



Proceeding Paper

# Trends of Shipping Impact to Particulate Matter in Two Adriatic Port-Cities <sup>†</sup>

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**Abstract:** Shipping contributions to atmospheric particulate matter were estimated by an approach based on high temporal resolution measurements of mass and number size distribution, correlated with meteorological and ship movements data, in two Adriatic harbours. Trends of contributions are discussed. Contribution to particle number concentrations (PNC) was 3–4 times larger than that to PM<sub>2.5</sub>. In Venice, strategies for reduction of shipping emissions were effective in lowering the PM<sub>2.5</sub> primary impact, while PNC contribution was significant in Brindisi. The maximum contribution was found to ultrafine particles (UFP), followed by a minimum at diameters between 1 and 1.5 μm and a growth in the coarse range.



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## 1. Introduction

International maritime sector is expected to expand rapidly, faster than other transportation modes, with an average annual growth rate of 3.5% over the 2019–2024 period [1]. This could be particularly evident in some busy areas (i.e., Mediterranean Sea) [2] and for some specific sub-sectors (i.e., cruising), thus leading to the formulation of more stringent regulations at global level. Annex VI “Regulations for the prevention of Air Pollution from Ships” of the International Maritime Organization (IMO) has imposed, since 2020, to reduce sulphur content in maritime fuels from 3.5% to 0.5% m/m on global basis (0.1% m/m since 2015 within Emission Control Areas), to curb ship emissions of sulphur oxides and particulate matter.

Although some studies reviewed maritime emissions and their potential impact on particulate matter and gaseous pollutants [3–5], the local/urban influence of harbour activities (ship traffic and logistics) has received less attention, although some have focused on their environmental issues and health implications (such as respiratory and cardiovascular diseases) on the exposed coastal population [6–8].

The objective of this paper is to give a comparable assessment of the impact of ship traffic to atmospheric particulate matter (PM<sub>2.5</sub> and PM<sub>10</sub>) and particle number concentration (PNC) in two important port-cities of the Adriatic Sea area (Venice and Brindisi). Relative contribution for different particles' sizes and temporal trend analysis were reported and discussed.

Discussed results of this work were developed within the framework of the projects: ECOMOBILITY (Interreg V Italy-Croatia CBC Programme); POSEIDON (MED 2007-2013); CESAPO (Interreg Greece-Italy 2007–2013).

## 2. Sampling Areas and Campaigns

Different sampling campaigns were carried out in summertime, covering the period 2007–2018 in two Italian Adriatic port-cities (Figure 1): Brindisi and Venice. The Brindisi harbour has a commercial and tourist vocation, recording a traffic volume of 7.9 Mtons of goods, 637,340 passengers (ferry + cruise), and 214,682 vehicles (private and Ro-Ro) in 2018 (<http://www.adspmam.it/>, accessed on 12 June 2021). The measurement site was located in the intermediate zone of the harbour close to the Terminal Passenger building (about 35 m) and facing (at about 50 m) the water and ferryboat docks ( $40^{\circ}38'43.32''$  N– $17^{\circ}57'36.39''$  E).



Figure 1. Sampling sites in (a) Brindisi and (b) Venice.

In Venice, the tourist harbour, namely Stazione Marittima, is separated from commercial piers, located at Porto Marghera within the large industrial area of Venice. The Venice Terminal Passenger, positioned at the corner of the Giudecca Canal, which is devoted to local ferries and catamarans, can host the largest cruise ships (with 5 km of quayside and 10 multifunctional passenger terminals). In 2018, 1.6 million cruise passengers transited there, designating Venice as one of the main Mediterranean homeports (<https://www.port.venice.it/>, accessed on 12 June 2021). Here, the sampling site was on the Sacca San Biagio island ( $45^{\circ}25'38.50''$  N– $12^{\circ}18'33.86''$  E, 1 km south of the passenger terminal) during the first campaigns (2007, 2009 and 2012), while it was on the neighbouring Sacca Fisola island ( $45^{\circ}25'42''$  N– $12^{\circ}18'46''$  E, 500 m from the location of ships at berth) for the last 2018 campaign.

