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Impact on air quality of cruise ship emissions in Naples, Italy

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GRAPHICAL ABSTRACT

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ABSTRACT

The Municipality of Naples, with about 1 million residents and about 3 million people living in the surroundings, suffers, as for many a city, from low air quality, as demonstrated by the concentration level of pollutants measured by fixed monitoring stations of the Regional Air Quality Network. The port of Naples is among the most important ports in the Mediterranean sea with a large traffic of passengers and goods. Therefore, it contributes to atmospheric pollution of the nearby urban area with ship emissions. Public authorities need to know the contribution of different sources of atmospheric pollutants to put effective environmental policies into practice. In this article, a bottom-up methodology has been developed to assess the amount of atmospheric pollutants emitted by cruise ships traffic and its impact on the atmospheric pollution in Naples. A detailed description of in-port activities of cruise ships has been applied to calculate emission rates of NO_x and SO_x by using standard procedures corrected and integrated by real data to better evaluate actual engine power applied and fuel consumption. Considered activities include: navigation in port both at arrival and departure; maneuvering for berthing and unmooring and hoteling at berth. The study covers all cruise ship calls during the year 2016. The impact of cruise ship emissions on the urban area has been assessed by using the Gaussian puff model CALPUFF, thus obtaining contour maps of 1-h and year average values. Finally, in order to assess the contribution of cruise ship emissions to air quality, simulations have been compared with concentrations measured at fixed monitoring stations and during a monitoring campaign.

1. Introduction

Shipping represents a growing asset within the transport sector. The latest UNCTAD (United Nations Conference on Trade and Development) review of marine transport confirms that more than 80% of global trade is transported annually by sea (UNCTAD, 2013). Mirroring the world economy, the demand for transport services in 2016 has improved moderately. The UNCTAD's projections for the medium term estimates an average growth rate of 3.2% over the period from 2017 to 2022. In Italy, 37% of the commercial exchange in the first nine months of 2016 has travelled by sea.

Cruise tourism has experienced rapid growth in recent years. Globally, from 2003 to 2013, the worldwide demand for cruising has increased from 12.0 to 21.3 million passengers (+77%); and from 2013

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to 2015 to 23.9 million passengers (+12%) (CLIA, 2014; CLIA, 2016). In 2013, ports in the Mediterranean and the Baltic sea were the most visited in Europe, thus generating an increase of visitors of 8.7% compared to 2012, out of a total of 250 port cities. In fact, the Mediterranean is the second largest cruise market in the world and represents 21.7% of the annual cruising capacity in 2013 (CLIA, 2014; MedCruise, 2014).

With the simultaneous decrease of terrestrial emission sources, following the Kyoto Protocol, for some pollutants, there was an increase in the relative weight of the maritime emissions on the total anthropogenic emissions (Viana et al., 2014). As a matter of fact, emissions from ships are included in the list of pressures that should be reduced or minimized in order to maintain or obtain a good ecological status in the Marine Strategy Framework Directive 2008/56/EC of the European Parliament (Blasco et al., 2014).

The regulation of pollutants from maritime traffic is the subject of MARPOL (MARine POLlutants) 73/78 Annex VI, legislation issued by the IMO (International Maritime Organization). According the current legislation, ships trading in the special areas, the so-called SECA (SOx Emission Control Areas), have been allowed to use fuel with maximum 0.1% since January 1st, 2015. Out of the SECA areas, the maximum sulphur limit has been reduced from 4.5% to 3.5% since January 1st, 2012 and finally it will come to 0.5% starting from January 1st, 2020. Nowadays the EU Directive 2005/33/EC imposes the use of fuels with sulphur content of less than 0.1% by weight to all ships at berth in harbours. There are also effective national regulations or initiatives that aim at reducing SO_2 emissions from ships, such as voluntary agreements at local scale in the Mediterranean Sea (Contini et al., 2015) and in harbours along the California coastline (Tao et al., 2013).

The impact of ship emissions is of global and local scale. The first concerns mainly emissions during the navigation phase. The contribution of maritime traffic to global emissions is estimated in 5.6 Tg of NO_X (as N) and 5.3 Tg of SO_X (as S) (Smith et al., 2014). In any case, there has been a reduction in terms of global GHG emissions from 2.8% in 2007 to 2.2% in 2012 (Smith et al., 2014).

Although local emissions are a small fraction of global transport emissions (Entec, 2002), they can have serious effects on human health, especially in coastal areas and port cities. About 70% of the ship emissions occurs within 400 km from the coast, and it contributes typically with 1–7% to the annual mean PM10 levels, with 1–20% to PM2.5, and with 8–11% to PM1 in coastal areas (Viana et al., 2014).

Therefore, numerous studies have been published with the aim of evaluating the emissions of ships in ports (Saxe and Larsen, 2004; Battistelli et al., 2012; Saraçoglu et al., 2013; Fan et al., 2016; Merico et al., 2017; Chen et al., 2017, 2018). Generally, there are two different approaches to estimating emission inventories: bottom-up and top-down. The bottom-up approach is much more accurate, but significant efforts need to be made for data collection and analysis, particularly for large-scale studies (Miola et al., 2009; Miola and Ciuffo, 2011; Berechman and Tseng, 2012; Smith et al., 2014; Tichavska and Tovar, 2015).

A complete bottom-up procedure includes the following steps: i) inventory of ships arriving and staying in port in the period of interest; ii) determination of the characteristics of ships; iii) determination/prediction of power released from engines on-board; iv) prediction of pollutants emission in port; v) determination of the impact on the environment by using a model to simulate the dispersion of pollutants in the atmosphere.

The first two steps are generally not problematic. Calendar of arrivals and departures are generally public. Data of ships (GT, Main Engine nominal power, length and so on) can be found in various specialistic databases.

Generally, for a ship in a port, two different phases are identified: maneuvering and mooring. The maneuvering mode, including slow cruising in port area, approaching/docking and departing, begins with the deceleration of the ship and ends at landing, restarting from the mooring and then ending when the speed is reached just outside the port's borders. Precise procedures consider separately the activities included in the maneuvering mode separately and evaluate the corresponding emission rates. The mooring phase corresponds to the time a cruise ship stays in port and provides hotel services on board to passengers and crew members. During this time the main engine (ME) is turned off and all power requirements are covered by auxiliary engines (AE) or, if the ship has a diesel-electric system, as usual for cruise ships, the ME works at limited load factor producing the energy required.

A comparative analysis of current methods for estimating energy consumptions and shipping emissions during navigation mode is reported by Moreno Gutierrez et al. (2015). Papaefthimiou et al. (2016) report the results of a bottom-up methodology based on in-port ships activity to calculate exhaust pollutant emission rates (NOx, SO2, and PM2.5) during moving, maneuvering and hoteling for international cruise ship journeys to and from 18 ports of Greece during 2013. De Melo Rodriguez et al. (2017) provide a regression analysis between emission indicators (CO2, NOX, SOX and PM) and independent variables (port time, passenger capacity and vessel GT). The analyses were performed (with surveys and interviews of cruise shipping companies) on 30 cruise vessels in the port of Barcelona by evaluating the load factor and working time of the thrusters, type of fuel used (HFO or MGO/MDO) and hoteling electric power (kW) used during berthing activity. The most appropriate indicators are: inventory emissions per port-time gross tonnage, port-time passenger and port time. These results can be applied to other ports as well.

