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ASSESSMENT OF SOURCE CONTRIBUTION TO AIR QUALITY IN AN URBAN AREA CLOSE TO A HARBOR: CASE-STUDY IN PORTO, PORTUGAL

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Abstract

Several harbors, like the Port of Leixões (Porto, Portugal), are located near urban and industrial areas, places where residential urban areas, highways and the refinery industry coexist. The need for assessing the contribution of the port to the air quality in its vicinity around the port is the motivation for the present study. This contribution was investigated using a numerical modelling approach based on the web-based research screening tool C-PORT. The impact of the meteorological conditions (namely atmospheric stability and wind direction) was first evaluated, and the most critical conditions for pollutants dispersion were identified. The dominant wind direction, from WSW, was responsible for the transport of pollutants over the surrounding urban area, which was potentiated by the diurnal sea breeze circulation. Multiple scenario runs were then performed to quantify the contribution of each emission sector/activity (namely maritime emissions; port activities; road traffic and refinery) to the ambient air quality. The multiple scenario runs indicated that land-based emission sources at the Port (including trucks, railways, cargo handling equipment and bulk material stored) were the major contributors (approximately 80 %) for the levels of surface PM10 concentrations over the study area. Whereas, the main drivers of NO_X concentrations were docked ships, responsible for 55-73 % of the total NOx concentrations.

Key words: ship emissions, source contribution, air quality, dispersion modeling, port areas

1. INTRODUCTION

Ports are a critical feature of the world’s economy. Ports serve as critical hubs for the continual flow of agriculture, energy and consumer products from coastal communities to the inland areas (APA, 2016). Despite the economic benefit they provide, activities associated with port operations are also an environmental concern with potential effects on local climate, the weather, human health and ecosystems (Lonati et al., 2010, Rosenbaum et al., 2011).

As multi-modal transportation hubs, ports can be significant sources of air pollution due to the maritime transit, manipulation and storage of materials in bulk and containers, and due to land transport associated with these activities which produce a significant release of atmospheric pollutants that can cause air quality problems (Alastuey et al., 2007, Moreno et al., 2007, Almeida et al., 2012).

Port emissions affect the residents of neighboring communities, especially sensitive population groups, including children and old people (Zhou and Levy 2007, Corbett et al., 2007, Kozawa et al., 2009, Matsuoka et al., 2011, Arunachalam et al, 2015).

In several ports located in Europe, studies have shown that the primary air pollution concern is emissions from dust and fumes that occur from everyday operational activities in harbors (Pérez et al 2016, Tian et al., 2013, Corbett et al. 2007). Despite strict measures to reduce air pollutants, several European countries still face air pollution episodes regularly exceeding the established legal limits values. Europe's most troublesome pollutants regarding human health are particulate matter (PM), nitrogen dioxide (NO_2) and ground-level ozone (O_3) (EEA, 2016). The majority of EU member states, mainly in urban agglomerations where human exposure is also higher (EEA, 2016), have reported exceedance of the NO_2 thresholds. The annual NO_2 limit value continues to be widely exceeded across Europe, with around 10 % of all the reporting stations recording concentrations above the standard limit in 2015 in 22 countries out of the EU-28 (EEA, 2016). In Portugal, over the last few years, air quality problems have been detected, particularly concerning PM10 (Monteiro et al., 2007; Borrego et al., 2011) and NO_2 in the northern region (Borrego et al., 2012).

According to the European Sea Ports Organization (ESPO, 2013), the top environmental priority for seaports is the local air quality, focusing on the health of the workers and nearby residents. With the projected increase of shipping activities, air quality in and around ports is gaining emphasis, especially for ports surrounded by high-density residential areas. Improved knowledge on this type of emissions remains scarce and there are relatively few monitoring and experimental data available to quantify the contribution of ship emissions to local air quality (Isakson et al., 2001; Sorte et al., 2018; EC, 2005). Since emissions from harbor-related activities can have a significant impact on air quality, the study of microclimate conditions and resulting pollutant dispersion patterns in port areas was of the utmost importance. Coastal areas, where harbors and city ports are located, experience specific meteorological patterns, like sea and land breeze phenomena, playing an important role in the dispersion, transformation, removal or accumulation of air pollutants (Baumgardner et al., 2006).

According to the “Shipping Emissions in Ports” report, issued by the International Transport Forum (ITF), shipping emissions in ports accounted for 0.4 million tons of NO_X, 0.2 million tons of SO_X and 0.03 million tons of PM10 worldwide during 2011. Around 85 % of the emissions come from container ships and tankers. Although container ships have short port stays (few hours to a few days), their emissions are very high (Merk, 2014). Approximately 230 million people are directly exposed to shipping emissions in the top 100 world ports (Merk, 2014). These emissions have increased at a large pace over the last few decades and are expected to continue to increase further in the near future.

