology was applied for manoeuvring and berthing of coastal passenger ships and cruise ships calling at the Greek passenger port of Piraeus in order to estimate the emissions of the main ship exhaust pollutants (NO_X, SO_2 and $PM_{2.5}$) over a 12-month period in 2008 and 2009. The estimated emissions were analysed in terms of gas species, seasonality, activity and shipping sector. The application of external cost factors led to the estimation of the emission externalities, in an attempt to evaluate the economic impact of the damage emissions produce mainly to the human population and the built environment. The results indicate that ship emissions in the passenger port of Piraeus reach 2 600 tonnes annually and their estimated externalities over this period are around EUR 51 million. Summer emissions and associated impacts are more profound and coastal passenger shipping, as opposed to cruise shipping, is the dominant contributor of emissions and associated externalities. Overall, in a port city such as Piraeus, the need to introduce stringent control on the emissions produced by passenger ships, beyond that dictated by the current 2005/33/EU Directive, is very urgent.

Emissions in the North Sea (ports, Netherlands continental shelf and the OSPAR region II) were estimated by the Maritime Research Institute Netherlands (MARIN) for 2008–2010. The inventory for 2008 is given by Saladas et al. (2010), for 2009 by Cotteleer and van der Tak (2011a), and for 2010 by Cotteleer and Hulskotte (2012). These inventories were based on monitoring data from the AIS, traffic data from the LMIU for 2008, and ship characteristics from the Lloyds List Group (LLG) database of October 2010. Emissions factors were determined by the TNO for the main and auxiliary engines.

In Cotteleer and van der Tak (2011b), the NO_X emissions in the North Sea by MARIN were compared with the inventory by ENTEC (Stavrakaki et al., 2005; Whall et al., 2002). The estimates are 472 and 622 Gg NO_X for the MARIN and ENTEC inventories, respectively. The difference is partly explained by the ENTEC assumption that ships sail at their designed service speed, which does not agree with AIS monitoring data for the period 2007–2010. In the pre-crisis year 2007, ships sailed at speeds of about 87 % of their service or design speed. The MARIN study used the real speeds from AIS data which ranged between 68 % and 89 % of the service speed. Especially due to the crisis and higher fuel prices, ships sail at lower speeds to save fuel. Other causes that explain the higher emissions by ENTEC are the use of an average speed for all size classes within a ship type category, and the relatively high assumed growth rate of shipping (fuel use) between 2000 and 2009/2010.

The emissions inventory for North Sea emissions in 2009 by Cotteleer and van der Tak (2011a) was updated with port emissions for all North Sea ports in the framework of the recent study 'Assessment of the environmental impacts and health benefits of a nitrogen emission control area in the North Sea' (Hammingh et al., 2012). The update with port emissions is reported in Cotteleer and van der Tak (2011b). NO_X emissions in ports (manoeuvring and at berth) constitute about 10 % of the total NO_X emissions (472 000 tonnes) in the North Sea in 2009. In Hammingh et al. (2012), the activities and emissions in the North Sea by Cotteleer and van der Tak (2011a, 2011b) were compared with an activity and emissions inventory (Jalkanen, 2012). That inventory was created for the recent study 'Economic impact assessment of a nitrogen emission control area at the North Sea' by the Danish Environmental Protection Agency (Danish EPA, 2012). The comparison between both inventories showed that the ship activities of MARIN and FMI compare reasonably well for 2009, but that the estimates for installed auxiliary engine power and associated fuel use and NO_X emissions differ substantially. NO_X emissions for the North Sea by FMI (652 Gg) were 38 % higher than the estimates by Cotteleer and van der Tak (2011b) (472 Gg). Hammingh et al. (2012) reports that 'since all experts at MARIN, TNO and FMI agree that these estimates are rather uncertain; we decided to include this uncertainty in a sensitivity analysis to the cost-benefit analysis'.

Fuel use and emissions from maritime transport in the Baltic Sea were estimated by Jalkanen et al. (2009, 2012). Jalkanen et al.(2012) developed a detailed emissions model (STEAM2) that uses AIS monitoring data and ship-specific information from IHS Fairplay (2010). A comparison between an AIS-based inventory and EMEP emissions for the Baltic Sea was made by Jalkanen et al. (2012). In 2009, the AIS-based emissions are 9.9 %, 1.9 %, 65.7 % and 70.5 % higher than the EMEP emissions for NO_X, SO_2, CO and $PM_{2.5}$, respectively. Especially for CO and $PM_{2.5}$, differences are attributed to a more detailed engine power calculation (i.e. speed dependency) and load-dependent emissions factors.

Table AI.1 Overview and details of the available studies on maritime emissions inventories in Europe and globally

Reference	Method (a)	Study areas (b)	Activity data (c)	Base year	Scenario years	Pollutants, fuel use (d)	Emissions factors (e)	Emission details included (f)
EU emissions inventories								
ENTEC (Whall et al., 2002)	B	EMEP area: NS, IS, ECh, BAL, BLA, ME, NEA	LMIU/LLI, fuel sales fishing vessels, movements between ports (shortest distance assumed), EU ports during 4 months	2000	2006, 2008, 2010	CO_2, SO_x, NO_x, VOC/HC, (PM_{10} only in ports)	ENTEC model	In port, per ship type. Emission categories EU-15, 15 Accession Countries, non-EU origin or departure, EU or non-EU flag, sulphur content max. 2.7 %, 50 x 50 km grid
ENTEC (Stavrakaki et al., 2005)	B	NS, IS, ECh, BAL, BLA, ME	See Whall et al. (2002)	2000	2010, 2015, 2020	See ENTEC, 2002	ENTEC model	See ENTEC, 2002
Tremove (De Ceuster et al., 2006)	B	EMEP area: NS, IS, ECh, BAL, BLA, ME, NEA	Based on Whall et al. (2002) and Stavrakaki et al. (2005)	2000	2010–2020	See ENTEC, 2002. PM_{10} emissions at sea and in ports	ENTEC model	See ENTEC, 2002
IIASA (Cofala et al., 2007)	B	NS (incl. ECh), BAL, BLA, ME, NEA	Activities and spatial distribution based on Whall et al. (2002) and Stavrakaki et al. (2005). Fuel use of smaller vessels in 12-mile zone estimated based on literature	2000	2010, 2015, 2020	CO_2, SO_x, NO_x, VOC, PM_{10}, $PM_{2.5}$, CO, fuel use	ENTEC model	Emissions distinguished by national or international, EU and non-EU–flagged ships, in/outside 12-mile zones, cargo and passenger vessels, MDO and RFO
EX-TREMIS (Chiffi et al., 2007; Schrooten et al., 2009)	C	EU-27, no spatial distribution	Eurostat (cargo volumes) ECMT-CEMT, UNECE, National statistics => ship movements, miles, hours	1980–2005	2016, 2020, 2030	CO_2, SO_x, NO_x, VOC, $PM_{2.5}$, CH_4, NMVOC	TNO model	Activities and emissions of non-EU international shipping in European seas not included. Emissions in 6 ship types and 3 size classes, port emissions included
AEAT (Bosch et al., 2009)	C	NS (incl. ECh), BAL, BLA, ME, NEA	Based on Cofala et al., 2007	2000	2010, 2015, 2020	SO_x, NO_x, NMVOC, PM_{10}, $PM_{2.5}$	ENTEC model, Extremis growth factors, TFEIP, PM_{10}/$PM_{2.5}$ emissions factors from Cooper & Gustafson, 2004	In SECA 1.45 % m sulphur (< current 1.5 % m sulphur). Outside SECA 2.7 % m sulphur
VITO (Campling et al., 2010)	C	EU-27	EX-TREMIS scaled up to the port callings reported in Eurostat and assigned to shipping routes	–	2016, 2020, 2030	NO_x, SO_2, NH_3, PM_{10}, NMVOC	TNO model	Emissions in 7 ship types and 5 size classes, port emissions
VITO (Campling et al., 2012)	C	EMEP grid/TNO-grid/EU-27	Updated database by VITO (Campling et al., 2010) emissions assigned to a new shipping routes map	–	2005, 2020, 2030, 2050	NO_x, SO_2, $PM_{2.5}$, BC	Oonk (2003) with refined PM emissions factors based on sulphur content of fuels. BC emissions factors, EF_BC=5mg/MJ, based on: Lack et al., 2012; Cappa et al., in prep; Jayaram et al., 2011; Petzold et al., 2008; Agrawal et al., 2010	Emissions of BC are also estimated, gridded emissions in 12-mile, 200-mile and OSPAR regions

