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Towards an integrated environmental risk assessment of emissions from ships' propulsion systems

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ABSTRACT

Large ships, particularly container ships, tankers, bulk carriers and cruise ships are significant individual contributors to air pollution. The European Environment Agency recognizes that air pollution in Europe is a local, regional and transborder problem caused by the emission of specific pollutants, which either directly or through chemical reactions lead to negative impacts, such as damage to human health and ecosystems. In the Marine Strategy Framework Directive 2008/56/EC of the European Parliament emissions from ships are mentioned explicitly in the list of pressures and impacts that should be reduced or minimized to maintain or obtain a good ecological status. While SOx and NOx contribute mainly to ocean and soil acidification and climate change, PM (particularly ultrafine particles in the range of nanoparticles) has the potential to act more directly on human and ecosystem health. Thus, in terms of risk assessment, one of the most dangerous atmospheric aerosols for environmental and human health is in the size range of nanoparticles. To our knowledge, no study has been carried out on the effects of the fraction that ends up in the water column and to which aquatic and sediment-dwelling organisms are exposed. Therefore, an integrated environmental risk assessment of the effects of emissions from oceangoing ships including the aquatic compartment is necessary. Research should focus on the quantitative and qualitative determination of pollutant emissions from ships and their distribution and fate. This will include the *in situ* measurement of emissions in ships in order to derive realistic emission factors, and the application of atmospheric and oceanographic transportation and chemistry models.

Emissions from the propulsion systems of commercial vessels in European waters constitute a significant proportion of total worldwide emissions of air pollutants and greenhouse gases. Large ships, particularly container ships, tankers, bulk carriers and cruise ships are significant individual contributors to air pollution (Capaldo et al., 1999; Cofala et al., 2007; Corbett and Fischbeck, 2000; Corbett et al., 1999; European Commission, 2002; Streets et al., 2000, 2003; Wang et al., 2007). Unlike emissions of sulfur and nitrogen oxides (SO_X and NO_X) and particulate matter (PM), from land-based sources, which show a decreasing trend, those from shipping are expected to increase in the future due to the continuous growth in world trade and globalization (Lawrence, 2010). Emissions from European vessels are expected to increase and could be equal to land-based sources by 2020 onwards (European Environment Agency, 2013).

In addition to the emission of SO_X and NO_X, ozone (O_3)-depleting substances and volatile organic compounds (VOC), ships contribute significantly to the release of transitional and alkali earth metals (V, Ni, Ca, Fe) and their soluble or insoluble chemical forms (sulfides, sulfates, and carbides), as well as PM.

This PM is a combination of particles of different composition and granulometric distribution. The size, number and chemical composition of the particles will vary in function of the various processes that generate them (Delmas et al., 2005); such emissions of particles include those from ships' propulsion systems, spanning the size range of <0.1, <2.5 to <10 μm ($PM_{0.1}$ (ultrafine particles); $PM_{2.5}$; and PM_{10}) (Popovicheva et al., 2009). Emissions from ships are estimated to contribute some 20–30% of the total atmospheric inorganic particle concentrations in coastal areas (Commission for Environmental Cooperation of North America, 2002). Annually, oceangoing ships are estimated to emit 1.2–1.6 million metric tons (Tg) of PM_{10}, 4.7–6.5 Tg of sulfur oxides (SOx as S), and 5–6.9 Tg of nitrogen oxides (NOx as N) (Corbett and Koehler, 2003; Corbett et al., 2007a; Endresen et al., 2003; Eyring et al., 2005).

In this context, ultrafine particles are associated with incidental nanoparticles (INPs), which are nanoparticles (NPs) created as by-products of other processes; the source of a large fraction of total INPs in the atmosphere is the combustion process (Majestic et al., 2010). After their release and evolution, the particles may be removed from the atmosphere by dry and/or wet deposition and heterogeneous chemistry (in-cloud scavenging or below-cloud scavenging) (Calvo et al., 2013), eventually reaching the marine compartment.

At a global level, the International Maritime Organization (IMO) is addressing the control of air pollution through the International

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Table 1
Annex VI MARPOL, amendments and resolutions.

Denomination	Entered into force	Description
MARPOL ANNEX VI. 1997	19 May 2005	Sets limits on SOx and NOx emissions from ships. Global cap of 4.5% on the sulfur content of fuel oil. Provisions allowing for Sulphur Emission Control Areas (SECAs). The sulfur content of fuel oil used on board of ships must not exceed 1.5% m/m.
IMO (1999) Resolution MEPC 82(43).	01 July 2010	Reduction in the global limit for sulfur content in fuel to 3.5% (from the current 4.5%). Reduction in sulfur limits for fuels in SOx ECAs to 1% (from the current 1.5%) being further reduced to 0.1% (effective from 1 January 2015).
IMO (2000) Resolution MEPC 53/24.	21 November 2006	Declared North Sea SECA
IMO (2008a) Resolution MEPC 176(58).		The sulfur content of any fuel oil used on board of ships shall not exceed the following limits:
	Prior to 1 January 2012	4.50% mass/mass (m/m)
	On and after 1 January 2012	3.50% m/m
	On and after 1 January 2020	0.50% m/m
Requirements within Emissions control area (ECAs).	Prior to 1 July 2010	1.50% m/m
	On and after 1 July 2010	1% m/m
	On and after 1 January 2015	0.1% m/m
IMO (2008b) Resolution MEPC 177(58).	July 2010	NOx emission limits: Tier 0, Tier I, Tier II (global limits) and Tier III standards apply only in NOx ECAs.
IMO (2011) Resolution MEPC.203(62).	1 January 2013	Energy Efficiency Design Index (EEDI)

Note: EEDI provides a specific figure for an individual ship design, expressed in grams of carbon dioxide (CO2) per ship's capacity-mile (the smaller the EEDI the more energy efficient ship design) and is calculated by a formula based on the technical design parameters for a given ship.