Data from the Los Angeles County Health Survey revealed that Long Beach communities near the Ports of Los Angeles and Long Beach (two large ports right next to each other and ranked top 2 in the U.S.) experience higher rates of asthma (2.9 % on average), coronary heart diseases and depression, compared to other communities in Los Angeles (HIP, 2010). Additionally, the California Air Resources Board attributed 3,700 premature deaths per year to port activities and shipment of goods (Sharma, 2006). On a global scale, calculations suggest that shipping-related PM emissions are responsible for approximately 60,000 cardiopulmonary and lung cancer deaths every year, with most deaths occurring near coastlines in Europe, East Asia and South Asia. These data show the impact of ports on air quality and human health. Thus, it is of absolute importance to study the dispersion behavior of pollutants in the vicinity of ports, so adequate minimization measures can be taken.

Several studies have tackled the contribution of ships to the local air quality using different approaches. It has been investigated using models with a specific focus on atmospheric aerosol (Gariazzo et al., 2007; Marmer et al., 2009); or using experimental analysis at a high temporal resolution (Contini et al., 2011; Diesch et al., 2013; Donateo et al., 2014); or even using receptor models based on the identification of chemical tracers associated with ship emissions (Viana et al., 2009; Cesari et al., 2014; Bove et al., 2014). Although the potential impact of ship emissions on air quality is known from model studies at a more aggregated level, the knowledge based on the attribution of local air quality problems to ship emissions in areas close to shipping lanes is rather limited, and there is a clear need to improve the observation-based knowledge.

To help community groups assess the impacts from port activities, researchers at the University of North Carolina’s Institute for the Environment (UNC-IE) in collaboration with the U.S. Environmental Protection Agency (EPA) have developed a research grade-screening tool for near-port assessments. The Community screening tool for near-PORT (C-PORT) assessments (Isakov et al., 2017) is designed to provide a platform for air-quality modeling and visualization that can inform users about potential local air quality impacts in the vicinity of ports (Arunachalam et al., 2015) in the U.S.

This paper presents a case study for assessing the relative contribution of various sources such as port activities, shipping emissions, roadway traffic and industry to air quality near the Port of Leixões, in northern part of Portugal. In this study, we expanded the C-PORT tool, which was initially focused on U.S. ports alone. Thus, this work presents the first case study for ports outside the U.S. This tool allowed the assessment of the air quality impact for different types of emission sources to be considered when simulating dispersion of pollutants in port and adjacent areas. One relevant feature of the different emission sources is their height of release, which causes different patterns of pollutant dispersion in port areas. Area sources or roads and rails (line sources) emit typically at ground level, while (some) point sources and ships-in-transit (line source) emit typically at greater heights, leading to plume rise. Special attention was given to the critical pollutants monitored in the study region, namely NO_X and PM10, which have been the focus of air quality plans due to the continuous exceedances measured in the last years.

Section 2 describes the case study, including local meteorological and air quality characterization. The modelling approach (based on C-PORT tool) is presented in Section 3, together with modelling setup and input data description. The main results are presented in Section 4, while Section 5 provides the main conclusions.

2. THE LEIXÕES PORT CASE STUDY

The Port of Leixões has become a crucial point for Europe's shipping lines. Due to its geographic location, it is one of the main operation centres in Portugal. This port is situated in the northern part of Portugal, in the North-West corner of the Iberian Peninsula, about 2.5 km north of the River Douro and near the city of Porto, being surrounded by the towns of Leça da Palmeira (to the North) and Matosinhos (to the South). Matosinhos and Leça da Palmeira belong to the metropolitan Porto area, with 130,984 inhabitants and 18,502 inhabitants, respectively (INE, 2011).

Representing 25 % of the Portuguese foreign trade by sea and moving 16.4 million tons of goods per year, Leixões is mainly an export port, serving virtually all types of ships and cargo, as well as cruise ships. With 5 km of quay, 55 ha of embankments and 120 ha of wet area, Leixões is equipped with the most updated information systems for vessel traffic control and management. In Figure 1, the simulation domain of C-PORT is shown, with the identification of the main emission sources (industrial; port and road) and monitoring (meteorological and air quality) stations.

It is worth noting that the simulation domain comprised another source of emissions that may affect air quality in the studied area. This source was a refinery facility with distillation capacity around 4.4 $Mt.year^{-1}$ (second largest in Portugal), located north of the Port of Leixões and connected to the tanker terminal by several pipelines of approximately 2 km length.

Figure 1. Geographical/simulation domain of the study area of Porto of Leixões, with the locations of the port terminals, refinery and surrounding urban area.

The following section details the meteorological and air quality characterization that was performed for the study area, based on monitoring data.

2.1. Meteorological characterization

There were two meteorological monitoring sites in the study region, including an onsite meteorological station located inside the harbor (see Figure 1). Wind roses for this onsite station, for a 3-year period from 2014 to 2016, are shown in Figure 2.