Table AI.1 Overview and details of the available studies on maritime emissions inventories in Europe and globally (cont.)

Reference	Method (a)	Study areas (b)	Activity data (c)	Base year	Scenario years	Pollutants, fuel use (d)	Emissions factors (e)	Emission details included (f)
Regional inventories								
Ghent University and ECOLAS (De Meyer et al., 2008)	C	Belgian part of the North Sea	Radar data, specific LNG and ferry ships data, fuel use dredgers and tugboats. Additional estimates for auxiliary engine power	April 2003 – March 2004	–	CO_2, NO_X, SO_2	ENTEC model	Emissions per 16 ship types, in open sea and in ports
NERI (Winther, 2008)	C	Danish territorial sea	Activity data for regional and local ferries and national sea transport. Fuel-based data for fisheries and international sea transport	1990–2005	2020	CO_2, NO_X SO_2, fuel use	NO_X emissions factors were taken from manufacturers data (MAN diesel) and the Danish Ministry of transport . SO_2 emissions factors were taken from Danish Energy Agency data	
EC JRC (Marmer et al., 2009)	C	ME	Comparison of three emissions inventories where data are from EMEP, EDGAR, and Eyring et al., 2005	2000–2004	–	SO_2, NO_X, BC, OC, $PM_{2.5}$, NMVOC	Derived or implied emissions factors are given for the 7 emissions inventories and 6 pollutants.	Emissions are divided by western and eastern part of the Mediterranean Sea
ENTEC (Whall et al., 2010)	C	UK waters (North Sea, English Channel, Irish Sea and North-East Atlantic)	LMIU 2007, LLG, estimates for missing smaller vessels in LMIU, AIS	2007	2020	CO_2, NO_X, SO_2, VOC, PM_{10}, $PM_{2.5}$, fuel use	Updated ENTEC model	Back-casting done for 2007 to 1990 emissions. Interim forecasts made for 2008 and 2009. Emissions per fuel type, vessel type, flag type, movement type, inside 12-mile zone
FMI (Jalkanen et al., 2009, 2012)	B	BAL	AIS, IHS Fairplay	2006–2009	–	CO_2, NO_X, SO_2, CO, PM	STEAM2	Steam model capable of PM speciation into BC, OC, Ash, SO_4 and associated water
MARIN (Cotteleer and van der Tak, 2011a, 2011b)	B	Dutch part of the North Sea and the whole NS (incl. ECh)	LMIU, LLG, AIS, ferry data from Marnis 2008	2009	–	CO_2, NO_X, SO_2, VOC, CO, PM_{10}, $PM_{2.5}$	TNO model	Per ship type, per ship size, ports included. There are also MARIN reports with North Sea emissions for 2008 and 2010
PBL, RIVM, EMRC, NMI, DCMR (Hammingh et al., 2012)	B	NS (incl. ECh)	LMIU, LLG, AIS, ferry data from Marnis 2008. Additional estimates for auxiliary engine power	2009	2030	CO_2, NO_X, SO_2, VOC, CO, PM_{10}, $PM_{2.5}$	TNO model	5kmx5 km grid, per ship type, per ship size, ports included
Selected global inventories								
IMO GHG (Buhaug et al., 2009)	C	GBL	AIS (B), fuel statistics (T)	2007	2020, 2050	CO_2, NO_X, SO_2, VOC, PM_{10}, NMVOC, CH_4, N_2O	SFC for 3 age and 3 power classes, other pollutants: CO-NAIR/ IPCC fuel-based emissions factors	
CE Delft (Faber et al., 2009)	C	GBL, LMIU (c) regions, EU-27 and LMIU region Europe	LMIU, LLG, LMIU port ID's, other ship characteristics and engine data from literature. Distribution of emissions by adjusted SEAKLIM routine	2006	2030	CO_2, fuel use	Based on Buhaug et al. (2009), Corbett and Koehler (2003)	Emissions per 10 ship types, 4 size classes, arriving and departing ships in EU ports

Note:

(a) B = bottom up, T = top down, C = combination B and T.

(b) NS = North Sea, IS = Irish Sea, ECh = English Channel, BAL = Baltic Sea, BLA = Black Sea, ME = Mediterranean Sea, NEA = North-East Atlantic, GBL = global, PRT = ports, EMEP area

(c) LMIU/LLI = Lloyds Marine Intelligence Unit, now called Lloyds List Intelligence – ship activity data, LLG = Lloyds List Group – ship characteristics data, LRF = Lloyds Register Fairplay, now called IHS Fairplay, AIS = Automatic Identification System, ECMT-CEMT = Statistical trends in transport, LNG = liquefied natural gas.

(d) SO_2 = sulphur dioxide, NO_X = nitrogen oxide, VOC = volatile organic compound, HC = hydrocarbon, NMVOC = non-methane volatile organic compound, PM = particulate matter (PM_{10}/$PM_{2.5}$), CO = carbon monoxide, BC = black carbon, OC = organic carbon, CH_4 = methane, N_2O = nitrous oxide.

(e) IVL = Swedish Environmental Research Institute, TFEIP = Task Force on Emission Inventories and Projections under the UNECE CLRTAP, Institute EMS = Emission registration and Monitoring Shipping (TNO, 2003, 2010, in Dutch), SFC = specific fuel consumption.

(f) PRT = emissions in ports from manoeuvring and at berth, MNV = emissions from manoeuvring, emissions at berth, MDO = marine diesel oil, RFO = residual fuel oil, OSPAR = Oslo Paris Commission.