A similar instrumental setup was used at both sites, for collecting real-time measurements of main meteorological parameters and concentration of particles (in mass and number). In detail, for the last sampling campaigns, a micrometeorological station, based on a three-dimensional ultrasonic anemometer (R3 Gill Instruments Ltd., Lymington, UK) measured the main meteorological variables (i.e., wind speed, wind direction) at 1 min resolution. The total sub-micrometric particle number concentration was obtained by a Condensation Particle Counter (CPC, 1 min resolution). The cut-off diameter (50% efficiency) was 9 nm, thereby the system was measuring particles in the size range 0.009–1  $\mu$ m (the latter is the upper limit of the CPC). An OPC provided particle number size distribution in the size range 0.25–31  $\mu$ m in 31 size channels, operating at controlled flow of 1.2 L/min. In addition, the OPC internal software was also able to reconstruct mass size distributions as well as PM<sub>1</sub>, PM<sub>2.5</sub>, and PM<sub>10</sub> mass concentration. Finally, a video camera operating at two frames per minute, was used to synchronise data of ship movements, provided by the Port Authorities, with concentrations and meteorological data.

The methodological approach for estimating primary ship contribution was originally introduced by Contini et al. [9] for the Venice harbour, then applied to the Brindisi har-

bour [10,11] and to other sites [12,13]. Experimental data collected at the two sites were statistically treated and compared to estimate relative contribution of shipping to particle number concentration (PNC), PM<sub>2.5</sub> and PM<sub>10</sub>. After selecting wind direction sectors favourable to measure ship plumes (measurement site downwind of the emissions) for each site, primary contribution from high temporal resolution measurements was calculated following Equation (1):

$$\epsilon = \frac{(C_{DP} - C_{DSP})F_P}{C_D} = \frac{\Delta_P F_P}{C_D} \tag{1}$$

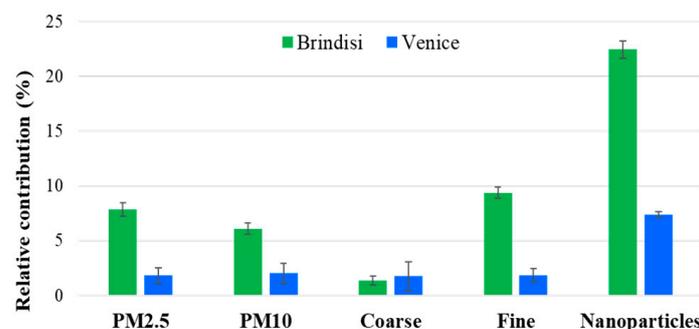
where  $(C_{DP} - C_{DSP}) = \Delta_C$  is the difference between average concentration in periods potentially influenced and not influenced by ships, in downwind conditions;  $C_D$  is the average concentration in the downwind sector;  $F_P$  is the fraction of cases (i.e., 30 min averages) influenced by ships. Uncertainties have been evaluated looking at the variability of  $\epsilon$  calculated in elaborations done with and without wind calm (velocities <0.2 m/s) and with small changes by  $\pm 10^\circ$  in definition of wind direction intervals.