In order to assess the impact of ship emissions on nearby urban areas, two different kinds of approach exist: experimental observations and numerical modelling of atmospheric dispersion. Some authors carried out monitoring campaigns on selected pollutants and applied data analysis techniques (e.g. source apportionment) to evaluate the contribution of each source (Pérez and Pey, 2011, Cesari et al., 2014). Particulate matter and heavy metals are generally adopted as tracer pollutants. A factor/source characterized by V and Ni is a typical factor associated with heavy oil combustion, including shipping (Viana et al., 2014; Bove et al., 2014). Among gaseous pollutants SO_2 is often indicated as tracer of ship emissions (Prati et al., 2015). However, the collection of monitoring observation followed by data analysis is a quite long and expensive procedure and does not always produce clear indications, due to the presence of other sources of pollutants such as: urban traffic, domestic and commercial heating, industry. Therefore, the use of dispersion models is more frequent. Many different dispersion models have been adopted (Saxe and Larsen, 2004; Merico et al., 2017; Chen et al., 2017, 2018; Fan et al., 2016; Saraçoglu et al., 2013). Gariazzo et al. (2007) used a Lagrangian particle model to assess the impact of harbour, industrial and urban activities on air quality in the Taranto area (Italy). Merico et al. (2017) have studied air quality shipping impact in the Adriatic/Ionian area focusing on four port-cities: Brindisi and Venice (Italy), Patras (Greece), and Rijeka (Croatia) and using a WRF-CAMx modelling system. Poplawski et al. (2010) have used CALPUFF model to investigate the impact of cruise ship emissions on level concentrations of fine particulate matter (PM2.5), Nitrogen dioxide (NO_2) and Sulphur dioxide (SO_2) in James Bay, Victoria, British Columbia (BC), Canada. The same model CALPUFF was used in order to assess the impact on local air quality due to atmospheric emissions of a new port in project in the Mediterranean Sea (Lonati et al., 2010).

A study of the impact of merchant ships with large size two-stroke diesel engines emission in the port of Naples is reported by Iodice et al. (2017). The aim is the development of a methodology to assess the impact of pollutant emissions from marine engines in manoeuvring mode and in fuel switch conditions from heavy sulphur residual fuel oil to low-sulphur distillate fuel oil. The authors use a steady state Gaussian model in long time version with a certain degree of approximation, as reported by the same authors. Their conclusion is that in the port of Naples NO2 and SO2 concentration levels may be affected by merchant ship emissions, albeit without a crucial percentage contribution. This outcome indicates that merchant ship emissions cannot constitute the sole source of air pollution in the port of Naples.

The aim of this paper is the assessment of the impact of cruise ship emissions in the port of Naples on air quality through a bottom-up procedure. Simulations are performed with CALPUFF and results are compared with field data. CALPUFF was preferred to a Lagrangian particle model because of the relatively simple orography of the calculation domain and to a WRF-CAMx modelling system because we aimed at obtaining a representation of horizontal spatial variation of pollutant concentration detailed up to street scale. Moreover, we consider the kinetics present in CALPUFF apt for the pollutants investigated.

2. Area investigated

2.1. Naples and its port

The city of Naples and its port were funded in IX B.C. in the East bay of the homonymous gulf. The Municipality of Naples with 970.185 residents is the third most populated city in Italy. It occupies 119,02 km^2 with a density of 8.151 inhabitants/km^2 (www.ISTAT.it). More than 3 million people live in the "Metropolitan Area" (Fig. 1) of 1 171 km^2 with a density of 2 649 inhabitants/km^2. The area includes several sources of risk for human health including common anthropic sources: road traffic, airport, port, industries; and specific natural sources like active volcanoes. Therefore, a study of the impact of each of these sources on human health is clearly very important.

The monitoring of air quality in the Metropolitan Area of Naples is guaranteed by a network of fixed stations of the Regional Agency of Environmental Protection (ARPAC) (Fig. 1). Equipment and measurement methods respect the standard established by European Community (2008/50/CE). No fixed stations are present inside the port area. In the last five years (2012–2016) limit values established by European Community (http://www.isprambiente.gov.it) to protect human health in urban areas have been exceeded by NO_2, PM10, Ozone and Benzene as documented by the Italian Institute for Environmental Protection and Research (ISPRA) in its annual report on the Quality of the Urban Environment.

In particular, for NO_2 the annual limit value of 40 μg/m^3 (Table 1) has been exceeded non-stop from 2012 to date, with values higher than 50 μg/m^3 in 2015, while the hourly limit (less than 18 exceedings of 200 μg/m^3 in the solar year) was exceeded only in 2015. The situation for SO_2 is better. In fact, due to reduction of sulphur content in fuels, emissions of this pollutant decreased, and EU limits in ambient air

Fig. 1. Up – Metropolitan area of Naples with fixed stations of Regional Air Quality Network (in yellow is the boundary of Municipality). Down - Map of the port of Naples with berthing areas. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
NO_2 and SO_2: limit values established by EC for the protection of human health.

Pollutant	1-h [μg/m³]	24-h [μg/m³]	Year [μg/m³]	Alert threshold [μg/m³]
NO_2	200[a]		40	400[d]
SO_2	350[b]	125[c]		500[d]

Maximum number of exceedances in one solar year: [a] = 18; [b] = 24; [c] = 3; [d] = 3 consecutive hours.

(Table 1) have never been exceeded since 2012.

The site of the port of Naples is very close to the urban area and to the East industrial area of Naples; it has 75 berths, a total length of about 11 km, an annual traffic of 5×10^5 TEU; 6×10^6 millions of passengers and 48,000 vessels. A map of Naples and its port is reported in Fig. 1 with the indication of docks for the various ship categories. From West to East there are terminals for hydrofoils and small ferries connecting the islands in the gulf of Naples, cruise ships, ferry boats, and finally commercial ships. Cruise ships make port at "Stazione Marittima" terminal including several berths; the terminal is only within 200 m of the nearest residential buildings. Terminals reserved to commercial ships are closer to the East suburbs of the town.

3. Methods

In this paper we analyze the 2016 field data measured at selected fixed stations and collected during a monitoring campaigns performed from January 20th to March 8th, 2016 (Murena et al., 2018). The fixed stations considered are inside the urban area (NA06, NA07) and in the surroundings (Acerra, Pomigliano d'Arco and Casoria) (http://www.arpacampania.it).

CALPUFF was adopted as model to simulate transport and chemical reactions in atmosphere of NO_x and SO_x emitted by cruise ships. The activities considered to calculate emissions in the atmosphere include: navigation in port - both arrival and departure; maneuvering for berthing and unmooring; hoteling at berth. Data of some stations (NA01, Pozzuoli, Portici) where analyzed to obtain information on background concentration of O_3 which is necessary to model atmospheric reactions of NO_x and SO_x.

3.1. Field data

A detailed map of all receptors corresponding to fixed stations and passive samplers inside the urban area, whose data have been analyzed for comparison with simulations, is reported in Fig. 2. NA06 and NA07 are receptors corresponding to fixed stations of the Regional Air Quality Network. Passive samplers used during the monitoring campaign from January 20th to March 8th, 2016 (Murena et al., 2018), located inside the urban area, are indicated with letters from A to Q. Receptors corresponding to passive samplers positioned inside the port area, due to the high spatial density, have been assembled in areas (P1-P2). Area P1 (12 receptors) includes terminals for high speed vehicles to close islands, cruise ships and big ferries. Area P2 (20 receptors) includes terminals reserved to commercial ships. Three receptors (BW1-BW3) were located at breakwaters and this area is indicated as P3.

Data on SO_2 from Regional Air Quality Network were not available in the urban area but only at stations in the surroundings (Acerra, Casoria, Pomigliano d'Arco) (Fig. 1). For this pollutant, data inside the port and the urban area were obtained by passive samplers used during the monitoring campaign lasted from January 20th to March 8th, 2016 (Murena et al., 2018).

Data from fixed stations were analyzed to obtain statistics of hourly average values (maximum and percentiles) and long time averages: period or year. Periods correspond to the duration of the monitoring campaign or to time interval of particular interest (e.g.; from June to September, months of maximum cruise ship traffic). Data from passive samplers gave only period averages.