Table AI.2 Overview of the available studies on maritime emissions projections and scenarios in Europe and globally

Reference	Baseline and scenario years	Baseline details				Scenario details	Other
		Growth in seaborne transport or fuel use in baseline (ᵃ)	Efficiency improvements in baseline (ᵇ)	LNG and Shore Side electricity in base-line (ᶜ)	Fuel and emissions standards		
European projections and scenarios							
ENTEC (Whall et al., 2002)	2006, 2008, 2010	1.5 % and 3 %, no growth assumed for ferry and fishing vessels	–	–	IMO, IVL, Lloyds Register Engineering Services data	Low sulphur fuels scenarios: 1.5 % at open sea, 0.1 % in ports, also with impacts on $PM_{2.5}$ emissions	Impacts and costs of emissions control measures included. Impacts on air quality and deposition shown
ENTEC (Stavrakaki et al., 2005)	2010, 2015, 2020	All vessels 2.6 %/yr	–	–	IMO, IVL, Lloyds Register Engineering Services data	A business as usual (BAU) baseline has been generated, and impacts on this BAU by individual measures have been assessed	Impacts and costs of emissions control measures for SO_2, NO_x and for shore side electricity are included
Tremove (De Ceuster et al., 2006)	2010–2020	Growth in fuel use: CG=2.5 %/yr PS=3.9 %/yr	Constant fuel economy	–	IMO and EU sulphur limits in fuels and NO_x emissions standards	Several scenarios for SO_2 up to 0.5 % m sulphur in open sea with small PM reductions associated. In ports up to 0.1 % m sulphur. Scenarios for NO_x up to IMO Tier III standards. Three scenarios for shore side electricity	Specific growth rates for cargo and passenger ships
IIASA (Cofala et al., 2007)	2010, 2015, 2020	Growth in fuel use: CG=2.5 %/yr PS=3.9 %/yr (based on Tremove, De Ceuster, 2006)	Constant fuel economy	–	IMO and EU sulphur limits in fuels and NO_x emissions standards	Several scenarios for SO_2 up to 0.5 % m sulphur in open sea with small PM reductions associated. In ports up to 0.1 % m sulphur. Scenarios for NO_x up to IMO Tier III standards	Specific growth rates for cargo and passenger ships
EX-TREMIS (Chiffi et al., 2007; Schrooten et al., 2009)	2016, 2020, 2030	Up to 2020: 2–3 % for most countries and markets, 4 % for specific markets in selected countries. These above rates were reduced by 1 % between 2020 and 2030	Constant fuel economy, no assumptions on ship size increases	–	IMO and EU sulphur limits in fuels and NO_x emissions standards, legislation up to 2007	Only a baseline has been generated	
AEAT (Bosch et al., 2009)	2015, 2020	Growth in fuel use: RFO = 2.7 %/yr MDO= – 0.5 %/yr	–	–	IMO and EU sulphur limits in fuels and NO_x emissions standards. Sulphur content outside SECA=2.7–2.9 %	SECAs in all EU seas or a selected set of EU seas. All SECA scenarios assume a NECA in the Baltic Sea, the North Sea and the Mediterranean Sea	Assumptions made on non-EU international shipping in European seas. Impacts and costs of emissions control measures included. Impacts on air quality and deposition shown
VITO (Campling et al., 2010)	2016, 2020, 2030	See Chiffi et al., 2007 (Extremis)	Constant fuel economy, no assumptions on ship size increases	–	IMO and EU sulphur limits in fuels and NO_x emissions standards	Business as usual (BAU) baseline and nine scenarios with increasing costs for NO_x and SO_2 abatement. has been generated, and cost curves by individual measures have been assessed	Impacts and costs of emissions control measures included. Impacts on air quality and deposition shown
VITO (Campling et al., 2012)	2005, 2020, 2030, 2050	2 %/yr in fuel use between 2005 and 2050	Renewal of the current fleet improves fuel economy especially between 2005 and 2030	–	IMO and EU sulphur limits in fuels and NO_x emissions standards	Business as usual (BAU) baseline and nine scenarios simulating additional SECAs and NECAs, slow steaming impacts, PM filters, and a maximum technical feasible reduction.	Impacts on costs of emissions control measures included

Table AI.2 Overview of the available studies on maritime emissions projections and scenarios in Europe and globally (cont.)

Reference	Baseline and scenario years	Baseline details				Scenario details	Other
		Growth in seaborne transport or fuel use in baseline (a)	Efficiency improvements in baseline (b)	LNG and Shore Side electricity in base-line (c)	Fuel and emissions standards		
Regional projections and scenarios							
NERI (Winther, 2008)	2020 (Danish waters)	Fuel consumption assumed to be constant	–	–	IMO and EU sulphur limits in fuels and NO_x emissions standards, legislation up to 2007	Only a baseline has been generated	
PBL, RIVM, EMRC, NMI, DCMR (Hammingh et al., 2012)	2030 (North Sea and also estimates for other EU seas)	2.1 %/yr in transported cargo (in TM)	1 %/yr by EoS, SPD and SDO	25 % coast-wise, 10 % tankers, 5 % SSE at berth	IMO and EU sulphur limits in fuels and NO_x emissions standards	Includes a baseline for 2030 for all air pollutants from shipping and two scenarios for a NO_x NECA on the North Sea	Specific growth rates for containers and 'other shipping'. Projections for other EU seas based on Cofala et al., 2007 but including the revised Marpol Annex VI and adjusted with a lower growth rate as used for future fuel consumption in the North Sea
ENTEC (Whall et al., 2010)	2020 (waters surround-ing the United Kingdom)	1–4 %	–	–	IMO and EU sulphur limits in fuels and NO_x emissions standards	Four scenarios are created using a 1, 2, 3 and 4 % growth in fuel consumption	
Selected global projections and scenarios							
IMO GHG (Buhaug et al., 2009)	2007–2050	A1B=3.3 %/yr in TM A2=2.1 %/yr in TM	0.9 %/yr by EoS, SPD and SDO	25 % LNG coast-wise, 10 % tankers, 50 % LNG coast-wise, 20 % tankers	IMO sulphur limits in fuels and NO_x emissions standards	Six main scenarios were derived from the IPCC special report on emission scenarios (SRES) scenarios	Specific growth rates and emissions for container, coast-wise and ocean-going shipping

Note:
(a) CG=cargo, PS=passenger, TM=tonne mile, tkm=tonne-kilometre, RFO=residual fuel oil, MDO=marine diesel oil.
(b) EoS=efficiency of scale, SPD=speed, SDO=ship design and operation.
(c) LNG=liquefied natural gas, SSE=shore side electricity, n.a.= no assumptions made.

Annex II Review of existing studies on the impacts of shipping emissions on air quality in coastal areas

Review of existing studies on the impacts of shipping emissions on air quality in coastal areas

An in-depth literature review was carried out and the summary of the main findings from each of the works reviewed may be found below and in the summary tables AII.1 (Europe) and AII.2 (non-European areas).

Querol et al. (1996): The impact of harbour loading and unloading operations was assessed in a Mediterranean harbour (Spain). Vanadium (V), thorium (Th) and nickel (Ni) levels in ambient particulates were found to be enhanced during harbour operations, and were thus considered tracers of shipping emissions.

Isakson et al. (2001): The effect of ship emissions in the urban environment of Göteborg, Sweden has been studied by multivariate analysis. The simultaneous measurements of relevant gases and sub-micron particles make identification of ship plumes possible. Increased concentrations of these species due to ship emissions are quantified for ships entering the inner part of the harbour. Exposure of transient particles (less than 0.1 μm in diameter) to this part of the harbour increased by a factor of 3 in number concentration when a ship plume was recorded. Ni, Pb, V and Zn are shown to have positive correlation with NO emissions from ships. Mean concentrations of NO_2 and SO_2 in a ship plume were 12 and 4.5 μg/m^3 above urban background levels, respectively (background levels of 11.3 and 1.6 μg/m^3, respectively) when measured at an average distance of 800 m from the ships during summer. In the winter period the excess concentrations were very similar to the summer levels. Measurements of sub-micrometre particles reveal a bi-modal number size distribution for ship plumes, which are strongly enhanced as compared to background air.