### 3. Results and Discussion

#### 3.1. Size-Segregated Shipping Contribution

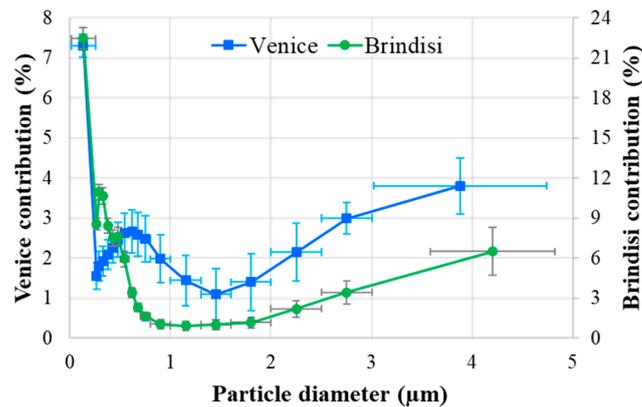
Measurements acquired with OPC and CPC in the last campaigns at the two locations allowed to investigate particle number and mass size distributions in a large size range (0.01–31  $\mu\text{m}$ ). Likewise, three size ranges were determined to analyse shipping impact to different particles' sizes: nanoparticles (diameter  $D < 0.25 \mu\text{m}$ ), fine particles ( $0.25 < D < 1 \mu\text{m}$ ), and coarse particles ( $D > 1 \mu\text{m}$ ).

The general trend of relative contribution was the same at both sites with larger values for nanoparticles, followed by fine and coarse particles' ranges (Figure 2). The relative shipping impact on nanoparticles was  $7.4 \pm 0.3\%$  in Venice and  $26 \pm 1\%$  in Brindisi; smaller contributions were found for number particle concentrations in the fine and coarse ranges ( $1.9\%$  and  $1.7\%$  in Venice, and  $9.4\%$  and  $1.4\%$  in Brindisi, respectively). Results were larger in Brindisi for all size ranges, likely as a consequence of the distance from the docks (lower in Brindisi compared to Venice) and of the greater internal harbour vehicular traffic and the absence of local mitigation measures as in Venice. The smaller distance from the docks in Brindisi site is an important aspect because the contribution of shipping emissions to air quality quickly decreases with distance from the harbour [14]. As reported, standard metrics for mass concentrations (i.e., PM<sub>10</sub> and PM<sub>2.5</sub>) have comparable contributions. In fact, the impact to PM<sub>2.5</sub> represented about 84% and 81% of that to PM<sub>10</sub> in Brindisi and Venice, respectively [11,15]. This happens because ship exhaust emissions are in the ultrafine range, as observed in several studies [11,12,16–20]. Definitely, this evidence supports the idea that particle number concentration, in nanoparticle or ultrafine size range, could be a better metric, compared to standard ones, to investigate the impact of shipping to local air quality.



**Figure 2.** Relative contribution to particles' concentration (in mass and number) for different sizes at both sites in 2014 (Brindisi) and 2018 (Venice).

A characterisation and comparison of the size distribution of shipping impact is reported for both port-cities (Figure 3). Results obtained showed general similarities and some different details between them. After a maximum for nanoparticles, a quick decrease and a secondary maximum in the fine range were recorded. The secondary maximum was in the range 0.3–0.45  $\mu\text{m}$  in Brindisi and between 0.4 and 0.7  $\mu\text{m}$  in Venice, being 2–3 times lower than the absolute maximum. For larger diameters, the relative contribution reached a minimum in the size range 1–1.5  $\mu\text{m}$ , followed by a noticeable growth in the coarse size range for both sites.

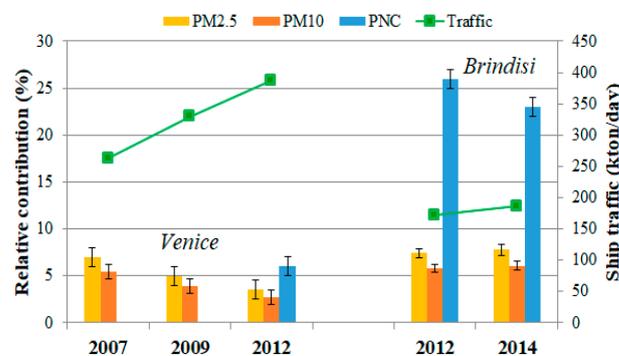


**Figure 3.** Relative contribution of shipping to number particle concentration as function of size for the two sites, during the last campaigns in 2014 (Brindisi) and 2018 (Venice) [15]. Vertical bars represent the errors and horizontal bars represent the size of the channel used in the evaluations.