3.2. Determination of the emission rate of atmospheric pollutants

Data on cruise ships traffic (arrival, departure and berthing time) in the port of Naples for the solar year 2016 were obtained by consulting the official site of the Port Authority of Naples (https://porto.napoli.it/). Then, each ship was characterized in terms of length, GRT, cruise speed (or max speed), overall power installed onboard and propulsion system using database furnished by specialized sites. The successive step was the determination of the power released from the engines onboard. In fact, emissions are strictly related to power produced by the engine. Even though the rate of power changes during the various phases when each ship is in port, the determination of the mean value of this power has been deemed sufficient. Indeed, the changes of power from engines working at fixed rpm can be considered as unimportant

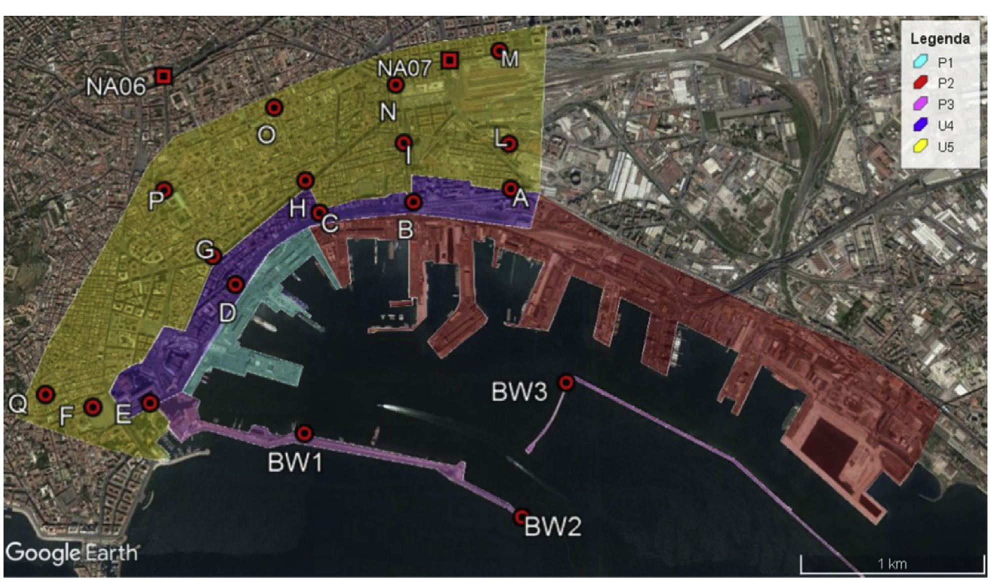

Fig. 2. Receptors inside the port and the urban area whose data were compared with simulations: monitoring areas and single receptors.

Table 2
Main parameters of three ships used to evaluate power rate during hoteling phase.

	Ship 1	Ship 2	Ship 3
Required power min [%]	9.4	9.7	12.8
Required power max [%]	19.0	15.6	20.4
Required power average [%]	11.7	11.8	15.0
Variance	1.8	1.8	2.3
Overall power [MW]	71.4	58	31.7
L [m]	333	294	275
V [kn]	22.9	23	21
number of data	267	265	271

Table 3
Summary of parameters adopted to evaluate emissions in arrival, departure and manoeuvring phases.

	Main Engines	Auxiliary Engines
Load Factors [%]	20	50
SFOC [g/kWh]	223	217
EF NOx [g/kWh]	9.9	13
EF SOx [kg/fuel ton]	20	

Manouvering times: 20 min (0.33 h).

and, therefore, can be neglected. With the method shown later, the reference overall power installed was considered as the overall electric power released by all the engines onboard in the DE systems (usual for cruise ships), or as the sum of powers from ME and AE for conventional propulsion power plants.

In order to evaluate the power rate during hoteling phase, real data of three ships have been used consisting of datasheets with more than 800 stops in various European ports, including Naples. For each ship and each stop available data include: i) overall installed power; ii) required power during the hoteling phase both in percentage of the overall power installed onboard, and in absolute terms; iii) overall time spent in port during stop (about 9 h in the port of Naples). In Table 2 all significant parameters related to these data are reported:

In order to predict the level of power released by each ship berthed in port during 2016, the average of the percentage of the overall power was evaluated from Table 2. This value is 12.9%. Such percentage is not deemed as varying significantly with size of the ship, and the same figure was used for all cruise ships.

The power released during the phase of arrival and departure, or navigation in port, has been considered as a sum of two components: power required for hoteling, that was considered as equal to the one released when the ship is effectively at berth; and power destined to the propulsion when the ship is in navigation in port using parameters reported in Table 3.

The evaluation of the propulsive power has been made by considering a "cubic" correlation between the power needed for the propulsion and the ship speed, supposed at 6 kn.

In considering the actual uncertainty in the determination of the power actually released by engines, for the maneuvering phase, the "reduced" EMEP-EEA method - i.e. using known values of total power installed onboard instead of applying the EMEP routine - has been implemented (also for transient states) by using both the load factors of the engines (ME and AE), and the EF. The time spent in maneuvering has been deemed of 20 min; the specific consumption of engines has been fixed by following the recommendations of the EMEP-EEA method.

With this routine the determination of power released by engines during both phases of navigation in port and maneuvering is less reliable, as compared to the method proposed for hoteling at berth. Moreover, the evaluation of the SFOC based only on the kind of engine without other characteristics, cannot be too accurate. However, results of the calculations and the simulation show that fuel consumption, power release and consequently emissions during phases of arrival/departure and maneuvering are considerably less important than during hoteling at berth. For this reason, the approximate figures coming from the application of the EMEP-EEA method at these phases, have been considered as sufficient for the scope of the work.

Overall the methodology proposed helped contain typical

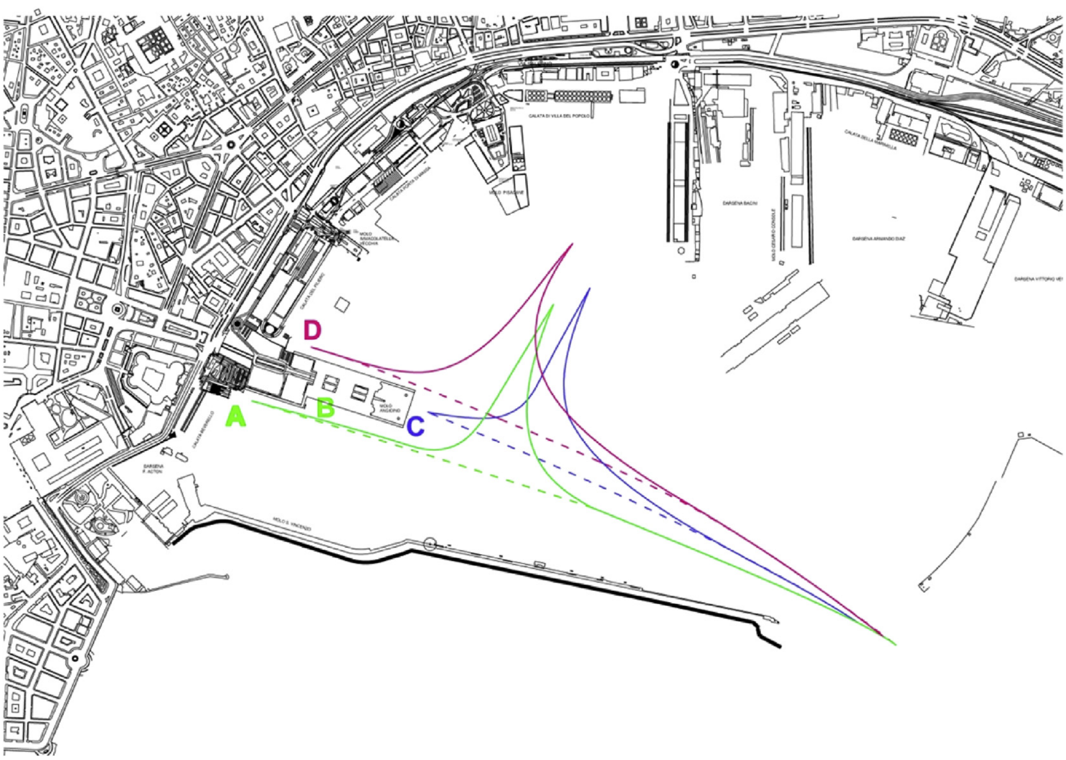

Fig. 3. Courses of navigation of cruise ship in port at arrival and departure (continuous line: arrivals; dotted lines: departures).