Viana et al. (2003): No significant difference in PM levels or chemical composition was found between the harbour and city background. However, evidence of the impact from handling operations (loading/unloading) in the form of re-suspension of mineral dust (road dust) was detected.

Marmer & Langmann (2005): Objective: Investigation of contribution of SO_X ship emissions to the sulphate aerosol concentration near the surface and at higher atmospheric levels. For this investigation, the fates of land and ship emissions were followed separately. In order to calculate the maximum possible reduction of secondary pollutants in the Mediterranean summer atmosphere, we have switched off all ship emissions. Locally released NO_X is mainly responsible for the production of O_3. Switching off the release of NO_X by ships reduces surface O_3 concentration by 15 % from 48.6 to 41.5 ppbv in this area. The formation of nitric acid (HNO_3) and formaldehyde (HCHO) in the experiment is reduced by 66 % and 24 %, respectively. OH concentration is simultaneously reduced by 42 % from 0.19 to 0.11 pptv, contributing to decreased formation of sulphuric acid (H_2SO_4) and sulphate aerosol. The resulting mean sulphate aerosol concentration over the Mediterranean Sea is reduced by 46 % to 0.56 mgS/m^3 in the lowest model level. The reduction of SO_X emissions does not result in a linear reduction of sulphate aerosol load, because of non-linear chemical reactions. Ship emissions are released only in the lowest model height level and their contribution to sulphate concentration dominates in the lowest 300 m of the model height layers. Ship emissions of NO_X contribute to the formation of secondary trace gases, hence considerably decreasing Mediterranean air quality in summer. Most significant is the formation of HNO_3, which is reduced by 66 % without ship emissions. Organic aerosols, soot and dust have not been considered in this study. Secondary organic aerosol production is strongly linked with all of the trace gases investigated here.

Dore et al. (2007): A statistical Lagrangian atmospheric transport model (FRAME) was used to generate annual maps of deposition of sulphur and oxidised and reduced nitrogen for the United Kingdom at a 5 x 5 km^2 resolution. The model was run using emissions for the year 2002. A future emissions scenario for the year 2020 was used to test the influence of shipping emissions on sulphur deposition in the United Kingdom. The results show that if shipping emissions are assumed to increase at a rate of 2.5 % per year, their relative contribution to sulphur deposition is expected to increase from 9 % to 28 % between 2002 and 2020. The model was compared to both a European scale and a global scale chemical transport model and found to give broad agreement with the magnitude and location of sulphur deposition associated with shipping emissions. Enforcement of the MARPOL convention to reduce the sulphur content in marine fuel to 1 % was estimated to result in a 6 % reduction in total sulphur deposition to the United Kingdom for the year 2020. The percentage area of sensitive habitats with exceedance of critical loads for acidity in the United Kingdom was predicted to decrease by 1 % with implementation of the MARPOL convention. The significance of shipping emissions in contributing to sulphur deposition over land lends strong support to the need for international legislation to constrain emissions from shipping, such as the MARPOL convention on MARine POLlution. Recent legislation involves the introduction of a 1 % sulphur limit on marine fuels used by all sea-going vessels in the North Sea and the English Channel from the year 2010, leading to a 33 % reduction in emissions of SO_2. These results suggest that targeting shipping emissions may be an effective way of protecting the environment from acid deposition.

Mazzei et al. (2008): We present results obtained for the urban area of Genoa (Italy) based on several hundred of PM_{10}, $PM_{2.5}$ and PM_1 daily samples collected in sites with different geo-morphological and urbanisation characteristics. The V to Ni concentration ratio calculated by positive matrix factorisation (PMF) is similar at three of the four sites and it is also fairly constant for the three size fractions. We conclude that heavy oil combustion is identified by the concentration ratio V/Ni = 3.2 ± 0.8 in all PM fractions. A particularly high contribution of heavy oil combustion to PM_1 (about 5 $\mu g/m^3$, over 25 $\mu g/m^3$, 20 %) was found in the summer data set of the Corso Firenze measurement station. This could be related to the notable increase of the traffic of passenger ships in the harbour during the holiday period. Significant stationary sources (e.g. power plants) that burn residual oil are not present in the urban area of Genoa, so it can be supposed that the harbour activity is the dominant source of heavy oil combustion.

Viana et al. (2008): Source apportionment (SA) studies across the EU identified $V/Ni/SO_4^{2-}$ and $SO_4^{2-}/NO_3^-/NH_4^+$ sources: The rationalisation and interpretation of SO_4^{2-}-related sources revealed the largest complexity, and therefore they have been grouped in a single category but separated as two individual sources. The first combination (SO_4^{2-}, V and Ni) was more frequent than the second ($SO_4^{2-}/NO_3^-/NH_4^+$). The $V/Ni/SO_4^{2-}$ source was occasionally found in combination with trace elements such as Pb or Cu (interpreted as regional-scale pollution), NH_4^+ and Na, OC and K, or Zn and Pb (long-range transport or anthropogenic pollution). Most authors interpreted $V/Ni/SO_4^{2-}$ as fuel-oil/petcoke combustion or industrial emissions based on the characteristic V/Ni signature of crude oil and its derivates (e.g. shipping emissions), but this interpretation was seen to be quite subjective given that the same authors during different studies labelled this combination as industrial or regional background even though the tracers were the same, based on their knowledge of the monitoring sites. Gap analysis: Apportionment of specific anthropogenic emissions sources: certain anthropogenic combustion emissions sources (e.g. shipping emissions) were not determined by any of the SA studies described above. This is most likely due to the absence of marker species in the input data sets and/or the inability of the models to separate sources with common tracers. Differentiation between SO_4^{2-}-containing sources: with the aim of differentiating sources such as secondary regional-scale aerosols vs. local- or meso-scale anthropogenic emissions such as industry or shipping. The contribution of the $V/Ni/SO_4^{2-}$ source was quantified as 10–30 % of PM_{10} and $PM_{2.5}$, including of course sources other than shipping (but also shipping).

Andersson et al. (2009): Seven-year average concentrations from different European regions and including international shipping as an emissions source were analysed using an Eulerian three-dimensional (3D) chemistry transport model (CTM), MATCH, based on EMEP emissions data. High concentrations of sulphate were evidenced over the whole Mediterranean area and south-eastern Europe (maximum of 6.5 $\mu g/m^3$ as an annual mean, calculated for the eastern Mediterranean Sea) due to high emissions from south-eastern Europe and Italy combined with volcanic emissions (Etna). The population-weighted exposure to airborne pollutants derived from shipping emissions was lower compared to the average concentration contributions, since the emissions occur in less populated areas. The relative contribution to population-weighted exposure (PWC) of sea traffic emissions was larger for secondary inorganic aerosols (80 % of total PWC) than for primary $PM_{2.5}$. However, differences were found between countries; for example, for Iceland and the Netherlands the primary shipping contribution to population exposure was more important. On average across Europe, shipping emissions contribute with 8 % of population exposure to primary $PM_{2.5}$, 16.5 % of population exposure to NO_X, and 11 % of population exposure to SO_X. The contribution from shipping emissions to population exposure to CO, NMVOC and NH_3 is lower than 1 %.

