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Review

Impact of maritime transport emissions on coastal air quality in Europe

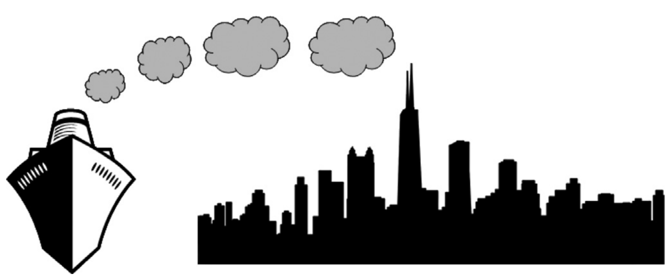
Mar Viana [a,*], Pieter Hammingh [b], Augustin Colette [c], Xavier Querol [a], Bart Degraeuwe [d], Ina de Vlieger [d], John van Aardenne [e]

[a] IDAEA-CSIC, C/Jordi Girona 18, 08034 Barcelona, Spain
[b] PBL, 3720 Bilthoven, The Netherlands
[c] INERIS, France
[d] VITO, 2400 Mol, Belgium
[e] European Environment Agency, 1050 Copenhagen, Denmark

HIGHLIGHTS

- Shipping contributions to European coastal air quality degradation are reviewed.
- Maritime transport is a significant and increasing source of air pollutants.
- Chemical tracers are available for use as markers in receptor models.
- Mitigation strategies are effective and should be implemented on EU-scale.
- Research gaps are identified.

GRAPHICAL ABSTRACT



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ABSTRACT

Shipping emissions are currently increasing and will most likely continue to do so in the future due to the increase of global-scale trade. Ship emissions have the potential to contribute to air quality degradation in coastal areas, in addition to contributing to global air pollution. With the aim to quantify the impacts of shipping emissions on urban air quality in coastal areas in Europe, an in depth literature review was carried out focussing on particulate matter and gaseous pollutants but also reviewing the main chemical tracers of shipping emissions, the particle size distribution of ship-derived particulates and their contributions to population exposure and atmospheric deposition. Mitigation strategies were also addressed. In European coastal areas, shipping emissions contribute with 1–7% of ambient air PM_{10} levels, 1–14% of $PM_{2.5}$, and at least 11% of PM_1. Contributions from shipping to ambient NO_2 levels range between 7 and 24%, with the highest values being recorded in the Netherlands and Denmark. Impacts from shipping emissions on SO_2 concentrations were reported for Sweden and Spain. Shipping emissions impact not only the levels and composition of particulate and gaseous pollutants, but may also enhance new particle formation processes in urban areas.

1. Introduction

Maritime transport of goods is a relatively clean form of transportation per kilogram of material, and it is therefore currently gaining relative weight with respect to air and road transport (Micco and Pérez, 2001; Grewal and Haugstetter, 2007). This form of

* Corresponding author.
E-mail address: mar.viana@idaea.csic.es (M. Viana).

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transportation has also been increasing (and will most likely continue to do so in the future) due to the globalization of manufacturing processes and the increase of global-scale trade (Corbett and Fishbeck, 2000; Marmer et al., 2009; US-EPA, 2009). However, emissions from the marine transport sector contribute significantly to air pollution globally (Wang et al., 2008; EEA, 2012). Around 15% of global anthropogenic NO_x and 5–8% of global SO_x emissions are attributable to oceangoing ships (Eyring et al., 2005; Corbett et al., 2007). Because nearly 70% of ship emissions are estimated to occur within 400 km of land (Endresen et al., 2003), ships have the potential to contribute significantly to air quality degradation in coastal areas. In addition, emissions are also generated while vessels are at berth, given that the main engines are not always switched off by all types of vessels (De Meyer et al., 2008). Large efforts have been made in Europe to reduce other types of emission sources (industrial, power generation, etc.), and this results in an increase of the relative weight of shipping emissions to the total of anthropogenic emissions. Only under new and strong climate (and air pollution) policies, energy intensity improvements could offset the growth in ship emissions (IEA et al., 2009). Ship emissions affect not only major ports, but also medium and small-scale ones (Viana et al., 2009). Despite this, even though shipping contributes significantly to the international transportation sector, its emissions are not well quantified and are one of the least regulated anthropogenic sources (IMO, 2008). Several studies point towards the need of international regulations on ship emissions, as those active in Europe, where the land based emissions of sulphur have been successfully reduced since 1980's, and where over the first decade of the 21st century total SOx emission have fallen by 54% in the EU (EEA, 2011). In this context, it is necessary to investigate the current impact of the ship emissions on the ambient air levels of primary and secondary aerosols, and how the predicted future growth of ship traffic and the geographical expansion of waterways and ports, possibly combined with international regulations, are going to affect the atmospheric composition (Becagli et al., 2012). In order to design and implement effective regulation to minimise environmental impacts of these emissions, detailed knowledge is necessary of their effects on climate and of their contribution to atmospheric pollution (Marmer et al., 2009).