Convention for the Prevention of Pollution from Ships, the Marine Pollution Convention, MARPOL (IMO, 1997). MARPOL is the main international convention on preventing pollution by ships from operational or accidental causes. Its annex VI, which entered into force on 19 May 2005, sets limits on SO_X and NO_X emissions from ships. The main resolutions are listed in Table 1.

The European Environment Agency in its report on air pollution (European Environment Agency, 2013) recognizes that air pollution in Europe is a local, regional and transborder problem caused by the emission of specific pollutants, which either directly or through chemical reactions lead to negative impacts, such as damage to human health and ecosystems. Emissions from ships and their atmospheric deposition are defined as hazardous and polluting substances in the Marine Strategy Framework Directive 2008/56/EC of the European Parliament and of the Council (European Commission, 2008a) which is the fundamental regulatory tool for marine environmental preservation. In this Directive, emissions from ships are mentioned explicitly in the list of pressures and impacts that should be reduced or minimized to maintain or obtain a good ecological status. Recognizing the problem, the EU Thematic Strategy on Air Pollution (European Commission, 2005) concluded that it is important to reduce emissions of sulfur dioxide (SO_2), NOx and PM from ships in order to improve health and the environment. Given that nearly 70% of emissions from ships occur within 400 km of land (Corbett et al., 1999; Endresen et al., 2003; Eyring et al., 2005), ships have the potential to contribute significantly to pollution in coastal communities, especially for SOx. Capaldo et al. (1999) have estimated that ship emissions contribute between 5 and 20% to total concentrations of non-sea sulfate salts, and between 5 and 30% to total SO_2 concentrations in coastal regions. In a study of emissions from a 12,600 kW medium speed diesel engine using low sulfur marine residual fuel and working with a Selective Catalytic Reduction System for NOx abatement, the size range of emitted particles measured was between 5.6 and 560 nm (Hallquist et al., 2013). Table 2 summarizes some of the most recent efforts to characterize, quantify, model and predict ship exhausts'

Table 2
Summary of recent studies concerning emission evaluation from ships, remote sensing and modeling approaches as well as regulation recommendations.

Approach	Reference	Main results
Emissions	Miola and Ciuffo (2011)	Review on available data and modeling approaches
	Gaston et al. (2013)	Chemical characterization of emissions, atmospheric particles, contribution of different sources
	Hallquist et al. (2013)	Characterisation of nanoparticle emissions from a ship
	Eckhardt et al. (2013)	Sulfur dioxide (SO2), ozone (O3), Aitken mode particle, equivalent black carbon (EBC) concentrations in Norway
	Gibson et al. (2013)	Extrapolation factor derivation from measured data
	Pey et al. (2013)	Chemical fingerprint and impact of shipping emissions in the Mediterranean
	Sullivan et al. (2013)	Source identification by chemical speciation analysis
	Durmusoglu (2013)	Temporal trend of air pollution from ships and estimation of costs of damage
	Tian et al. (2013)	Human health effects of shipping emissions
	Hassellov et al. (2013)	Contribution of SOx and NOx from shipping to ocean acidification
	Astiaso Garcia et al. (2013)	Development of methodology for seasonal monitoring atmospheric pollutants from ports
	McArthur and Osland (2013)	Evaluation of emissions from ships at berth in the Port of Bergen in Norway
	Yau et al. (2013)	Contribution of ship emissions on fine particulates ($PM_{2.5}$), Hong Kong
	Saracoglu et al. (2013)	Calculation of exhaust gas emissions from ships in Izmir Port by ship activity-based methodology
	Alfoldy et al. (2013)	Analysis of chemical composition of the plumes of seagoing ships and derivation of emission factors
	Zhao et al. (2013)	Ship traffic source identification of air pollutants
Remote sensing	Streets et al. (2013)	Review of studies of satellite data applied to emission estimation, recommendations on ways to improve the usability of satellite retrievals
Modeling	Milford et al. (2013)	Modeling of $PM_{2.5}$ concentrations of in south-west Spain and Portugal
	Brandt et al. (2013)	Development of an integrated model system to assess the health-related economic externalities of air pollution
Regulation	Cullinane and Cullinane (2013).	Description of current and planned regulatory regime for the atmospheric emissions from ships
	Schembari et al. (2012)	Effects of application of European directive on ship emissions
	Mestl et al. (2013)	Review on reducing sulfur limits in fuel
	Adamo et al. (2014)	Analysis of emissions resulting from berthing operations and regulation. Recommendations
	Homsombat et al. (2013)	Management of port pollution
	Schinas and Stefanakos (2012)	Cost assessment of environmental regulation for marine operators