Relatively fresh ship exhaust particle size distributions were found to have either unimodal or bimodal shape, however, a typical bimodal size distribution was observed with the modes centred at around 40–60 nm and 100–200 nm [18,19]. Additionally, a contribution of shipping in the nucleation range (at about 10 nm) was found at the banks of the Elbe in Northern Germany [17].

### 3.2. Temporal Trends

Estimates from previous studies performed in Venice [21,22] and Brindisi [11] in the same period (summer months), with similar instrumental setup and methodological approach (even if in nearby different sites), were compared with the more recent results (Figure 4).



**Figure 4.** Relative contribution of particles' concentration in previous campaigns in Venice and Brindisi, with indication of ship traffic volume [21,23]. Results for  $\text{PM}_{10}$  from indirect calculation were obtained considering a ratio  $\text{PM}_{2.5}/\text{PM}_{10}$  equal to 0.78.

Looking at contribution to mass concentration ( $\text{PM}_{2.5}$  and  $\text{PM}_{10}$ ) estimates in Venice showed a general decrease from 2007 to 2012, while in Brindisi, essentially comparable

results were found between the two campaigns in 2012 and 2014. Despite an increasing ship traffic (as gross tonnage) of about 47%, the effect of the implementation (starting from 01/01/2010) of the 2005/33/EC Directive and to the local mitigation strategies (namely, “Venice Blue Flag”), signed in 2007 and 2008, was recorded. These agreements foresaw the use of cleaner fuels within the Lagoon, with maximum S content of 2.5% ( $\pm 0.5\%$ ) since 2007 during manoeuvring and at berth, decreasing up to 2% ( $\pm 0.5\%$ ) for manoeuvring and 1.5% ( $\pm 0.25\%$ ) at berth since 2008. Contributions to PM in Brindisi were higher compared to Venice, however, a not significant change from 2012 to 2014 was observed, although a slight increase in ship traffic of about 8%. It should be noted that harbour logistics (i.e., loading/unloading of ships, vehicular traffic) could influence particle concentrations (both in number and mass) mainly in Brindisi site located near the docks, while this influence is more limited in the Venice site, located on an island directly facing the passenger terminal.

#### 4. Conclusions

In this study, an estimate of the local impact of harbour activities on particulate matter concentration of different sizes in two Adriatic coastal cities was provided. Different campaigns, performed during the period 2012–2018 with the same instruments and applying the same statistical approach, allowed a direct comparison of results between sites and, in addition, a temporal analysis of estimated contributions.

The relative contribution to measured concentration of atmospheric particles (both in mass and number) was larger in Brindisi compared to Venice, as a consequence, mainly because of harbour logistics and because of the smallest distance of the measurement site from the docks, as well as the local mitigation strategies adopted within the Lagoon since previous years. At both sites, size distribution of relative impact showed a maximum for nanoparticles, a quick decrease, and a successive secondary maximum in the fine range. Trend analysis for the 2007–2012 period revealed that although there was an increase in ship traffic, there was a gradual decrease of ship contribution to PM in Venice, as an effect of local mitigation strategies and international legislation, while no significant changes for PM and PNC were observed in Brindisi between 2012 and 2014.

Although harbours are the pulsating economic heart of port-cities, as well as sources of development and innovation, the compelling need of further local reduction measures i.e., regulating emissions from specific type of vessels both in manoeuvring and berthing phases or of some climate change drivers (i.e., CO<sub>2</sub>, black carbon), should be addressed. In this way, a green port perspective could be achieved, with the objectives of health protection and sustainable development.

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**Data Availability Statement:** The data presented in this study are available on request from the corresponding author.

**Conflicts of Interest:** The authors declare no conflict of interest.

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