OSPAR (2009): The OSPAR Convention is the current legal instrument guiding international cooperation on the protection of the marine environment of the North-East Atlantic. Work under the Convention is managed by the OSPAR Commission, made up of representatives of the governments of 15 contracting parties and the European Commission, representing the EU. In their 2009 report, assessments are presented on the 'Trends in atmospheric concentrations and deposition of nitrogen and selected hazardous substances to the OSPAR maritime area'. Model calculations largely suggest that atmospheric deposition of selected heavy metals and organic contaminants (lindane and polychlorinated biphenyls) and of nitrogen substantially declined in the period 1990–2006 in the OSPAR maritime area. For the heavy metals cadmium, lead and mercury, most of the reductions in measured concentrations in precipitation and air and in modelled deposition were achieved in the 1990s. However, the rate of reduction has slowed since 1998. Model calculations suggest that atmospheric deposition of nitrogen has decreased in the Greater North Sea over the period 1995–2006, but stagnated or increased in the other OSPAR regions. This is broadly supported by measurements of nitrogen in precipitation and air.

Viana et al. (2009): The contribution of shipping emissions to ambient PM urban background levels was quantified by PMF in Melilla, located in the vicinity of the Gibraltar Strait. Results evidenced that shipping emissions contributed with 2 % and 4 % of mean annual PM_{10} levels (0.8 μg/m^3 primary particles and 1.7 μg/m^3 secondary particles, with 20 % uncertainty) and 14 % of mean annual $PM_{2.5}$ levels (2.6 μg/m^3). Tracers: V/Ni = 4.

Eyring et al. (2010): This work presents an exhaustive review of the impacts of shipping emissions on air quality and climate. Locally, results show that there is a considerable local impact of shipping-related emissions on air quality in the vicinity of major harbours, in particular, from NO_X, SO_2, PM, and VOC emissions. Ship manoeuvring in harbours contributes about 6 % of NO_X and 10 % of SO_2 to total shipping emissions (Corbett and Fischbeck, 1997). Besides manoeuvring, loading and unloading of tankers also contribute substantially to harbour emissions since this is a highly energy-consuming process (Wismann and Oxbol, 2005). As an example, near the waterways of the port of Rotterdam shipping causes an enhancement of the surface NO_2 mixing ratio of 5–7 ppb (Keuken et al., 2005).

Hellebust et al. (2010): PM ($PM_{10–2.5}$ and $PM_{2.5–0.1}$) has been collected over a period of one year in Cork Harbour, Ireland using a high-volume cascade impactor (HVCI) and polyurethane foam collection substrate. Fresh ship plumes were not found to make a significant contribution to primary $PM_{2.5–0.1}$ concentrations adjacent to the shipping channel. However, this was partially attributed to the ultrafine nature of ship emissions. The majority of the toxic metal content was attributed to emissions associated with heavy oil combustion sources, which include ship engines. By means of Principal Component Analysis (PCA), four principal components were extracted (explaining 85 % of the variance). The shipping component was characterised by the following marker species: Pb, Ni and V. Thus, it was characterised by the trace metals (water-soluble fraction only). The shipping/industry factor contribution is too small to give a sensible estimate in the present model, but clearly contributes less than 5 % of ambient $PM_{2.5–0.1}$ mass, indeed more likely less than 1 %. The anthropogenic input of heavy metals is clearly present, but that source accounts for a minor fraction of the ambient $PM_{2.5–0.1}$ mass. The dominance of V and Ni indicates that it originates from heavy oil combustion, such as ship bunker fuel. This component represents an anthropogenic industrial/heavy fuel combustion source and is a combination of heavy fuel combustion emissions.

Even though the contribution from this source was small in terms of mass, it is important to stress that this component may have a significant contribution to both particle numbers (not measured) and toxicity. This is because primary particles emitted by ships are predominantly in the sub-micron size fraction (Healy et al., 2009; Isakson et al., 2001; Cooper, 2003; Lu et al., 2006; Petzold et al., 2008). Another reason shipping emissions were poorly resolved was the long collection period (3 days and 4 days), which precludes identification of fresh ship plumes, which would be dispersed within minutes. Therefore, the low contribution of this component to total $PM_{2.5–0.1}$ mass does not indicate that the local air quality is not influenced by frequent ship emissions. Their contribution should not be measured in terms of mass, but in terms of toxicity. Particles in this size range are most likely to penetrate deep into the respiratory system while also containing the highest concentrations of toxic trace metals. It must also be noted that emissions from industry, ships and vehicles will contribute to formation of secondary aerosols. The reason they are not recognised as such by the SA model is that the species making up the secondary aerosol component, being formed in the atmosphere from primary emissions, will be transformed between source and receptor in a way that distorts their association with the primary species measured from the same source. Vanadium is used as a marker for ship emissions, and the main anthropogenic source V and Ni is likely related to shipping activities or heavy oil combustion. The sources of trace metals in ambient aerosols are separate from the main sources of aerosols and not directly associated with high PM concentrations.

Pandolfi et al. (2011): Shipping emissions were characterised in the Gibraltar Strair (Bay of Algeciras, Spain) by La/Ce ratios between 0.6 and 0.8 and V/Ni ratios around 3 for both PM_{10} and $PM_{2.5}$. In contrast, elevated La/Ce values (1–5) are attributable to emissions from refinery zeolitic fluid catalytic converter plant, and low average V/Ni values (around 1) result mainly from contamination from stainless steel plant emissions. The direct contribution from shipping in the Bay of Algeciras was estimated at 1.4–2.6 $\mu gPM_{10}/m^3$ (3–7 %) and 1.2–2.3 $\mu gPM_{2.5}/m^3$ (5–10 %). The total contribution from shipping (primary emissions + secondary sulphate aerosol formation) reached 4.7 $\mu gPM_{10}/m^3$ (13 %) and 4.1 $\mu gPM_{2.5}/m^3$ (17 %).

Reche et al. (2011): Concentrations of SO_2 reached a peak at times different from those of the other gaseous pollutants (described above). SO_2 levels attain a maximum around 12:00 h UTC, coinciding with maximum sea breeze intensity. These breezes drive harbour emissions across the city, and thus SO_2 may be attributed to shipping emissions. No other major sources of SO_2 are present in the city. Hourly SO_2 maxima coincided with the noon peak of nitrogen, suggesting that SO_2 from shipping could be a major contributor to nucleation episodes at midday. The correlation between hourly levels of potential precursor gases (NO_2, NO, SO_2) and the particle number concentration was tested to assess the potential contribution of these gases to the nucleation process. However, no significant correlations were found in any of the cases in Barcelona (Spain).

Velders et al. (2011): An SO_2 decrease was also observed in the Netherlands, as well as in Mediterranean harbours (see Schembari et al., 2012, below). In the Rotterdam port area concentration levels were more or less constant between 2000 and 2006, and decreased rapidly between 2007 and 2010. The 2010 levels were about 50 % below the 2000–2006 average. The concentrations in the rest of the Netherlands decreased gradually from 2000 to 2010, with the 2010 levels also about 50 % below the 2000–2006 average. The behaviour of both the monitored and modelled SO_2 concentrations is in line with the changes in emissions over time from the sectors that contribute most to the total concentration of SO_2. Concentrations in the Rotterdam port area were dominated by emissions from refineries, sea shipping on the North Sea, nearby inland shipping and within port, and by emissions originating from other countries. The SO_2 emissions from sea shipping decreased after 2006 as a result of the use of fuel with a lower sulphur content. The SO_2 emissions from refineries decreased prior to 2010 because of a regulated switch from HFO to natural gas use. An additional decrease in 2010, compared to 2009 levels, originated from the EU directive to use fuel with a sulphur content of maximally 0.1 % for sea ships at berth in ports. A drop in concentration levels between 2009 and 2010 was also visible in the observations.

