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Impact of Ship Traffic to $PM_{2.5}$ and Particle Number Concentrations in Three Port-Cities of the Adriatic/Ionian Area

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***Abstract*—**Emissions of atmospheric pollutants from ships and harbour activities are a growing concern at international level given their potential impacts on air quality and climate. These close-to-land emissions have potential impact on local communities in terms of air quality and health. Recent studies show that the impact of maritime traffic to atmospheric particulate matter concentrations in several coastal urban areas is comparable with the impact of road traffic of a medium size town. However, several different approaches have been used for these estimates making difficult a direct comparison of results. In this work, an integrated approach based on emission inventories and dedicated measurement campaigns has been applied to give a comparable estimate of the impact of maritime traffic to $PM_{2.5}$ and particle number concentrations in three major harbours of the Adriatic/Ionian Seas. The influences of local meteorology and of the logistic layout of the harbours are discussed.

***Keywords*—**Ship emissions, $PM_{2.5}$, particle number concentrations, impact of shipping to atmospheric aerosol.

I. Introduction

EMISSIONS of atmospheric pollutants from shipping and harbour activities are a growing concern at international level and, specifically, in the Mediterranean area. The continuous increase of global trade and of harbour services made maritime transport a key contributor to atmospheric pollution [1].

Nearly 70% of the ship emissions occur within 400 km of land [2] and in-port ship and harbour-related emissions represent only a small fraction of the global emissions associated to shipping. However, they can have important impacts on air quality and climate on coastal regions as well as on health of local communities [3]-[5].

The evaluation of the impact of ship emissions to atmospheric particulate concentrations was performed, in several harbours using different approaches. The first approach is based on model simulations and emission inventories, in which the main uncertainty is related to the accuracy of emission inventories used [6]-[8]. A second approach is based on the application of receptor models for source apportionment of atmospheric aerosol looking for the markers of primary ship emissions, typically Ni and V [9]-[14]. The main difficulty with receptor models is the non-specificity of the markers that could originate also from industrial releases or oil combustions [15]. High temporal resolution concentrations and size distributions measurements have also been used for identification of single ship plumes and for quantitative statistical evaluation of primary contribution of ship emissions to atmospheric aerosol concentrations [16]-[19]. A recent review showed that, 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, further emissions from shipping may enhance new particle formation processes in urban areas [20]. A gap present in available data regards the homogenisation of monitoring strategies and the inter-comparability of results obtained in different coastal/harbour areas given to the heterogeneity of the approaches used and to logistic and meteorological specificities of the areas studied.

The objective of this paper is to give a comparable assessment of the impact of ship traffic and harbour activities to atmospheric $PM_{2.5}$ and particle number concentrations (PNC) in three important post-cities of the Adriatic/Ionian Seas areas: Venice (Italy), Brindisi (Italy), and Patras (Greece). The work was developed within the framework of the POSEIDON project (Pollution monitoring of ship emissions: an integrated approach for harbours of the Adriatic basin, MED 2007-2013 Programme). The analysis is based on an integrated approach using emission inventories and dedicated measurement campaigns.

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II. The Measurement Sites and the Emission Inventories

A. Measurement Sites

Fig. 1 From top to bottom: location of the measurement sites, detail of Venice site, detail of Brindisi site, detail of Patras site

The measurement sites are located near three major harbours of the Adriatic/Ionian area (Fig. 1). The first site is in the Northeastern part of Italy near the Venice tourist harbour (Passenger Terminal). The second site is located in Southeastern Italy inside the harbor area of Brindisi. The third site is located on the North part of the Peloponnese peninsula near the new harbour area of Patras (Greece). The three harbours have significant differences in the typology of ship traffic as well as in the volume of traffic and in the layout and logistic organization that could influence the impact of pollutant emissions on nearby urban areas.