Table 4
Field data from fixed stations and monitoring campaign in 2016.

Period	Receptor		Period average		1-h maximum	
			NO_2 [μg/m^3]	SO_2 [μg/m^3]	NO_2 [μg/m^3]	SO_2 [μg/m^3]
Year	NA06	CA	44.0		178.6	
	NA07	CA	56.2		198.8	
	UP	CA	28.2	2.7	154.9	53.2
Jun–Sep	NA06	CA	39.5		149.7	
	NA07	CA	56.4		174.5	
	UP	CA	20.3	2.2	80.4	44.6
20 th Jan - 8th Mar	P1[a]	PS	7.87	3.46		
	P2[a]	PS	10.3	1.83		
	P3[a]	PS	6.57	7.23		
	U1[a]	PS	7.94	1.35		
	U2[a]	PS		1.23		
	NA06	CA	45.7		178.6	
	NA07	CA	53.3		155.8	
	UP	CA	36.5	2.4	124.7	9.5

CA = continuous analyser; PS = passive sampler.
[a] Murena et al., 2018.

Table 5
Data on traffic ships in the port of Naples compared with other ports.

Port	Reference period	Total tonnage	Cruise passengers	Total passengers	TEU
Naples	2017	22.396.568	927.458	6.684.772	509.876
Venice	2017	25.077.324	1.446.635	1.650.631	606.008
Genoa	2016	31.595.637	1.017.368	3.110.432	2.297.917
Barcelona	2017	60.070.134	2.712.247	4.136.999	2.968.757

uncertainties of EMEP-EEA procedure. The mere knowledge of the power installed onboard allowed to eliminate a first approximation of the EMEP-EEA method: indeed, this method suggests an exponential regression, based on the tonnage of the ship, that can supply the value of the power released by engines of passenger ships (without distinction among ferries, cruise ships, Ro-Ro pax, etc).

A second inaccuracy due to the EMEP-EEA method was by-passed: in fact, while it assumes the rate of power from generators in port as simply coincident with the 6% of the overall power installed onboard (thus always underestimating this value), the adopted method is based on real data and, therefore, more precise.

To evaluate the emission rates of SOx we have assumed a S content in fuel = 0.1% wt as established by the directive of 2015 (N22/2015) of the Port Authority of Naples that fixed at this level the maximum S content to be adopted for all ship activities in port and within at least two miles away from the port entrance.

3.3. Simulation model

Numerical simulations were performed by using the modelling chain composed by LANDUSE®, CALMET, CALPUFF and CALPOST. The orography in the calculation domain was evaluated by using the software LANDUSE®. The orographic file together with files containing hourly average values of meteorological parameters measured at Naples Airport of "Capodichino" (wind speed and direction; cloud height; sky cover; temperature; relative humidity; pressure; precipitation) and vertical profiles of wind velocity, direction and temperature are given in input to CALMET producing the 3D weather file.

CALPUFF (California Puff Modelling System) is a multi-layer, multi-species, non-steady state Lagrangian Gaussian puff dispersion model which can simulate the effects of temporally and spatially variable meteorological conditions from point, line, area or volume sources (Scire et al., 2000). CALPUFF contains modules for complex terrain effects, overwater transport, coastal interaction effects, building

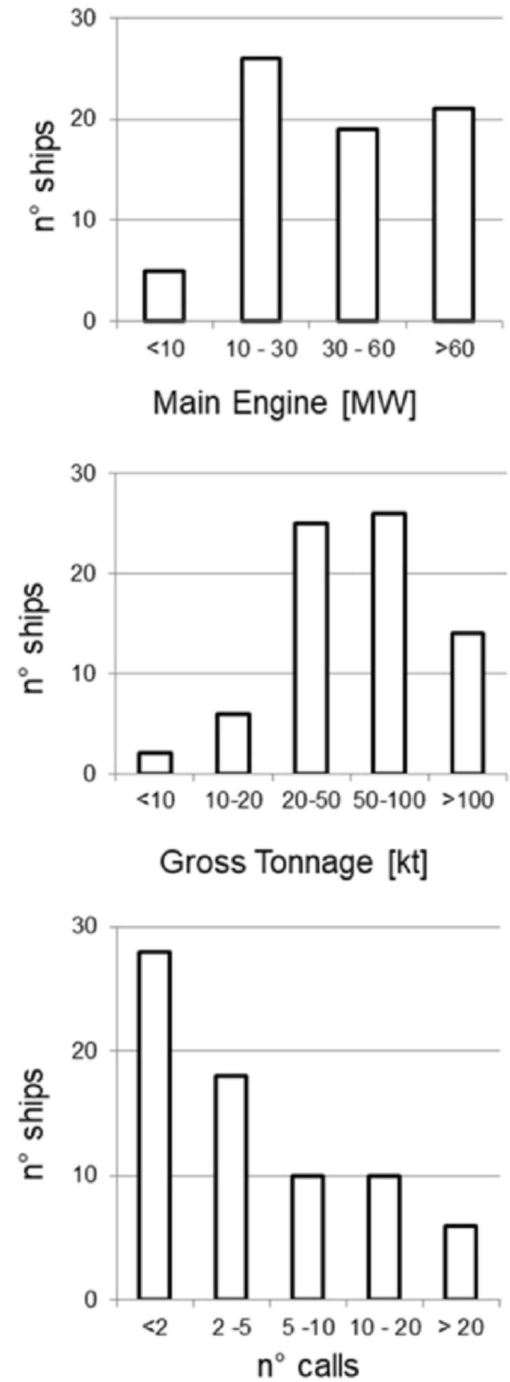

Fig. 4. Statistics of cruise ships fleet visiting the port of Naples in 2016.

downwash, wet and dry removal and simple chemical transformation. Input meteorological data for the CALPUFF model are the 2D and 3D fields of the main local meteorological parameters (such as wind speed and direction, atmospheric stability parameters, temperature, mixing layer height, and precipitation rate). Such input data are the output of the CALMET diagnostic meteorological pre-processor, that can simulate local effects like slope flows, kinematic terrain effects and sea breeze circulations. These latter effects can be reproduced only by running CALMET based on local meteorological input data and on a detailed description of the terrain properties in the simulation domain.

In this case meteorological fields for reference year 2016 were generated by CALMET model for an about 35 km^2 Cartesian grid centered on the port site and subdivided into a 36 × 24 cells grid system

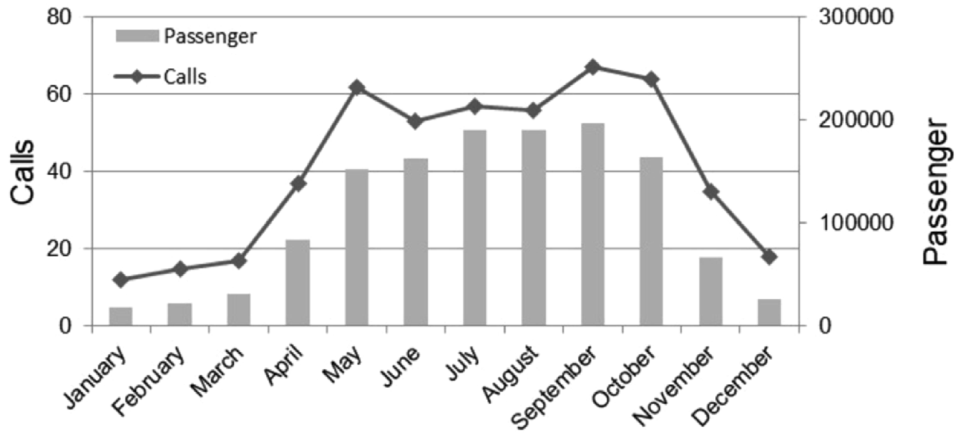

Fig. 5. Monthly variation of cruise ships calls and passenger traffic in 2016.