The trends in monitored and modelled SO_2 concentrations based on Velders et al. (2011) have been extended by ETC/ACMwith data for the year 2011 (nd supplemented with data on cargo transferred in the port of Rotterdam. This clearly shows how the economic crises hit the marine transport sector in 2009 in the port of Rotterdam, but also reveals the recovery afterwards. The comparison of trends in SO_2 concentrations and transferred cargo also indicates the decoupling of both trends.

Becagli et al. (2012): Measurements of aerosol chemical composition made on the island of Lampedusa, south of the Sicily channel, during years 2004–2008, are used to identify the influence of ship emissions on aerosol particles in the central Mediterranean. A very intense event in spring 2008 was studied in detail, also using size-segregated chemical measurements. Evidence of influence of ship emissions is found in 17 % of the daily samples. Ship emissions account, as a summer average, at least for 30 % of the total non sea salt (nss) SO_4^{2-} (1.2 $\mu g/m^3$, with a maximum of 47 %), 3.9 % of PM_{10} (with a maximum of 15 %), 8 % of $PM_{2.5}$, and 11 % of PM_1. Aerosol samples influenced by ships are characterised by elevated Ni and V soluble fraction (about 80 % for aerosol from ships, versus about 40 % for crustal particles), high V and Ni to Si ratios, and values of Vsol > 6 ng/m^3. Elements arising from heavy oil combustion (V, Ni, Al, Fe) are distributed in the sub-micrometric fraction of the aerosol, and the metals are present as free metals, carbonates, oxides hydrates or labile complex with organic ligands. Data suggest a characteristic nss SO_4^{2-}/V ratio in the range 200–400 for ship emissions aerosols in summer at Lampedusa. The Ni/Si ratio is one order of magnitude higher than expected for crustal particles in 79 % of the measured samples. Mazzei et al. (2008) report a characteristic value of V/Ni = 3.2 for ships, obtained by applying statistical approaches (PMF) to an extensive chemical data set of aerosol sampled near a harbour. Viana et al. (2009) obtained a characteristic ratio V/Ni = 4 for shipping emissions using also PMF in the Gibraltar Strait (Melilla). A wide V/Ni ratio (2.3–4.5) was measured by direct sampling of the exhausts of different auxiliary ship engines fed by different fuels (Nigam et al., 2006), and from the main propulsor ship engine at different speed modes (Agrawal et al., 2008). As expected, V and Ni in the ship aerosol event display a maximum in the finest mode (diameter < 0.4 μm). Conversely, their concentrations peak at larger size (1.1–2.1 μm for Ni, and 0.4–0.7 μm for V) during the Saharan dust event.

Hammingh et al. (2012): NO_X emissions from North Sea shipping are responsible for 7–24 % of country-average NO_2 concentrations in North Sea coastal countries in 2030. Contributions to nitrogen deposition range from 2–5 %. NO_X emissions from ships are also responsible for 1–5 % of the PM concentrations ($PM_{2.5}$) in the North Sea countries. A NECA in the North Sea would reduce all these North Sea shipping contributions by about one third. Compared with the contribution made by North Sea shipping to NO_2 concentrations, the contribution to nitrogen deposition and PM concentrations is relatively lower due to the relatively higher contributions from various land-based sources.

Sea shipping contributions to $PM_{2.5}$ concentrations depend on the proximity of a country to the North Sea and the busy shipping lanes, and can be as high as 7 % in certain coastal areas. The contribution to country averages is the highest in the Netherlands and the United Kingdom with 5 % and 4 %, respectively, and the lowest in Sweden and Norway with about 1 %. The contribution in Luxembourg and Switzerland is about 2 % and 1 %, respectively.

The contribution from North Sea shipping to NO_2 concentrations can be higher than 25 % in certain coastal areas. The contribution to country averages is the highest in the Netherlands and Denmark with 24 % and 19 %, respectively, and the lowest in Germany and France with 7 % and 8 %, respectively. The contribution to the country average concentrations in Ireland is around 7 %, but absolute concentrations are relatively low.

Keuken et al. (2012): The composition of combustion aerosol from road traffic, a harbour and an airstrip has been investigated by measurements of $PM_{2.5}$, elemental carbon (EC), OC and size-resolved particle number concentrations (PNCs). Combustion emissions from a harbour have not been distinguished from background concentrations probably due to the height of these emissions and their large temporal variability.

Schembari et al. (2012): In the framework of the APICE project. Ships have been found to be major sources of air pollution in harbours. However, from 1 January 1 2010 an EU directive requires that all ships at berth or anchorage in European harbours use fuels with a sulphur content of less than 0.1 % by weight while previously, outside of SECAs, up to 4.5 % was allowed. The impact of this directive on air quality in some Mediterranean harbours was investigated. The concentrations of SO_2 were found to decrease significantly (at the 5 % significance level) from 2009 to 2010 in 3 out of the 4 EU harbours; the average decrease of the daily mean concentrations in the different harbours was 66 %. No decrease was observed in the non-EU harbour of Tunis. Neither NO_X nor BC concentrations showed significant changes in any of the harbours. Benefits of using low-sulphur fuels are evident concerning ambient SO_2 concentrations, but also an effect on PM contributions may be found in future SA studies.

Non-EU studies

Kim & Hopke (2008): Although the impacts of residual oil combustion were relatively small compared to other sources (4–6 % of $PM_{2.5}$), a clear influence of ship emissions was found in the downtown Seattle (USA) area, where multiple site results point clearly to the Port of Seattle as a likely source area. Also, the edge between the secondary sulphate particles and the oil combustion particles indicated the contribution of ship emissions to the secondary sulphate formation at multiple sites.

Minguillón et al. (2008): Ship emissions' contribution was lower than 5 % of total OC at all sites. In terms of total fine PM, vehicular sources together with road dust explain up to 54 % of the mass, whereas ship contribution is lower than 5 % of total fine PM mass. Our results clearly indicate that, although ship emissions can be significant, PM emissions in the area of the largest US harbour are dominated by vehicular sources.

Table AII.1 Summary table of contributions from shipping emissions to air quality in European coastal areas