The Venice harbour is located in a lagoon and it is divided into two parts. Passenger ships dock at the Stazione Marittima located near the urban area (specifically studied in this work, Fig. 1), instead, commercial ships follows a different path in the lagoon and docks at Porto Marghera harbour located in the large industrial area of Venice at about 6 km WNW from the measurement site. The measurement site is located at about 1 km S of the passenger terminal, in the Sacca San Biagio island (45° 25’ 38.50” N – 12° 18’ 33.86” E), at the end of the Giudecca channel, the navigational channel for tourist ships moving to and from the Venice cruise ship terminal (Fig. 1). On arrival, ships navigate through the Giudecca channel, with engines on and accompanied by tugs. Departing ships follow the same path out to sea. Prevalent wind direction in the Venice area shows a clear daily pattern with winds coming from NNE-NE directions, following a circulation from the Alps mountains, mainly during the night and winds coming from SSE-SE during the day, from the Adriatic Sea, especially in spring and summer seasons [21]. This is an important aspect in the interpretation of the maritime transport impact because the measurement site is downwind of ship and harbour emissions only during the night and the first hour of the morning, however, it is rarely downwind of the emissions between 10am and 10pm.

The Brindisi area is included in the list of SIN (National Sites of Interest) for relevant and potentially dangerous pollution, according to Italian Legislation (D.M. 471/99). The municipality of Brindisi is characterised by a quite complicated scheme of emission sources including urban emissions (88500 inhabitants), harbour, airport, petrochemical and power-plant emissions (there are three thermo-electric power plants in the area), and industrial emissions. Near Brindisi is present a large industrial area The Brindisi harbour, with commercial and tourist ship traffic, is divided in three zones. The internal zone (about 700000 m^2 with 2 km of docks) could accommodate at the same time up to 8 Ro-Ro ships and it is mainly dedicated to tourist activities. The intermediate zone (about 1200000 m^2 with 3 km of docks) is dedicated to commercial ships. The outer zone (Costa Morena) is dedicated to the traffic of coal-ships, bulk carriers, and small general cargo. Brindisi faces the sea towards E. The meteorology of the Brindisi area is characterised by two prevalent wind directions: NW-NNW and SSE. However, a specific daily pattern in wind direction is not present. The highest wind velocities are generally associated to the NW-NNW directions. The Brindisi measurement site was located in the intermediate zone of the harbour near the passenger terminal The Brindisi site was a Mobile Laboratory located inside the harbor close (about 35m) to the passenger terminal building (40° 38′ 43.32″ N–17° 57′ 36.39″ E).

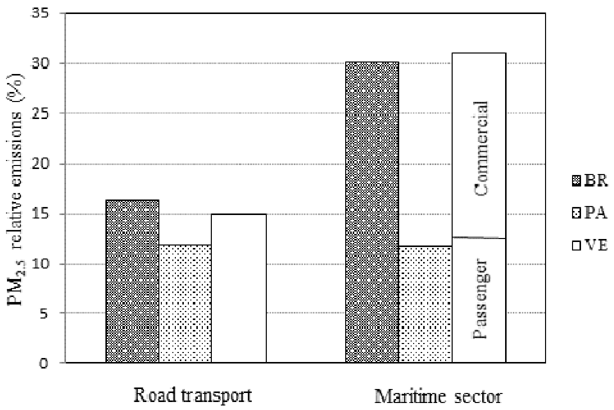

Fig. 2 Road transport and harbour emissions of $PM_{2.5}$ in the three sites with respect to total emissions of the area

The site was facing (about 50 m) the water and ferryboat docks. The measuring platform in Patras was a Mobile Laboratory located in the new port area (38° 13’ 74” N – 21° 43’ 12.36” E). The Patras harbour area covers almost all the coastal zone of the city and it has three main areas. In Area #1 there is a marina with a capacity of 415 yachts and boats under 15 m length. The Area #2 is the north (old) port, actually where some cargo vessels moor; it is also used for long term (several days) mooring of cargo ships. The harbour of the fishing fleet of Patras is located at the southern part of this area #2. The Area #3 is the south (new) port used by the ferries connecting Greece with Italy. It became operational on July 2011. It consists of 4 dock stations and it has 15 docks, 11 of which can be used for mooring by poop. The breakwaters have 1236 m total length. A 5th dock and two more terminal station buildings are currently under construction. It is also foreseen to build a 300 m commercial pier with a depth of 14 m at the south border of the south port, as well as land facilities of 140000 m^2 for cargo and accommodation of merchandise traffic.