The assessment of shipping emissions on the global and regional scales is of interest due to their various impacts on human health, climate and ecosystems. A detailed description of these impacts may be found in EEA (2013). Based on this assessment, it seems evident that urgent efforts should be made to reduce emissions from the maritime transport sector. Different approaches are used in different countries to reduce shipping emissions; however, actions to address these emissions have not yet achieved the goals for protecting human health (US-EPA, 2009).

Thus, the aim of the present work is to review existing studies dealing with the impact of shipping emissions on air quality in European coastal areas, in order to obtain a quantitative picture of these impacts.

2. Results and discussion

An in depth literature review was carried out focussing on the assessment of the impacts of shipping emissions and activities on urban air quality in European coastal areas. The summary of the main findings from each of the works reviewed, as a function of the specific topics addressed, may be found below. The details of the studies reviewed may be found in EEA (2013).

2.1. Chemical tracers of shipping emissions

Numerous studies in the literature have succeeded in identifying specific tracers of shipping emissions. As tracers of combustion processes based on crude oil as the main fuel, vanadium (V) and nickel (Ni) are generally identified as markers of shipping emissions. In addition, other markers identified are thorium (Th) (Querol et al., 1997), lead (Pb) (Isakson et al., 2001; Hellebust et al., 2010), zinc (Zn) (Isakson et al., 2001) and sulphate (SO_4^{2-}) (Viana et al., 2008; Becagli et al., 2012). However, the direct identification of shipping emissions by means of these tracers is complex, given that they are also markers for other types of combustion processes such as energy generation, petroleum refinery and other types of industrial processes, which are located on land and very frequently in the vicinity of harbour areas. Consequently, more detailed analyses have been carried out focussing not only on tracer species, but on tracer ratios (in terms of airborne concentration), which might aid in the more exhaustive identification of shipping emissions by means of modelling approaches such as, e.g., the multi-linear engine (Reinikainen et al., 2001).

In Genoa (Italy) (Mazzei et al., 2008), V/Ni concentration ratios were calculated by means of receptor modelling tools (PMF), which were found to be fairly constant for the three size fractions analysed (PM_{10}, $PM_{2.5}$, PM_1). It was concluded that heavy oil combustion may be identified by the concentration ratio V/Ni $= 3.2 \pm 0.8$ in all PM fractions. From an emission point of view, a wide V/Ni ratio (2.3–4.5) was measured by direct sampling at 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 mode (Agrawal et al., 2008a,b). Similar results were obtained for ambient air concentrations in Spain across the Gibraltar Strait (Viana et al., 2009), where valid tracers of commercial shipping emissions in ambient PM_{10} and $PM_{2.5}$ were ratios of V/Ni $= 4 \pm 1$. The ratio V/EC < 2 was also suggested as a tracer in this study. Characteristic ratios obtained from land sources (non vessel-derived) for their study area were V/Ni $= 12$ and V/EC > 8, excluding the influence of shipping emissions (by means of wind rose analysis). Other ratios (V/S (Viana et al., 2007), La/Ce (Moreno et al., 2008), Zn/Ni and Pb/Zn (Isakson et al., 2001), OC/EC (Fridell et al., 2008)) and tracers (Pb, Zn) were also tested, but did not always correlate with this source (Viana et al., 2009). Also in the South of Spain, shipping emissions were characterised by La/Ce concentration ratios between 0.6 and 0.8 and V/Ni ratios around 3 for both PM_{10} and $PM_{2.5}$ (Pandolfi et al., 2011). In contrast, elevated La/Ce values (1–5) were attributable to emissions from refinery zeolitic fluid catalytic converter plant, and low average V/Ni values (around 1) resulted mainly from contamination from stainless steel plant emissions. Finally, on the island of Lampedusa (Italy) (Becagli et al., 2012), PM_{10} samples influenced by ships were characterized by elevated Ni and V soluble fraction (80% for aerosol from ships, versus about 40% for crustal particles), high V and Ni to Si ratios, and values of soluble V > 6 ng/m^3. Data suggested a characteristic non sea-salt SO_4^{2-}/V concentration ratio in the range 200–400 for ship emission aerosols in summer at Lampedusa. The Ni/Si ratio was one order of magnitude higher than expected for crustal particles in 79% of the measured PM_{10} samples. As expected, V and Ni concentrations in a ship aerosol event characterised in this study displayed a maximum in the finest mode (diameter < 0.4 μm). Conversely, their concentrations peaked at larger size (1.1–2.1 μm for Ni, and 0.4–0.7 μm for V) during a Saharan dust event monitored during the same period.

These particulate tracers were found to correlate with gaseous tracers in a number of studies. In Gothenburg, Ni, Pb, V and Zn were shown to have positive correlation with NO emissions from ships (Isakson et al., 2001). In addition, 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 (Saxe and Larsen, 2004; Eyring et al., 2010). In addition, shipping emissions also impact particle