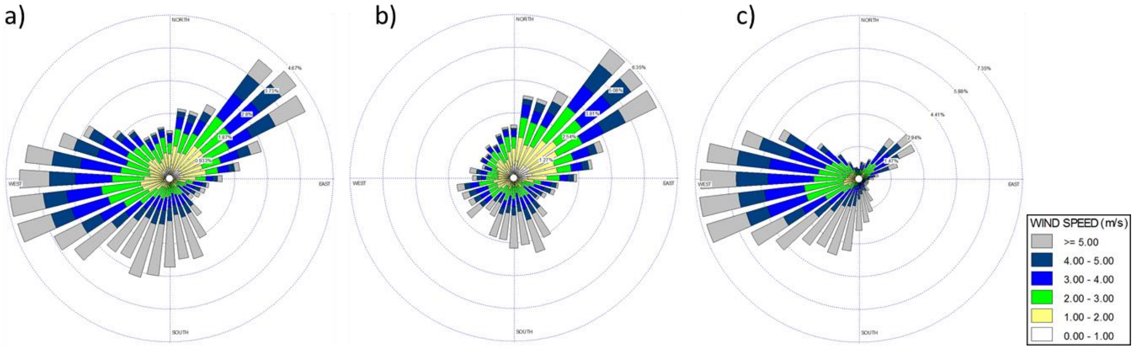


Figure 2. Wind roses for the onsite meteorological station during a 3-year period (2014 to 2016) considering a) all hours, b) nighttime hours: 00 a.m. to 9 a.m., and c) daytime hours: 10 a.m. to 8 p.m.

The presence of local sea/land breeze features can be clearly seen in the wind roses for daytime and nighttime periods (Figures 2b to 2c). The most common wind patterns showed a diurnal pattern, with winds blowing from the West – Southwest quadrant (from ocean to land) during the daytime and from Northeast wind (from land to ocean) during the nighttime. This diurnal pattern suggested that pollutant concentrations over the urban area close to the Port of Leixões would be higher during the day, but pollutants emitted from the port during nighttime were expected to be dispersed and transported over the sea. The pattern of dispersion of pollutants emitted during the nighttime and daytime periods was different due to differences in wind speed and stability. Higher wind speeds were typically experienced during the daytime.

Atmospheric stability conditions played a crucial role in understanding the air quality impacts of port activities and will be discussed further below.

2.2. Air quality characterization

There were three monitoring stations, part of the monitoring network maintained by the Portuguese Environmental Agency (http://qualar.apambiente.pt), located inside the study domain: 1) Seara; 2) João Gomes Laranjo; and 3) Custóias, as shown in Figure 1. These stations continuously measure hourly data for the main atmospheric pollutants (PM10, SO_2, NOx and CO). QualAr database provided continuous measurements based on 1 h averages with data registry every 15 min. Air quality monitoring stations were placed according to specific legislation to guarantee the representativeness of the Portuguese territory. Besides these stations, PM10 concentrations measurements were made inside the Port (for the 4-year period from 2013 to 2016). All these air quality monitoring sites were highlighted in Figure 1.

The 95% confidence intervals for the annual average of PM10 and NO_2 observations from the air quality network are shown in Figure 3. The data collection efficiency was > 80 % for all sites presented in Figure 3. The Figure also includes PM10 annual average concentrations from onsite observations (2013-2016 period).