Study	Study area	Methodology	Conclusions	Tracers
Querol et al. (1996)	Castellón harbour, Spain	Sampling at harbour site; chemical analyses	- Vanadium (V), thorium (Th) and nickel (Ni) levels in ambient particulates were found to be enhanced during harbour operations	V, Ni, Th
Isakson et al. (2001)	Göteborg harbour, Sweden	Sampling at harbour site; chemical analyses; multivariate analysis	- Mean concentrations of NO_2 and SO_2 in a ship plume were 12 and 4.5 µg/m^3 above urban background levels, respectively, when measured at an average distance of 800 m from the ships (background levels of 11.3 and 1.6 µg/m^3, respectively) - Significant impact on sub-micron particles: measurements of sub-micrometre particles reveal a bi-modal number size distribution for ship plumes, which are strongly enhanced as compared to background air - V levels in the harbour of Göteborg ≈ three times larger than regional levels	V, Ni, Pb and Zn
Viana (2003)	Tarragona, Spain	One year sampling at harbour & city in parallel; chemical analyses	- No evidence of direct impact of (ship) stack emissions on air quality in the city - Evidence of impact from handling operations (loading/unloading) in the form of re-suspension of mineral dust (road dust)	V, Ni
Keuken et al. (2005)	Rotterdam, the Netherlands		- Enhancement of the surface NO_2 mixing ratio of 5–7 ppb in the Rotterdam harbour area, when compared to the urban background	
Marmer & Langmann (2005)	Mediterranean Sea	Regional three-dimensional online atmosphere-chemistry model Remote	- Switching off the release of NO_x by ships reduces surface O_3 concentration by 15 % in this area - The formation of HNO_3 and HCHO is reduced by 66 % and 24 %, respectively. OH concentration is simultaneously reduced by 42 % contributing to decreased formation of H_2SO_4 and sulphate aerosol - The resulting mean sulphate aerosol concentration over the Mediterranean Sea is reduced by 46 %	SO_2
Dore et al. (2007)	United Kingdom, N and S wet and dry deposition	Statistical Lagrangian atmospheric transport model (FRAME)	- If shipping emissions increase at 2.5 % per year, their relative contribution to sulphur deposition is expected to increase from 9 % to 28 % between 2002 and 2020 - Enforcement of the MARPOL convention (reduction of S in marine fuel to 1 %) would result in 6 % reduction in total S deposition to the United Kingdom in 2020 - The percentage area of sensitive habitats with exceedance of critical loads for acidity in the United Kingdom was predicted to decrease by 1 % with the MARPOL convention	SO_2
Mazzei et al. (2008)	Genoa, Italy	Sampling of PM_{10}, $PM_{2.5}$ and PM_1 in several urban sites; chemical characterisation, PMF	- The V to Ni concentration ratio calculated by PMF is similar at three of the four sites and it is also fairly constant for the three size fractions - Heavy oil combustion is identified by the concentration ratio V:Ni=3.2±0.8 in all PM fractions - A particularly high contribution of heavy oil combustion to PM_1 (about 5 µg/m^3, over 25 µg/m^3, 20 %) was found in one station	V/Ni = 3.2
Viana et al. (2008)	European cities	Receptor modelling at urban, coastal and background stations across Europe	- The contribution of the V/Ni/SO_4^{2-} source was quantified as 10–30 % of PM_{10} and $PM_{2.5}$, including shipping but also other sources	V, Ni, SO_4^{2-}
Andersson et al. (2009)	Europe	Eulerian 3D chemistry transport model (CTM) MATCH	- Population-weighted exposure (PWC) to shipping emissions was lower compared to exposure from other sources - On average across Europe, shipping emissions contribute with 8 % to population exposure to primary $PM_{2.5}$, 16.5 % to population exposure to NO_x, and 11 % to population exposure to SO_x - The relative contribution to PWC of shipping was larger for secondary inorganic aerosols (80 % of total PWC) than for primary $PM_{2.5}$ - Differences were found between countries — for example, for Iceland and the Netherlands the primary shipping contribution to PWC was more important	
Viana (2009)	Melilla, Spain Gibraltar Strait	One year PM_{10} and $PM_{2.5}$ sampling at city background site; chemical analyses; PMF	- Shipping emissions contributed with 2–4 % of mean annual PM_{10} and 14 % of $PM_{2.5}$ - PM_{10} particles derived from shipping emissions were 30 % primary and 70 % secondary particles	V/Ni = 4

Table AII.1 Summary table of contributions from shipping emissions to air quality in European coastal areas (cont.)

Study	Study area	Methodology	Conclusions	Tracers
Eyring et al. (2010)	Mediterranean basin	Literature review		
Hellebust et al. (2010)	Cork harbour, Ireland	One year sampling using a high-volume cascade impactor (HVCI) and polyurethane foam; chemical analyses; principal component analysis (PCA)	- Fresh ship plumes were not found to make a significant contribution to primary PM$_{2.5–0.1}$ concentrations adjacent to the shipping channel - Shipping represented < 1 % of the sample mass (PM$_{2.5–10}$ and PM$_{0.1–2.5}$) - Even though the contribution from this source was small in terms of mass, it is important to stress that this component may have a significant contribution to both particle numbers and toxicity	V, Ni
Pandolfi et al. (2011)	Algeciras, Spain Gibraltar Strait	One year PM$_{10}$ and PM$_{2.5}$ sampling at 4 locations; chemical analyses; PMF	- Shipping emissions were characterised by La/Ce=0.6–0.8 and V/Ni = 3 - The direct contribution from shipping in the Bay of Algeciras was estimated as 1.4–2.6 µg/m^3 to PM$_{10}$ (3–7 %) and 1.2–2.3 µg/m^3 to PM$_{2.5}$ (5–10 %) - The total contribution from shipping (primary + secondary emissions) reached 4.7 µg/m^3 in PM$_{10}$ (13 %) and 4.1 µg/m^3 in PM$_{2.5}$ (17 %)	V, Ni, La, Ce
Reche et al. (2011)	Barcelona, Spain	One year monitoring at an urban background station; chemical analyses	- Hourly SO$_2$ maxima coincided with the noon peak of N, suggesting that SO$_2$ from shipping could be a major contributor to nucleation episodes at midday (new particle formation)	SO$_2$, N
Velders et al. (2011)	Rotterdam harbour, the Netherlands	SO$_2$ measurements for the whole country, and the Rotterdam port area	- The 2010 SO$_2$ levels were about 50 % below the 2000–2006 average, due to the sulphur content limitation of fuels from 2010	SO$_2$
Becagli et al. (2012)	Lampedusa, Italy	Sampling at background station; chemical analyses; back-trajectory analysis	- Influence from ships detected on 17 % of the days/year - On average for the summer period, shipping emissions contributed with 30 % of the total non-sea-salt-SO$_4^{2-}$, 3.9 % of PM$_{10}$, 8 % of PM$_{2.5}$, and 11 % of PM$_1$ in Lampedusa. Maximum values of 47 % nss SO$_4^{2-}$ and 15 % to PM$_{10}$ were obtained	nss SO$_4^{2-}$/V ratio = 200–400; V/Ni = 2.3–4.5
Hammingh et al. (2012)	North Sea	Integrated assessment method (CIAM); starting point was existing emissions inventory for shipping activities, complemented with data for port emissions	- NO$_X$ emissions from North Sea shipping are responsible for 7–24 % of country-average NO$_2$ concentrations in North Sea coastal countries in 2030 - NO$_X$ emissions from ships are also responsible for 1–5 % of PM$_{2.5}$ in the North Sea countries - Sea shipping contributions to PM$_{2.5}$ concentrations can be as high as 7 % in certain coastal areas - PM$_{2.5}$: mean annual contribution from North Sea shipping is highest in the Netherlands and the United Kingdom with 5 % and 4 %, respectively, and lowest in Sweden and Norway with about 1 %. The contribution in Luxembourg and Switzerland is about 2 % and 1 %, respectively - NO$_2$: mean annual contribution from North Sea shipping can be > 25 % in certain coastal areas. The contribution to country averages is highest in the Netherlands and Denmark with 24 % and 19 %, respectively, and the lowest in Germany and France with 7 % and 8 %, respectively. The contribution to the country average concentrations in Ireland is around 7 %, but absolute concentrations are relatively low	
Keuken et al. (2012)	the Netherlands	PM$_{2.5}$, N, BC sampling at 6 sites in the Netherlands; chemical analyses	- Combustion emissions by a harbour were not distinguished from background concentrations probably as a result of the height of shipping emissions and their relatively large temporal variability	
Schembari et al. (2012)	Mediterranean harbours	SO$_2$ monitoring at four Mediterranean harbours	- An average decrease of the daily mean SO$_2$ concentrations in the different harbours was measured at 66 %, due to the sulphur content limitation of fuels from 2010	