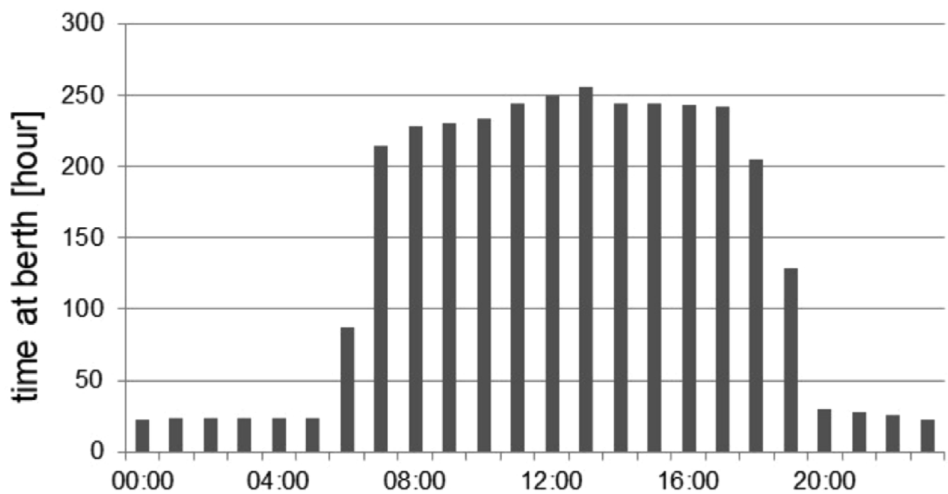

Fig. 6. Typical day of cruise ships time at berth in the port of Naples: year 2016.

with 200 m cell spacing; the CALMET vertical grid system considers 10 layers up to 3 000 m height.

In order to model the input of emissions in the calculation domain, 38 point sources (corresponding to ships funnel) have been defined: four in correspondence of each berth and remaining 34 were placed along the courses in port to simulate emissions during maneuvering and navigation in port. All ships are considered at berth by the bow (this is true for almost all cruise ships berthing in Naples). This means that the inversion maneuver is done during the arrival. Actual courses in port depend on the berth assigned (Fig. 3). Navigation in port is assumed at constant and very low steaming both at arrival and departure.

Data on funnel height from sea level and diameter are difficult to obtain for each cruise ship. Therefore, we have assumed the following average values: height from sea level 40 m, diameter 1 m and exit gas velocity 10 m/s (ARPAV, 2014).

The hourly variation of emission rates was input to the model creating a PTEMARB (Point Source Emissions File With Arbitrarily Varying Emissions) file according to detailed ship schedules for year 2016.

Chemical transformation module RIVAD/ARM3 was adopted to simulate chemical reactions of NO_x and SO_x in the atmosphere. The RIVAD/ARM3 module assumes that the conversion processes of NO into NO_2 and the NO_2 into NO_3 take place in equilibrium with gaseous HNO_3 and NH_4NO_3 in aerosol form (Morris et al., 1988). In RIVAD condensed pseudo-first-order chemical scheme, the rate of sulphate and nitrate production in gas-phase is estimated by calculating the concentration of hydroxyl radical, OH^-. Hydroxyl radical is the primary oxidizer of SO_2 and NO_2. In the RIVAD model a constant speed of heterogeneous SO_2 oxidation is equal to 0.2% per hour. This speed is added to the conversion speed of SO_2 into SO_4^{2-} in the gas-phase (Scire et al., 2000).

RIVAD/ARM3 requires average monthly concentrations of O_3 and NH_3 as input. Data for ozone are available from the air quality monitoring network. Measurements at stations NA1, Casoria, and Portici (Fig. 1) have obtained the following averaged monthly values in μg/m^3: 42.6 (Jan); 49.7 (Feb); 55.4 (Mar); 66.2 (Apr); 58.9 (May); 67.0 (Jun); 65.6 (Jul); 69.7 (Aug); 53.6 (Sep); 48.9 (Oct); 42.9 (Nov); 31.3 (Dec). Since field data for NH_3 were not available, default values have been assumed.

To check the reliability of results obtained with RIVAD/ARM3, CALPUFF was also run without chemical reaction module. In this case NO_x concentrations were converted to NO_2 using the Ambient Ratio Method (MoE, 2008). Results obtained with the two procedures were comparable. Therefore, the only results reported in the following paragraphs are the ones obtained with RIVAD/ARM3 module.

4. Results

4.1. Analysis of air quality data

To offer an insight on the air quality in the area of interest, concentrations measured at receptor points indicated in Fig. 2 are reported in Table 4 as period average and 1-h maximum values. Interval time of period averages correspond to: solar year 2016, high cruise traffic

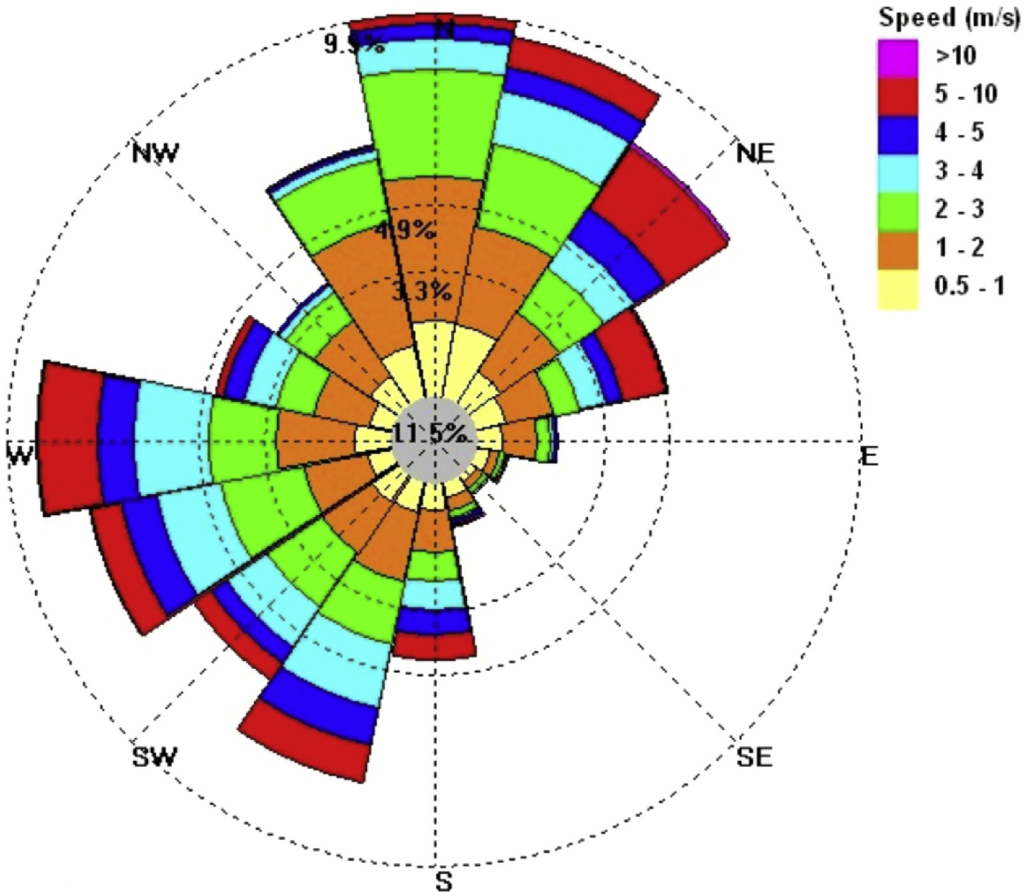

Fig. 7. Wind rose of meteorological file at h = 10 m in 2016.

Table 6
Annual emissions from cruise ships in the port of Naples in year 2016.