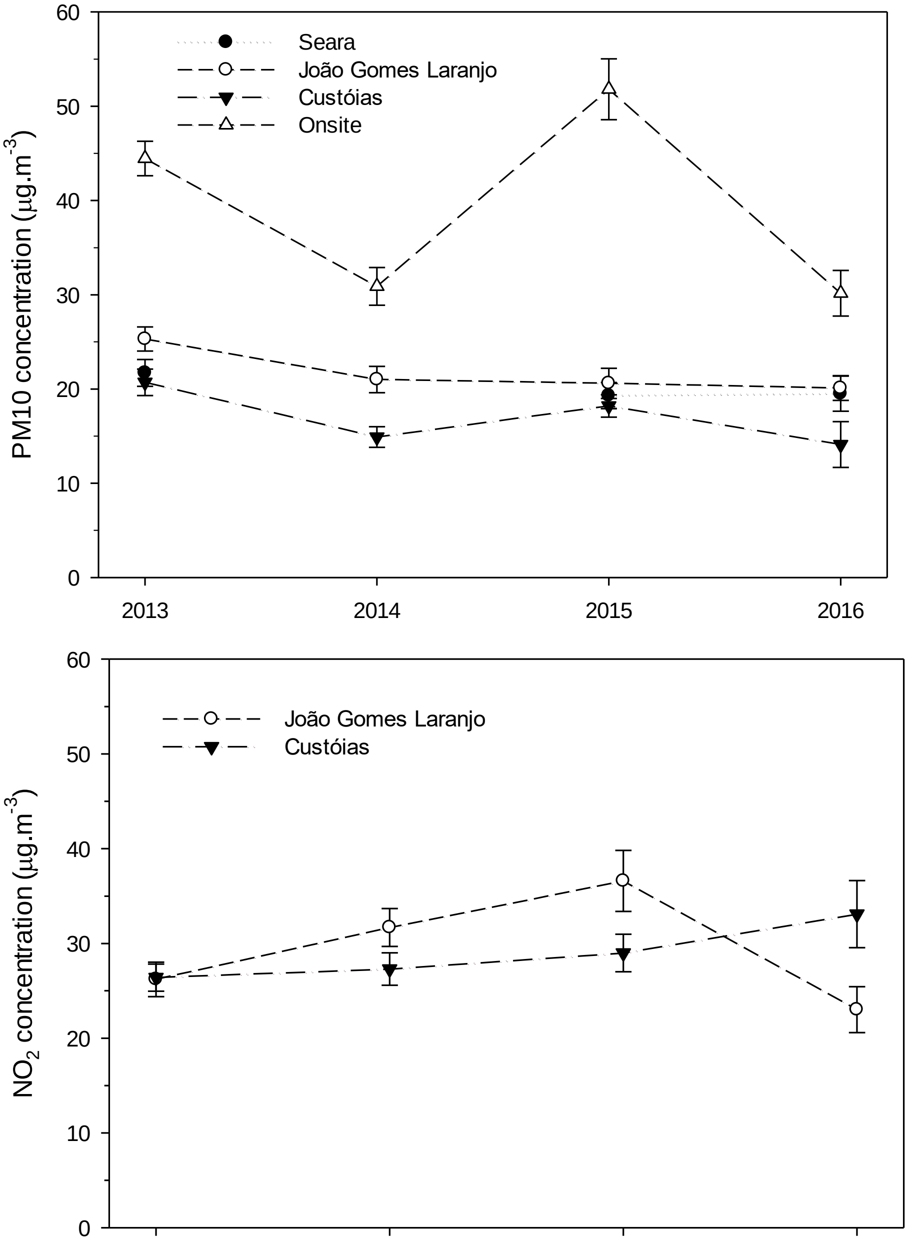


Figure 3. The 95% confidence intervals for the annual average of PM10 and NO_2 observations from the air quality monitoring network, and PM10 observations from the onsite monitoring station (inside port area).

PM10 concentrations at the Seara and João Gomes Laranjo sites were within 19-21 µg.m^{-3} range. These two stations are classified as urban sites and located closer to the port terminals than the Custóias suburban site. Concentrations at Custóias were between 14-18 µg.m^{-3}, about 25 % lower than at the urban sites. Similar differences between João Gomes Laranjo (urban) and Custóias could be seen for NO_2 in 2014 and 2015. Nevertheless, for 2016 the Custóias (suburban) station had higher concentrations than the João Gomes Laranjo (urban) site. This inversion in the NO_2 trend observed in João Gomes Laranjo station compared to Custóias may be due to some shift in the urban dynamics, namely the introduction of a toll charge in the highway near this station, and/or changes in traffic patterns due to support of public transport in the Porto municipality. On the other hand, Custóias station is representative of the suburban area of Matosinhos city, which has been undergoing rapid urbanization. In fact, we recommend that the classification of this monitoring station as "suburban" environment should be re-assessed to verify if it is still applicable.

Table 1 presents the number of exceedances to the hourly limit value of PM10 (50 µg.m^{-3}) and NO_2 (200 µg.m^{-3}) measured at the air quality stations from 2013 to 2016.

Table 1. The number of exceedances to the PM10 and NO_2 limit values, from 2013 to 2016 at the air quality stations.

	PM10 daily exceedances				NO_2 hourly exceedances			
Station	2013	2014	2015	2016	2013	2014	2015	2016
Onsite	36	42	267	258	NA	NA	NA	NA
Custóias	17	1	2	0	0	0	0	0
João Gomes Laranjo	16	2	0	3	5	0	0	0
Seara	7	NA[a]	0	0	NA	NA	NA	NA

[a] NA – Not available

No exceedances to the hourly limit value of NO_2 were registered, except for João Gomes Laranjo station, in which 5 exceedances were recorded in 2013. All the air quality stations were complying with the requirements of the EU Directive 2008/50/EC, which states that the number of exceedances to the hourly limit value could not exceed more than 18 times in a year.

On the other hand, according to the same legislation, maximum PM10 concentration of 50 µg.m^{-3} must not be exceeded more than 35 days per year. In this work, this limit was not complied in the Onsite station, in all studied years.

3. MODELLING APPROACH

3.1. Description of C-PORT

As a research grade-screening tool, C-PORT is designed to be an easy-to-use computer modeling tool for exploring the range of potential impacts that changes to port operations might have on local air quality. C-PORT predicts concentrations of multiple primary pollutants: CO, SO_2, NO_X, PM10 and selected Mobile Source Air Toxics (benzene, formaldehyde, acetaldehyde, and acrolein) at fine spatial scales in the near-source environment with access through an easy-to-use web-based platform. C-PORT can also be used to model air quality concentrations based on representative emissions and meteorological conditions, such as Summer rush hour traffic within a stable atmosphere. The key model inputs include emissions and meteorology, and model outputs are presented as geospatial maps. Users can run the model with the included default data or input their own locally derived values. C-PORT was constructed with an intended purpose of calculating differences in annual averaged concentration patterns and relative contributions of various source categories over the spatial domain within about 10 km of the port. However, this tool also has some limitations, such as it not does not include atmospheric chemistry to account for secondary pollutants such as ozone or secondary aerosols and does not account for local variations in terrain. Further, C-PORT is not intended to assess model predictions for specific hours (e.g., a specific date and time).