B. $PM_{2.5}$ Emissions from Ships and Harbour Operations

In Table I the volume of ship traffic and their emissions of $PM_{2.5}$ are reported for the three harbours studied. The emissions for Venice were obtained within the APICE project [22]. The emissions for Brindisi and Patras were obtained within the CESAPO project [23], [24]. Results indicate that the volume of ship traffic is significantly higher in Venice and Patras with respect to Brindisi that presents the lowest volume of traffic. In Patras the emissions are dominated by passenger ships, however, in Venice and Brindisi the cargo ships have larger emissions with respect to passenger ships. In Fig. 2 the emissions of the maritime sector, relative to the total emissions are compared with the emissions associated with road traffic. For the Patras area the relative weight of maritime transport emissions are comparable with those of road traffic. Instead, in Venice and Brindisi the weight of maritime sector is larger than that of road traffic. However, if the Venice emissions are limited to the passenger ships, docking at the site analysed, the emissions are slightly smaller than those of road traffic.

TABLE I
SHIP NUMBER AND $PM_{2.5}$ YEARLY EMISSIONS (2010)

Ship tipology	Number			$PM_{2.5}$ (Mg/year)		
	VE	BR	PA	VE	BR	PA
Passenger	1266	1191	2903	94	67.7	218.1
Cargo	2825	848	386	130	96.5	13.3
Fishing	-	156	300	-	0.35	14.3
Tugs	19	13	35	20	0.16	0.01
Others	533	91	1050	5	1.7	10.8
Harbour operations	-	-	-	-	-	0.19
TOTAL	**4643**	**2299**	**4674**	**249**	**166.5**	**256.7**

VE=Venice; BR=Brindisi; PA=Patras

III. MEASUREMENT CAMPAIGNS AND INSTRUMENTS USED

Dedicated measurement campaigns were performed in the summer 2012 in Venice (between 03/07/2012 and 24/09/2012), in Brindisi (between 10/06/2012 and 22/10/2012). Measurement in Patras were performed in 2013 (between 25/08/2013 and 01/09/2013) and in 2014 (between 19/01/2014 and 27/01/2014). The instruments used in Venice and Brindisi were very similar. A micrometeorological station placed at 9.6 m above ground level, based on a three-dimensional ultrasonic anemometer (R3 Gill Instruments Ltd), operating at 100 Hz in calibrated mode, and a slow-response Rotronic MP100A thermo-hygrometer (Campbell Scientific). The station was coupled with a fast-response optical detector pDR-1200 (Personal Data logging Real time Aerosol Monitor by Thermo Electron Corp) used to measure $PM_{2.5}$ concentrations (1 Hz). The pDR-1200 was operated in active sampling mode (flow-rate 4 l/min) at 1 Hz and was equipped with a cyclone separator (2.5 µm cut-off). Concentrations measured with the pDR-1200have been corrected to take into account the effect of relative humidity (RH) using the correction procedure developed in [25]. A Condensation Particle Counter (TSI, 3775 model) was used to measure (1 minute resolution) the total particle number concentrations (PNC). The CPC was installed inside an air conditioned shelter using an inlet based on a conductive plastic tube (2.5 m long with 26 mm internal diameter) and a stainless steel sampling head located outside the shelter at about 2.5 m above the ground. The flow rate at the inlet was maintained at 25 l/min using a pump (Aquaria CF20e) and a portion (1.5 l/min) was directed, using a conductive silicon tube (0.5 m long with 6 mm internal diameter), towards the CPC passing through a silica gel dryer, appositely developed in the laboratory of ISAC-CNR, (0.24 m long with 20 mm internal diameter). The calculated penetration factor shows that the system was measuring particle number concentration in the range 5-3000 nm (the latter is the upper limit of the CPC).