Activity	NO_x		SO_x	
	[t/y]	[%]	[t/y]	[%]
Navigation in port	6.09	1.45	0.18	1.29
Docking approach	2.02	0.48	0.08	0.57
Hoteling at berth	411	98.1	13.7	98.1
Total cruise ship	419	100	14.0	100

season (June–September) and duration of monitoring campaign: January 20th –March 8th. Values in correspondence of areas P1-P3 have to be interpreted as spatially averaged values, since they were obtained as average on all the passive samplers present in the area. Concentrations reported as urban periphery (UP) are the average of data collected at Acerra, Pomigliano d'Arco and Casoria stations (Fig. 1).

Year average limit value of 40 μg/m^3 for NO_2 (Table 1) is exceeded both at NA06 (44.0 μg/m^3) and NA07 (56.2 μg/m^3) while there is no exceeding of limit value of 200 μg/m^3 for 1-h averages. The limit of 40 μg/m^3 is exceeded also from June to September (56.4 μg/m^3 at Na7) and from Jan 20th to Mar 8th (45.7 μg/m^3 at NA06 and 53.3 μg/m^3 at NA7). Data of SO_2 are not available in NA06 and NA07. However, from other data reported in Table 2 and monitoring of previous years, it can be argued that this pollutant is largely below both the 1-h and the 24-h limit values (respectively 350 μg/m^3 and 125 μg/m^3).

4.2. Ship traffic data

In Table 5 the most recent data about traffics in the port of Naples are reported together with those of some representative Italian ports and of the port of Barcelona.

The fleet of cruise ships visiting the port of Naples in 2016 and object of this study is composed of 73 ships. Statistics of distribution in terms of main engine power (MW), gross tonnage (GT) and n° of calls per ship are reported in Fig. 4.

Cruise ships traffic depends on the seasons of the year as reported in Fig. 5. The activity is at a maximum from May to October with about 60 calls per month and a peak in September (67 calls). A medium activity is registered in April and November (about 36 calls per month), while minimum is in the period from November to April (about 15 calls per month). This evidence could have some consequences on the assessment of the impact on air quality due to the increment of hoteling emissions in Summer (Papaefthimiou et al., 2016).

The global time at berth in 2016 was 4 946 h. A typical day curve of time at berth is reported in Fig. 6. Cruise ships are at berth normally from 7 a.m. to 8 p.m. The average time at berth is about 13 h/day.

4.3. Meteorological conditions

Meteorology in Naples is characterized by breeze regime as in most coastal areas. Prevailing wind directions are from SSW-W especially during summer and from N-NE mainly in Winter (Fig. 7). The most frequent classes of wind velocity are: 1–2 and 2–3 m/s. The occurrences of wind direction from E to SSE are rare. Considering that the urban area is mainly located downwind of port in the directions from W to N (Fig. 1) actual typical wind directions minimize the impact of ship emissions on the urban area.

4.4. Cruise ship emissions

Annual and seasonal emissions of cruise ships were evaluated both

Fig. 8. Simulations: maps of year average [μg/m^3]: up NO_2, down SO_2.

for NO_x and SO_x by applying the methodology reported in the previous paragraph (Table 6).

The partition of annual emissions among the different activities is: hoteling at berth (98.1%), navigation in port (1.45%) and dock approaching (0.48%) for NO_x. For SO_x they are respectively 98.1%; 1.29% and 0.57%. As reported by other authors emissions during hoteling represent the largest part of total emissions in port. As an example Papaefthimiou et al. (2016) evaluate emissions of NO_x and SO_x, due to cruise ships at hoteling, equal to 89.2% of total emissions as average values of several Greek ports. The very high percentage of emissions due to hoteling phase reported in Table 6 depends also from the limited distance (about 2 km) from port entrance to docks that minimizes emissions due to navigation in port.

Total emissions were evaluated also using other methods (De Melo Rodriguez et al., 2017; Papaefthimiou et al., 2016) to verify the correctness and reliability of the methodology adopted.

To calculate emission rates on the basis of the procedure of De Melo Rodriguez et al. (2017) the following emission indicators were used: 1.68 gNOx/h-GT and 1.50 gSOx/h-GT, considering 85% for the hoteling phase and 15% for the maneuvering phase. To evaluate emission rates following the procedure proposed by Papaefthimiou et al. (2016) we applied to our data the ratio auxiliary engine power/main engine power (AE/ME) = 0.278. During hotelling load factors of AE are assumed as 0.60 and 0.30 respectively in Summer and the rest of the year. During maneuvering load factors are: 0.20 for ME and 0.75 or 0.60 for AE respectively on summer and during the rest of the year. Therefore, this procedure consider the variability of emission factors with the season of the year.

Since De Melo Rodriguez et al. (2017) and Papaefthimiou et al. (2016) assumed in their studies, respectively, S = 3% wt and S = 1.5% wt ìn fuel, we have modified the emission calculated with their procedures to consider the directive (N22/2015) of the Port Authority of Naples fixing as maximum S = 0.1% wt.

Annual emissions evaluated are therefore: NOx = 687 t/y and SOx = 19.4 t/y according to De Melo Rodriguez et al. (2017); NO_x = 352 t/y and SO2 = 7.3 t/y according Papaefthimiou et al.

Fig. 9. Simulations: maps of 10th maximum value of 1-h average [μg/m^3]. Up NO_2, down SO_2.

(2016).

Emissions calculated with De Melo Rodriguez et al. (2017) procedure are always higher than ours for factors: 1.64 for NOx and 1.39 for SO_x. On the contrary, those calculated with Papaefthimiou et al. (2016) procedure are lower for factors: 1.19 for NO_x and 1.92 for SO_x. These differences show the uncertainties inherent to such calculations. Uncertainties that we have tried to reduce by using real data as reported in the paragraph "Methods".

4.5. Modelling simulations

Contour maps of annual average modelling simulations for both NO_2 and SO_2 are reported in Fig. 8. Direction of the impact for year average is strictly related to the wind rose diagram in Fig. 7 and land orography. In fact areas of maximum concentration are along NE-E and SW directions from cruise terminal. The area of maximum impact of NO_2 is inside the port area (toward commercial ships terminals) and in the industrial area at east of the centre of Naples. However the urban area is also interested by a noticeable impact. Anyway values are well below the limit of 40 μg/m^3 as annual average for NO_2 (Table 2). Map of SO_2 shows some differences due to the different chemical reactions occurring in the atmosphere. The maximum happens next to emission sources. The difference in absolute values is mainly due to different emission rates between the two pollutants (Table 4).

To show the impact at short averaged time (1-h) contour maps of modelling simulations of 10th maximum value of 1-h average of NO_2 and SO_2 are reported in Fig. 9. As expected, the values are much higher than those reported in Fig. 8. Again the maximum is inside the port area. But a large part of the town is affected by possible high contribution to 1-h averaged concentration both for NO_2 and SO_2.

To verify the effect on surface concentrations if a different estimation procedure of emission rates was adopted, simulations were repeated by giving emission patterns deriving from procedures of De Melo Rodriguez et al. (2017) and Papaefthimiou et al. (2016) in input. Results are coherent with the differences in emission rates previously reported. In performing simulations with the procedure based on data by

Table 7
Contribution of cruise ship emissions to actual concentration levels – Period average.

Period	Area/ Receptor		Monitoring		Cruise contribution	
			NO_2 [μg/m^3]	SO_2 [μg/m^3]	NO_2 [%]	SO_2 [%]
2016	NA06	CA	44.0		0.74	
	NA07	CA	56.2		2.47	
	UP	CA	28.2	2.74		
Jun–Sep 2016	NA06	CA	39.5		1.17	
	NA07	CA	56.4		3.58	
	UP	CA	20.3	2.24		
20 th Jan – 8th Mar 2016	P1[a]	PS	7.87	3.46	2.65	0.89
	P2[a]	PS	10.3	1.83	6.10	1.53
	P3[a]	PS	6.57	7.23	6.06	0.62
	U1[a]	PS	7.94	1.35	2.78	1.00
	U2[a]	PS		1.23		1.46
	NA06	CA	45.7		0.27	
	NA07	CA	53.3		1.33	
	UP	CA	36.5	2.38		

CA= continuous analyser; PA = passive sampler.
[a] Murena et al., 2018.