Meteorological inputs include hourly observations of wind speed and direction, ambient temperature, and other atmospheric boundary layer parameters needed for dispersion modeling. These data were processed through AERMET (https://www3.epa.gov/scram001/metobsdata_procaccprogs.htm), a meteorological data preprocessor for AERMOD. Subsequently, using the methods described in Isakov et al (2017), the typical hourly inputs for five different atmospheric conditions related to stability class for each of two seasons is identified from the annual dataset. For Portugal applications, C-PORT uses hourly weather measurements from the onsite monitoring site that is nearest to the study location to calculate the representative hours. C-PORT allows the user to simulate short-term (hourly) or long-term (annual) concentrations. For short-term, the user can model any of the five representative meteorological conditions: 1) Stable, 2) Slightly Stable, 3) Neutral, 4) Slightly Convective, and 5) Convective), and for each season (Winter & Summer), and an annual average option, based on 100 representative meteorological hours for each station, is also available. These 100 hours include a combination of 5 wind speeds, 4 wind directions and 5 stability conditions. The dispersion algorithm is run explicitly for the 100 hours, and then weighted by frequency (how often these 100 hours occur in the annual dataset) to estimate the annual averages. This method called the METeorologically - weighted Averaging for Risk and Exposure (METARE) is described further in Chang et al., (2015).

C-PORT allows the user to upload custom inputs for port terminals, ships-in-transit, roadways, rail, and point sources. The required parameters include source locations (latitude and longitude in decimal degrees) and annual emissions (in tons/year) for multiple pollutants: NOx, CO, SO2, PM2.5, PM10, EC2.5, OC2.5, benzene, formaldehyde, and acrolein. For ships-in-transit and point sources, stack parameters are required: stack height (m), stack diameter (m), stack temperature (deg. K), and stack exit velocity (m.s^{-1}).

C-PORT includes dispersion algorithms for area, point, and line sources related to freight-movement activities and emissions from the port terminals. The dispersion code for area and point sources is based upon model formulations used in AERMOD (Cimorelli et al., 2005), while the road and rail are modeled as line sources, based upon an analytical approximation that is used in the C-LINE modeling system (Barzyk et al., 2015).

The dispersion algorithm of C-PORT allows for the vertical distribution of emissions above the surface for point sources, reflecting the stack heights of ships and refinery. The model assumes that the concentration distributions in the vertical and horizontal are Gaussian except for convective conditions, in which case, we used a bi-Gaussian distribution (Isakov et al., 2017).

The dispersion algorithm for line sources is designed to calculate near-source pollution profiles representing emissions from roadway traffic and rail. This tool represents a highway as a set of line sources located at the center of each lane of the highway. Each line source is represented as a set of elemental point sources (Isakov et al., 2017). C-PORT modeling system is the dispersion algorithm that calculates near-source pollution gradients for buoyant line sources.

The dispersion algorithm is designed to specifically model moving line sources such as ships in transit (Isakov et al., 2017). Assuming that the averaging time for the calculation is long compared to the transit time of the ship, we can model the moving ship as a line source laid along its path. This source has buoyancy corresponding to the exhaust gases of the ship (Isakov et al., 2017). The dispersion algorithm is designed to efficiently model area sources representing emission sources such as dray trucks or rubber tire gentry at port terminals. As in AERMOD, an area source is treated as a polygon. The emissions from the area source are distributed among a set of line sources that are perpendicular to the near surface wind (Isakov et al., 2017).

The roadways emissions in C-PORT were consistent with the C-LINE web-based model (Barzyk et al., 2015) that estimates the air quality impacts of traffic emissions for roadways in the U.S. Roadway emissions in C-PORT are calculated based on a combination of road network, traffic activity and emissions factors. A road network is the system of interconnected roadways, and a description of their types (e.g., principal arterials such as interstates). Traffic activity describes the number, types, and speeds of vehicles on a given roadway and for a given time period.

3.2. Modelling inputs and setup for Porto case study

Several scenarios were defined and simulated to estimate the relative contributions of the different source sectors, namely harbor, roadway traffic, and industry to the air quality over the Port of Leixões case study. For these simulations, the modeling domain defined covered an area of approximately 10x10 km^2 with spatial resolution of 40 m (Figure 1). We provide a brief description of the model input data, namely meteorology and emissions data below.

Meteorological data

Hourly meteorological observations from the onsite meteorological station were used to create the meteorological inputs in C-PORT for 2016, using the same methods as in Isakov et al, 2017.