Table AII.2 Summary table of contributions from shipping emissions to air quality in non-European coastal areas

Study	Study area	Methodology	Conclusions	Tracers
Kim and Hopke (2008)	Seattle harbour, United States of America	Integrated 24 h $PM_{2.5}$ speciation data (2000–2005) at 5 US EPA STN monitoring sites in Seattle; receptor modelling by PMF	- Impacts of residual oil combustion were relatively small compared to other sources (4–6 % of $PM_{2.5}$) - Clear influence of ship emissions was found in downtown Seattle area (not only in the harbour area) - Ship emissions contribute to secondary sulphate formation at multiple sites	V, Ni, SO_4^{2-}
Minguillón et al. (2008)	LA harbour, United States of America	Sampling at harbour and background sites in 2007; chemical analyses of ultrafine and fine fractions (PCIS); CMB model	- Ship emissions' contribution < 5 % of total OC and < 5 % of fine PM mass	V, Ni

Annex III Comparison of European emissions inventories with the Global Energy Assessment

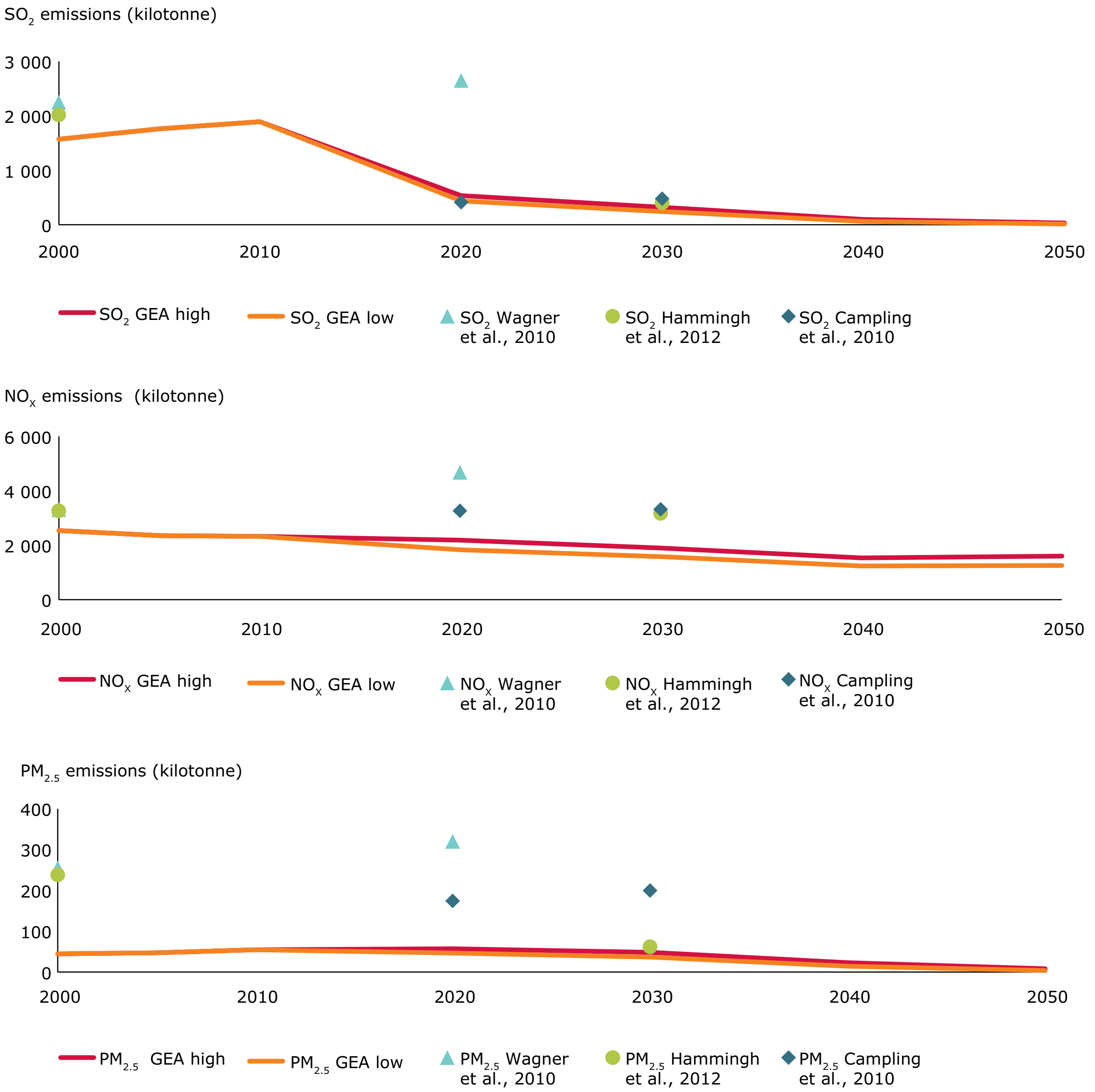
The two most recent emissions inventories for European international shipping (Campling et al., 2010; Hammingh et al., 2012) were compared to the maritime emissions in European seas by two scenarios of the GEA(Riahi et al., 2012). The GEA emissions were applied in earlier model studies of the ETC/ACM in evaluating co-benefits of air pollution and climate change policies (Colette et al., 2012b). The two scenarios differ with respect to levels of future air quality legislation and with respect to levels of policies towards climate change and energy efficiency and access. The 'High' or reference scenario includes all current and planned air quality legislations until 2030 and no further climate policies. The 'Low' or mitigation scenario includes all current and planned air quality legislations until 2030 and further climate policies leading to a stabilisation of global warming (2 °C target) in 2100. After 2030, GEA scenarios apply the environmental Kuznets theory to extrapolate improvements in emissions factors.

The comparison shows that the SO_2 emissions are reasonably simulated by the GEA scenarios up to 2020 (Figure AIII.1). They clearly account for the stricter IMO sulphur requirements from 2020 onwards. After 2030, the GEA scenarios assume that the emissions factors for SO_2 will decrease, further assuming the applicability of the environmental Kuznets theory. Without that theory, sulphur emissions would rise again after 2020 (shown by Campling et al., 2010, 2012) due to the assumed growth in shipping activities and the absence of further sulphur policies.

The estimated NO_X emissions by the GEA scenarios are substantially lower compared to the other two inventories. The gradual decrease is probably explained by gradually decreasing emissions factors that take into account the Kuznets theory to some extent. The difference between the High and Low GEA scenarios is small.

The trend in the particulate emissions by the GEA scenarios cannot be explained. As mentioned earlier, $PM_{2.5}$ emissions from shipping are quite strongly linked to the SO_2 emissions. However, the trends for SO_2 and $PM_{2.5}$ are not similar in the GEA scenarios.

Figure AIII.1 Air polluting emissions from maritime transport in European seas by recent European and global baseline scenarios


Air polluting emissions for European maritime transport by the global energy assessment and European inventories

Source: EEA, based on Riahi et al., 2012; Wagner et al., 2010; Hammingh et al., 2012; Campling et al., 2010.

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