Table 8
Contribution of cruise ship emissions at NA07 for NO_2 1-h peak concentration (C > 99° percentile).

Period	Receptor	99°	Maximum cruise contribution	Average cruise contribution
		[μg/m^3]	[%]	[%]
Year	NA7	133	86.2	3.65
Jun–Sep	NA7	140	86.2	5.18
Dec–Mar	NA7	130	1.77	0.10

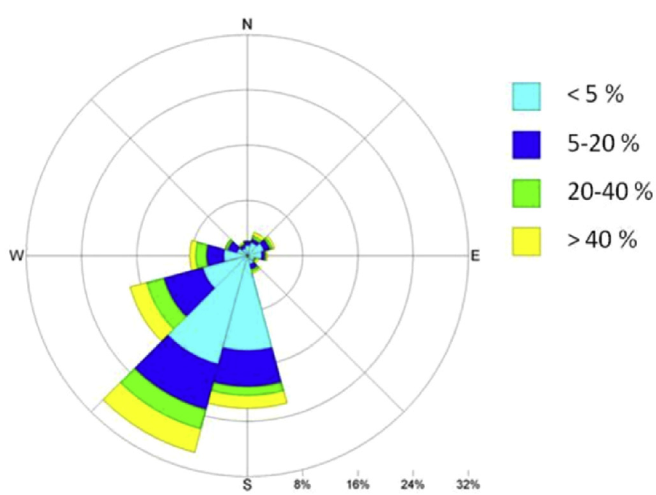

Fig. 10. Distribution of SC% occurrences of NO_2 at NA07 in 2016 (occurrences with SC% < 0.1% are not considered).

Papaefthimiou et al. (2016), we observed that the map of 1-h average concentration showed some peaks higher than those obtained with our method, even though total emissions evaluated with our methodology are higher than those obtained with data of Papaefthimiou et al. (2016). This is due to the dependence of emission from season that Papaefthimiou et al. (2016) have considered and we have not. As a matter of fact, during Summer, emissions in hoteling phase are larger due to higher electrical consumption for air conditioning. This observation, together with the fact that during Summer cruise traffic is at a top (Fig. 5) indicates that seasonal variation of emission factors should be taken into higher consideration.

4.6. Comparison of simulations with experimental data

To assess the contribution of cruise ship emissions to actual air quality concentration levels, surface concentrations calculated by simulation models are compared with those obtained from field measurements and the impact of cruise ship emissions on the air quality is expressed through a relative contribution calculated as percentage of actual concentration by the formula:

$$SC\%_{ij} = \frac{C_{sij}}{C_{mij}} \tag{1}$$

where *SC%* is the percentage of surface concentration due to cruise ship emissions; C_m is concentration measured and C_s is concentration obtained by simulations. Indices i and j correspond to pollutant *i* and averaging time *j*. Merico et al. (2017) in order to estimate shipping contribution over the Central and Eastern Mediterranean pollutant concentrations (surface concentrations) used the same formula but compared results of simulations with and without ship emissions.

First we compared the results corresponding to period average (Table 7). For NO_2 cruise contribution depends on the average period considered and on the location of the receptor (distance from source). At NA06 and NA07 maximum contribution is observed from June to September: 1.17% at NA06 and 3.58% at NA07. This was expected, since the period corresponds to maximum calls per month of cruise ships (Fig. 5). With respect to distance, the data of monitoring campaign from January 20th to March 8th (Murena et al., 2018) show that maximum contribution is observed inside the port area (6.10% at P2) but not in the area closest to cruise docks (2.65% at P1). This is due to the combined effects of prevailing winds from SW (Fig. 7) and atmospheric reactions converting NO to NO_2. A high contribution is observed also at breakwaters area (6.06% at P3) probably due to emissions during navigation in port. Lower contributions are observed, in the same period, inside the urban area (2.78% in U1; 1.33% at NA07 and 0.27% at NA06). In all three periods examined contribution at NA07 is always higher than at NA06. Once again the reason is the prevailing wind from W-SSW.

For SO_2 there are less data. The main difference with NO_2 is that contributions of ship emissions at receptors in port area are not higher than in the urban area. This could depend also upon the very low concentration measured in the urban area (1.35 μg/m^3 and 1.23 μg/m^3 at U1 and U2 respectively). On considering short averaging time data (1-h) it is interesting to evaluate the contribution of ship emissions when high concentration levels are measured. For this reason 99° percentile of NO_2 of 1-h concentration measures was evaluated at NA07 (the most impacted receptor in the urban area by NO_x emissions of cruise ships) for different periods: solar year; months of high traffic of cruise ships (June–September) and months of minimum traffic (January–March and December). Then SC% was evaluated for each hour when 1-h concentration is higher than 99° ($C_{mNO2} > 99°$). Maximum and average SC% were than reported in Table 8. As shown 99° of NO_2 is 133 μg/m^3 in solar year and for $C_{mNO2} > 99°$ maximum SC% was 86.2%, while average SC% was 3.65%. Table 8 shows that only in few days in the year can the cruise ships emission contribution be significant to determine high concentration levels of NO_2 but on average their contribution is limited. Similar results are obtained by considering the maximum cruise ships calls period (June–September). The 99° percentile is 140 μg/m^3 the maximum SC% was the same = 86.2% while average SC% = 5.18% is higher than that observed in the whole year. Interestingly, in the months of minimum cruise ship traffic SC% both maximum and average are very low (1.77% and 0.10% respectively). As a conclusion, maximum average SC% occurs in Jun–Sep and minimum in Dec–Mar, in accordance with cruise