The typical hourly inputs for five different atmospheric conditions related to the stability class (stable; slightly stable; neutral; slightly convective and convective) and for each of the two seasons – Winter and Summer - are identified from the annual dataset. Table 2 summarizes these meteorological inputs that include hourly observations of wind speed (Ws), direction (Wd), surface friction velocity (uStar), height of the mechanically generated boundary layer (Zimech), Monin-Obukhov length (Lmon), surface roughness length (Zo), reference height for wind (RefHt) and ambient temperature (Temp), and the respective atmospheric stability class (Disp).

Table 2. Meteorological inputs data (for year 2016).

Season	Disp	Wd (º)	Ws (m/s)	uStar (m/s)	Zimech (m)	Lmon (m)	Zo (m)	RefHt (m)	Temp (K)
WINTER	Stab	209	0.8	0.172	674	32.7	1	10	284
WINTER	sStab	209	2.9	0.688	1404	521.1	1	10	284
WINTER	Neutral	209	11.1	1.929	4000	-3456.3	1	10	284
WINTER	sConv	209	3.9	0.688	1439	-529.1	1	10	284
WINTER	Conv	209	1.8	0.369	574	-47.8	1	10	284
SUMMER	Stab	241	0.8	0.172	228	32.8	1	10	291
SUMMER	sStab	241	2.4	0.568	1045	354.9	1	10	291
SUMMER	Neutral	241	5.4	1.325	3641	3273.8	1	10	291
SUMMER	sConv	241	3.9	0.709	1430	-234.6	1	10	291
SUMMER	Conv	241	1.8	0.375	585	-41.7	1	10	291

In both seasons, we found typical wind directions from Southwest, characterized by higher wind velocities during the winter period (and mainly for neutral atmospheric conditions). As expected, the highest boundary layer heights were found in neutral conditions (reaching 4000 m in winter) and the lowest for stable conditions with values inferior to 300 m in summer season. The difference estimated in surface temperature between the two seasons is only 7 degrees.

Methodologies for port-related emission input

In order to support the local air quality modelling study, a local-scale emission inventory has been developed for the Port of Leixões case study.

Emission sources were categorized as mobile sources (e.g., automobiles, trucks, buses and ship in transit), point sources (e.g., a refinery and ship hoteling), and area sources (e.g., cargo handling equipment and bulk material stored). Mobile sources were further categorized as on-road sources (e.g., automobiles, trucks, buses) and non-road mobile sources (e.g., construction equipment, cranes, yard trucks, locomotives, and marine vessels). Mobile source port-related emissions were generated by ships and by land-based sources at ports. Marine emissions came primarily from diesel engines operating on ships, tugs, and other ships operating within a port area.

Land-based emission sources included cargo-handling equipment (CHE), such as terminal tractors, cranes, container handlers, reach stacker, backhoes and forklifts, as well as heavy-duty trucks and locomotives operating inside a port area. The harbor-related emissions with high spatial and temporal resolution were estimated.

The Port of Leixões is equipped with 14 operating terminals, with the container terminal having the highest port traffic. In 2016, there was a record of 2,717 ship calls corresponding to a total of 32,849,816 Gross Tonnage (GT). A summary of the ship and cargo activity in the Port of Leixões is shown in Table 3.

Table 3. Number of ships and cargo in the Port of Leixões (for year 2016).

Terminal	Number of Ships	Number of cargo	Units
South container	1288	434,604	(TEU)
North container		132,535	(TEU)
Solid bulk	379	2,567,999	(tons)
Liquid bulk		8,352,890	(tons)
Roll on Roll Off	134	705,033	(tons)
Cruise	85	79,065	passengers

Shipping emissions

A bottom-up methodology to estimate emissions, proposed by the European Monitoring and Evaluation Programme/European Environment Agency (EMEP/EEA), was used to prepare emissions input for the model.

Regarding shipping emissions (marine emissions), the activity-based method was based on ship movement information and involved the application of emission factors to a particular ship activity, namely maneuvering or hoteling. Those emission factors expressed the emitted quantities for the operational status of the ship's engines during each activity, depending on engine type and size, engine nominal power, fuel type and time spent in port (EEA, 2016).

Fugitive Emissions

The storage of materials in open-air storage was another main area source (considering land-based emissions sources). Emissions from those stockpiles stored at terminals were estimated based on the methodology developed by the US Environmental Protection Agency (EPA, 1995). This methodology was proposed for loading/unloading operations of particulate material cargo. Additionally, an emission reduction factor was applied to the General Cargo and Bulk Terminal of Leixões, which was previously developed and applied by Borrego et al. (2007). This reduction percentage was due to the application of containers and windbreaks around bulk piles, since it promoted a decrease of the total amount of particulate emissions from the terminal, through the diminishing of the wind velocity in the pile surface.

Road mobile Emissions

Non-road mobile sources (cargo handling equipment) were divided into groups by engine fuel type, and pollutant emission factors were established based on the equipment model year, as well as the engine power (EEA, 2017).