In Brindisi the instruments used were very similar to those used in Venice. A mobile laboratory was installed inside the harbour area equipped with the same micrometeorological station used in Venice, a second optical detector pDR-1200 configured in the same way as in Venice and a Condensation Particle Counter (CPC, Grimm Aerosol Model 5.403) to measure (1 Hz acquisition frequency) the total particle number concentrations. The CPC was equipped with the same dryer as in Venice and the total penetration factor had a cut-off diameter (at 50% efficiency) around 9 nm in the used configuration. The system was therefore measuring particle number concentration in the range 9-1000 nm (the latter is the upper limit of the CPC).

In Patras it has been used a mobile laboratory located inside the new harbour area. The measurements of PM_1, $PM_{2.5}$, and PM_{10} were taken using an optical detector TSI DustTrak DRX 8533. The PNC were measured using a TSI CPC (Model 3775) able to detect particles in the size interval between 4nm and 3000 nm.

IV. Discussion of Results

The daily patterns of ship traffic, recorded during the measurement campaigns and expressed in terms of gross tonnage summing arrival and departure of ships from the different harbours, are reported in Fig. 3. The data of Venice refers only to passenger ships. Results in Brindisi and Venice show a similar pattern with two peaks, the first in the morning around 07am visible in Brindisi and Venice, relative to the arrival of ships in the harbour, and the second in the evening, relative to the departure of ships, that happens at different hours and it is early in Venice. The Venice harbour presents also a smaller peak around midday non visible in Brindisi. In general terms the gross tonnage of ship traffic in Venice is significantly larger than that observed in Brindisi, even if the number of passenger ships is not larger and it is a consequence of the presence, in Venice, of large cruise ships.

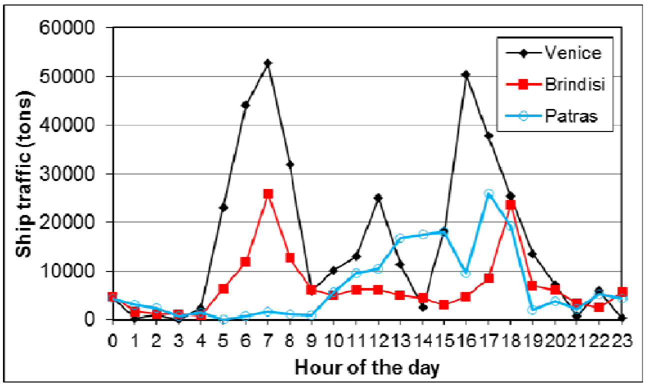

Fig. 3 Average daily patterns of hourly ship traffic (gross tonnage) in the three harbours. Results represent the sum of arrival and departure of ships. The Venice data are limited to passenger ship traffic

Tourist ship traffic in Venice harbour is mainly associated to large cruise ships concentrated in spring and summer (83.1% of berths are between May and October). Considering cruise ships, in 2012, 61.3% of berths were associated with ships larger than 40000 tons and 22.5% of berths were of ships larger than 100000 tons (source: Venice Port Authority). The daily pattern of ship traffic is significantly different in Patras where traffic is very limited in the morning being mainly concentrated in the central hours of the day and in the evening.