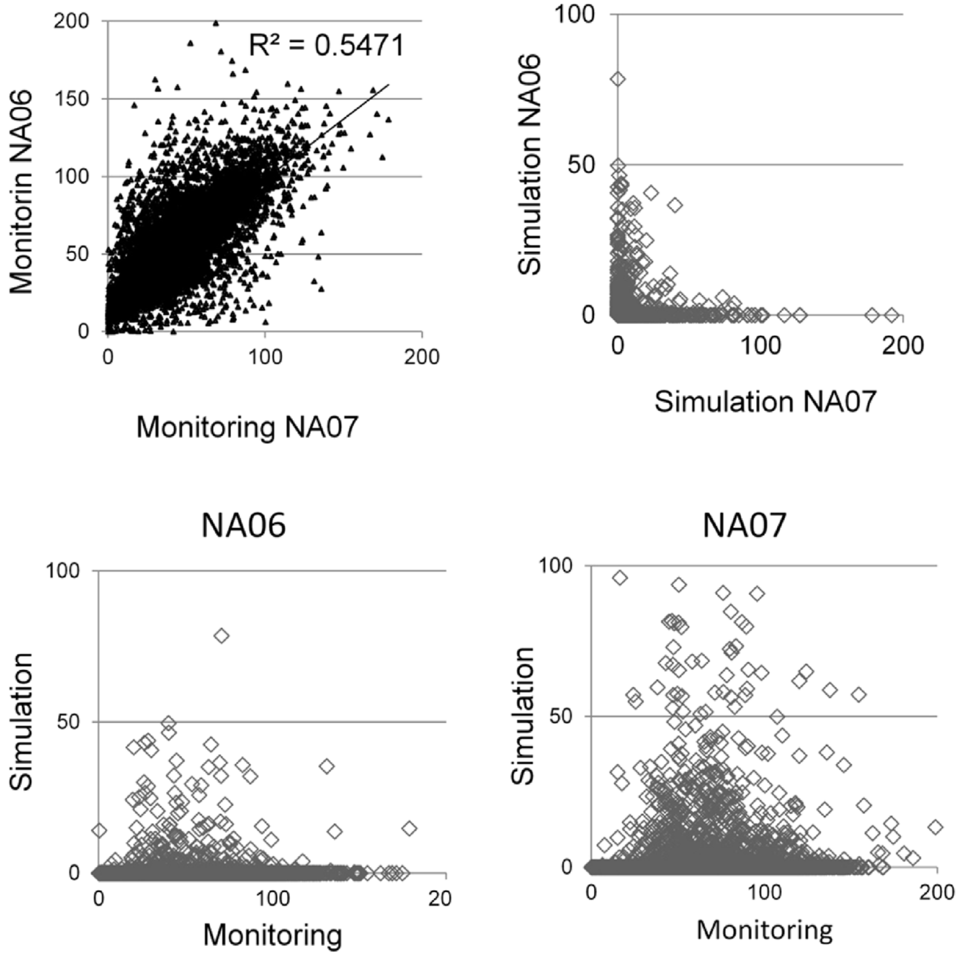

Fig. 11. Correlations between 1-h NO_2 concentrations. Up correlation between NA6 and NA7: left monitoring data; right simulations. Down correlations between monitoring and simulations: left NA6; right NA7. All values are concentrations in μg/m^3.

ship traffic (Fig. 5). Due to the absence of data the same analysis was not possible for SO_2.

Cruise ship emissions contribution at NO_2 concentrations in the urban area depends on wind direction. In Fig. 10 1-h SC% occurrences in the year at NA7 are plotted as function of wind sectors. Data with very low SC% (SC% < 0.1%) representing the majority of the cases (87%) have been excluded from the analysis because they are of no interest. In the remaining hours it is evident that significant contribution occurs only when the wind blows from sectors S to W, namely when NA07 is downwind of cruise terminals. When the wind blows from other sectors the contribution of ship emissions to hourly average concentration at NA07 is negligible.

Other information about the contribution of cruise ship emissions to actual concentration levels can be obtained by an analysis of correlation of data at NA06 and NA07 in 2016. Fig. 11 shows that there is a rather good correlation among NO_2 data measured at NA06 and NA07 in the year (R^2 = 0.55). This is an indication that the main source, or sources, of NO_2 at these receptors must be the same. On the contrary, a low correlation of NO_2 concentrations obtained by simulations at NA06 with those obtained at NA07 is observed: diagram in the upper right corner of Fig. 11. As a consequence low correlations between measured and simulated NO_2 concentrations at NA06 (down left) and NA07 (down right) are observed. This proves that cruise ships emissions are not a main cause of NO_2 measured at NA6 and NA7.

Cruise ship contributions on air quality reported in Table 7 are generally lower than those reported in literature. The ship emission contribution for NO_2 surface concentration evaluated by Merico et al. (2017) is 16.7–32.5% for Brindisi and 2.8–9.1% for Venice in January and July respectively. For SO_2 the contribution is: 23.5–46.3% in Brindisi and 5.2–16.5% in Venice. Similar results are reported by the same authors for other Mediterranean ports. Such differences with our results have several reasons: i) in our study we have considered only cruise ship emissions; ii) the city of Naples has about ten times more residents than Venice and Brindisi. Therefore, has higher emissions from other sources (e.g.; road traffic); iii) with respect to SO_2 Merico et al. (2017) calculated emission factors for SO_2 assuming 0.1% wt of S content in fuel for hoteling phase and different values in maneuvering phase for passenger ships (1.5%) and for all other ship typologies (3.5%).

Another consideration concerns the meteorology. As showed by the wind rose in Fig. 7 the urban area of Naples is rarely downwind of the cruise terminals. In fact when wind blows from W to NE pollutants are mainly transported on the sea, which happens for more than 50% of hours in the year. Calm wind represent about 11.5% of the observations. Therefore, pollutants emitted by cruise ships are transported toward the urban area only for about 35% of hours. This is a very different situation with respect to that reported, for example, by Poplawski et al. (2010) for Victoria BC (Canada), where the monitoring station analyzed is generally downwind of the port during the cruise ship season. As a consequence in Victoria BC (Canada) cruise ships contributed for 57% to the maximum predicted 1-h NO_2 and for 84% to the maximum predicted 24-h SO_2 at about 500 m downwind to berth. Furthermore, for SO_2 they assume S% = 1.6% wt in fuel.

On the contrary, Saxe and Larsen (2004) in their modelling study in the Danish port of Elsinore, Copenhagen observed that ship emissions do not significantly contribute to SO_2 in populated areas. In that case they assumed cruise ships using fuel with 0.5%wt sulphur content.

5. Conclusions

The results of the present study supply a significant insight of the impact of cruise ship emissions to air pollution in Naples by comparing simulation results with data collected by fixed stations and also with those from a monitoring campaign. Even though our results do not represent the whole impact of ship emissions of the port of Naples, cruise ships are responsible of an important fraction of total emissions. In fact, as inferred from preliminary calculations, emissions of NOx and SOx of all other passenger ships are lower for at least one order of magnitude of corresponding cruise ship emissions, and the additive effect on ground level concentration due to merchant ship emissions is probably limited because respective terminals are distant.

While considering the year averages, cruise ships contribution seems limited but non negligible. In correspondence with fixed station NA07, placed at about 2 km in NE direction from the cruise ships terminal, the contribution to year average is estimated at 2.47% for NO_2. It reaches the value of 3.58% if the period of maximum cruise ship traffic (Jun–Sept) is considered. Higher contributions are observed inside the port area (6.10% at commercial ships terminals). When short-time averages are analyzed, the contribution of cruise ship emissions on pollutant concentration levels can be significantly high. In particular, if 1-h peak concentrations are considered (values > 99° percentile) the contribution can reach 86.2% but on the average it is 5.18% during high season (Jun–Sept) and 3.65% in the solar year.

The contribution of cruise ship emissions to SO_2 actual concentration is lower than NO_2 ($\approx$1%) for long time averages. The low contribution to SO_2 concentration may be due to the low S content of fuel (0.1% wt) to be used by all ships inside a distance of minimum 2 miles from the port of Naples as a consequence of a directive of the Port Authority.

An analysis of correlation between field data and simulations for NO_2 at monitoring stations NA06 and NA07, shows a good enough correlation among field data and a low correlation between field data and simulations. This is another indication that contribution of NO_2 emissions from cruise ships is limited inside the urban area of Naples at least at a distance of about 2 km in N-NE direction.

In the interpretation of the results presented, the uncertainties of the whole procedure should be taken into account. The first concerns the exact evaluation of emission rates of each pollutant. Even though we have used real data to evaluate the actual power applied during hoteling phase, much information is necessary to asses actual emission rates for each pollutant and each ship with good accuracy. As a matter of fact, when comparing our estimates with those of other authors NO_x emissions could have been underestimate for a factor of 1.64 while SO_x for a factor of 1.39 (De Melo Rodriguez et al. 2017). On the contrary, the same comparison with other authors (Papaefthimiou et al., 2016), gives an overestimation of a factor 1.19 for NO_x and of 1.92 for SO_x.

Ships maneuvering is characterized by unsteady state working condition of the engines and as a consequence emission factors of exhaust gases can vary significantly from those measured at steady state (Winnis and Fridell, 2010). This is another source of uncertainty that should better be considered, although the reduced time of the maneuvering phase, reduces the error in evaluating ship emissions in port.

Finally, in order to have a more precise knowledge of the impact of ship emissions in the port of Naples on air quality, it is necessary: i) to extend the study to other pollutants mainly PM and to all the categories of ships; ii) to reduce uncertainties in the evaluation of emission rates for each pollutant through a thorough knowledge of engine load in the different phases of activity in port; iii) to better model dispersion by considering as accurately as possible the geometry of the urban canopy with the mass exchange in correspondence of each street canyon; iv) to consider the formation of secondary pollutants as well. These activities will be the object of future researches of the group.

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