Finally, on-road sources (roadway emissions) were estimated using the TREM (Transport Emission Model for Line Sources) model (Borrego et al., 2004), based on estimated origin/destination (O/D) matrices, traffic counts available for the Porto urban area, the vehicles' average speed in each main route, and statistical data from the Porto vehicle fleet. This emission model has already been extensively applied in Portugal and in the Porto region, exhibiting good agreement when compared/validated against observational data (Borrego et al., 2012; Relvas et al., 2017).

Figure 4 below shows the percentage of each source (ships, trucks, locomotives, and CHE) that contributed to the overall Port of Leixões emissions.

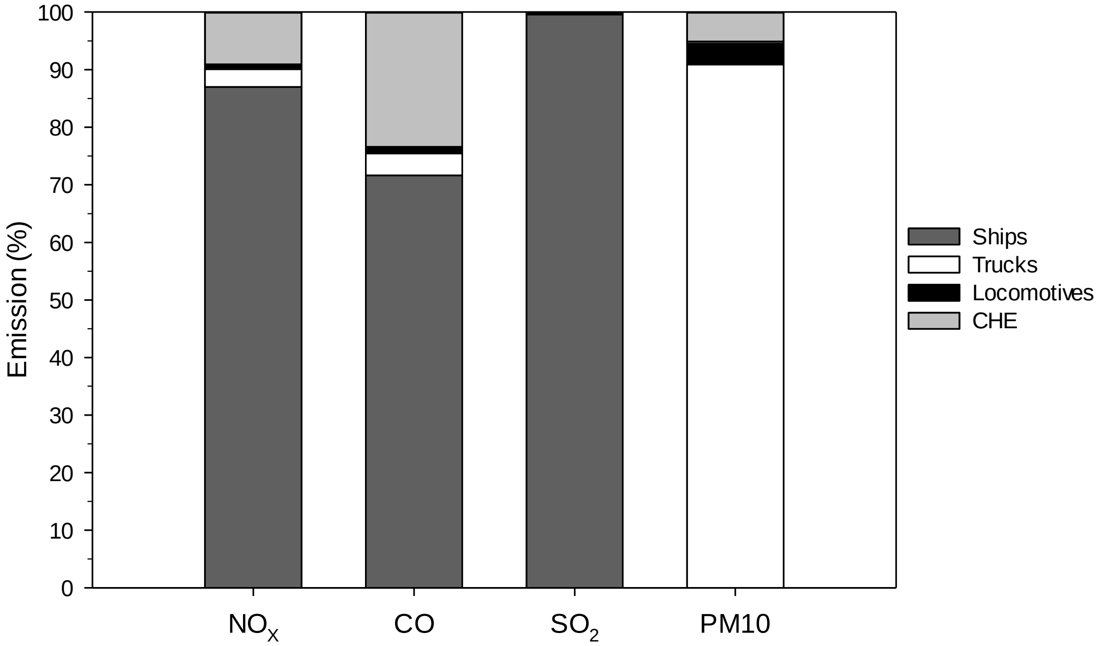


Figure 4. Relative contribution by each source category for the harbor emissions, at Port of Leixões, in 2016.

The dark gray bars highlight the fact that ships are by far the biggest source of emissions at the Port of Leixões. CHE is the second biggest source, followed by trucks and trains. Trucks and trains contribute less than 11 % and 3 % of the port's emissions, respectively.

4. Air quality modelling results

The analyses of the C-PORT modelling results include the model evaluation using observations and several sensitivity tests regarding meteorological conditions and sources contribution. The background concentrations, required by the model, were obtained throughout the regional modelling simulation done for the Portugal domain in the scope of the forecasting system operating daily (Monteiro et al., 2007; http://previsao-qar.web.ua.pt/). The background values used were 5 µg.m^{-3} NO$_X$ and 6 µg.m^{-3} PM10, and the total concentrations were obtained by adding these to the C-PORT based local source contributions.

4.1 C-PORT tool results

In order to evaluate the model performance, Figure 5 shows the observed and modelled concentrations at each monitoring point.