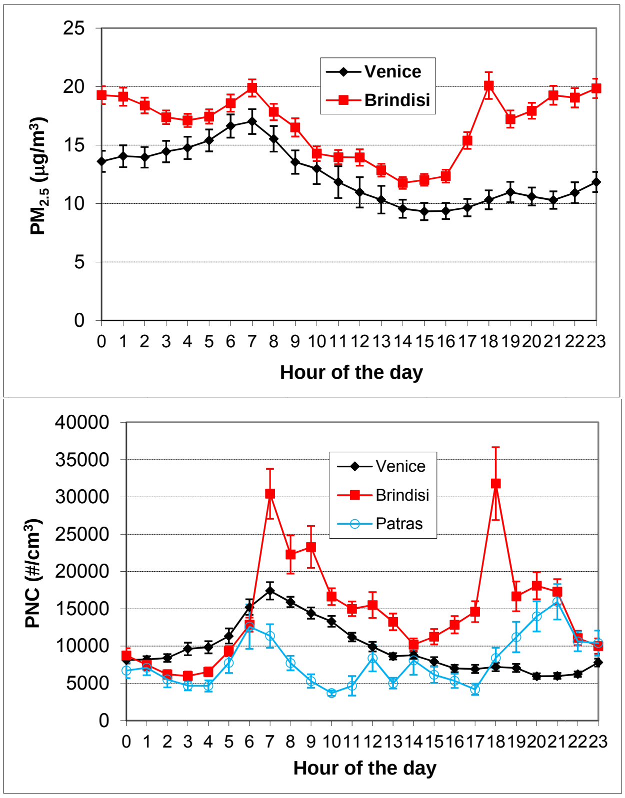

Fig. 4 Average daily pattern of hourly $PM_{2.5}$ (top) and PNC concentrations (bottom) in the different harbours. The error bars represent the standard error

The average daily patterns of $PM_{2.5}$ and PNC concentrations are reported in Fig. 4. Results show that $PM_{2.5}$ concentrations are, on average, slightly larger in Venice with respect to Brindisi. The same apply for PNC concentrations with the exclusion of nocturnal hours. It is interesting to observe that PNC pattern in Brindisi shows two clear peaks at 07am and 18pm that are superimposed to the morning and evening increase associated to road traffic. These peaks are also visible in $PM_{2.5}$ concentrations even if they are less evident, especially in the morning. The daily patterns in Venice are significantly different from those of Brindisi. It is still evident a broad peak in the morning on both PNC and $PM_{2.5}$ concentrations, however, there is no evidence of an evening peak. The morning peak in Venice is likely associated to both urban sources and ship traffic (that are both located in the same general wind direction sector NE-NW, Fig. 1). The peak in the evening is not visible, on average terms, because the wind direction is typically from SE and the site is upwind of both urban area and harbour.

The direct contribution, ε, of ship traffic to atmospheric concentrations have been evaluated on 30 minutes averages, using the approach developed in [18]. In this approach the periods in which the site is downwind of the source are firstly selected. Successively, ε is evaluated using (1):

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

where C_{DP} is the average concentrations in the selected wind direction sector considering periods potentially influenced by ship emissions, C_{DSP} is the average concentrations not significantly influenced by ship emissions, C_D is the average concentration in the specific wind direction sector, and F_P is the fraction of cases influenced by ship emissions. Results are reported in Table II. The direct contribution to PNC is significantly larger with respect to the contribution to $PM_{2.5}$ in all the harbours studied. This is in agreement with the observation performed in Cork, Ireland [26]. This happens because primary particles emitted by ships are predominantly in the submicron size fraction and shipping emissions could increase particle number concentrations in the ultrafine size range [26]-[28]. The relative direct contributions calculated for Brindisi are larger than those observed in Venice and Patras. This could be due to the different distances of the measurement sites from the docks of the harbour (it was larger in Venice and Patras). However, it could also reflect the different weights in the emissions (Fig. 2) and the effect of local meteorology and micrometeorology. For example, in Venice the air masses circulation make the measurement site influenced by ship only in specific periods in the morning (generally associated with ship arrivals) interesting about one half of the entire passenger ship traffic.

TABLE II
DIRECT RELATIVE CONTRIBUTION OF SHIP TRAFFIC TO $PM_{2.5}$ AND TO PARTICLE NUMBER CONCENTRATIONS

Site	$PM_{2.5}$	PNC
Venice	3.5% (± 1%)	6% (± 1%)
Brindisi	7.4% (± 0.5%)	26% (± 1%)
Patras	3.8% (± 1.4%)	11% (± 3.8%)

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