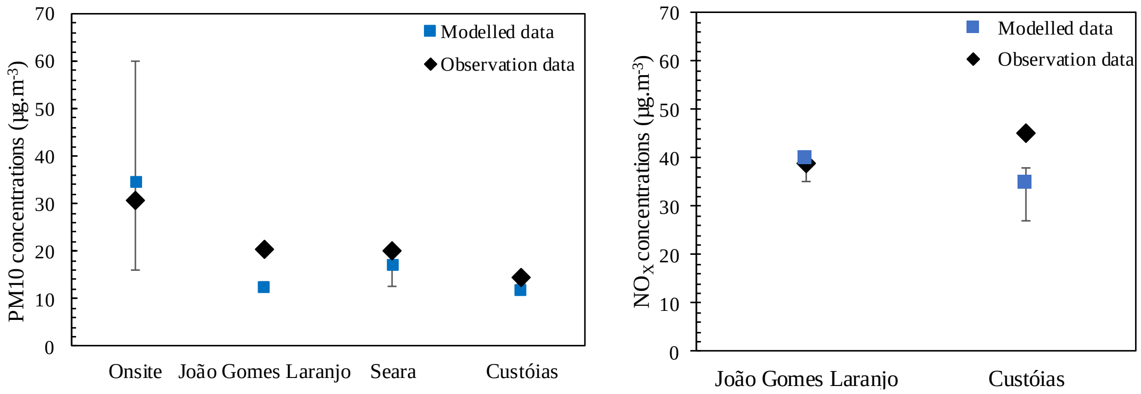
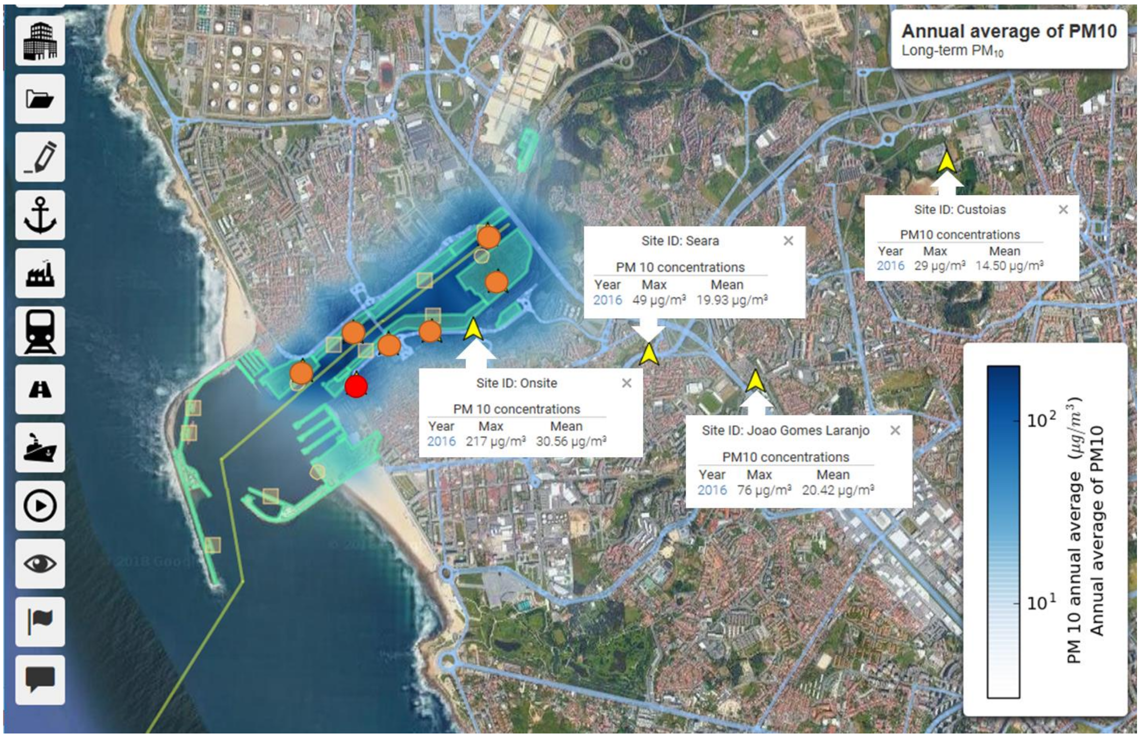


Figure 5. Observed and modelled annual averages of PM10 (left) and NO$_X$ (right) at the air quality stations. The modelled values represent the range of concentrations simulated in the grid cells in and around the one containing the monitoring site.

The PM10 concentrations measured in the air quality stations are close to the values obtained by C-PORT, aside from the João Gomes Laranjo (urban) station, which presented a difference between the modelled and observed concentrations of 10 µg.m^{-3}. Furthermore, modelled data ranges allowed the evaluation of spatial variability of the modelled results nearby the main receptor. Port of Leixões' onsite station showed the widest range of modelled concentrations, corresponding to the solid granulate and the containers terminals emission sources. Regarding the other stations, Seara and Custóias, the concentrations measured in the air quality stations were also within the range of the modelled concentrations by C-PORT.

In relation to NOx, it was possible to observe the spatial variabilities of the simulated values when compared to the observed values in the two stations. The model is able to capture perfectly the NOx magnitude values at the urban station - João Gomes Laranjo.

Figures 6 and 7 show the modelled annual averages of PM10 and NO_X together with the observed values for the air quality stations (AQS) nearby the Port of Leixões, respectively.



Site ID: Seara

PM 10 concentrations

Year	Max	Mean
2016	49 µg/m³	19.93 µg/m³

Site ID: Custoias

PM10 concentrations

Year	Max	Mean
2016	29 µg/m³	14.50 µg/m³

Site ID: Onsite

PM 10 concentrations

Year	Max	Mean
2016	217 µg/m³	30.56 µg/m³

Site ID: Joao Gomes Laranjo

PM10 concentrations

Year	Max	Mean
2016	76 µg/m³	20.42 µg/m³

Figure 6. Contour map of the annual average PM10 concentrations obtained with C-PORT tool, comprising: the measured values at the distinct AQS locations (yellow triangles), the receptors with concentrations higher than the annual legal limit value of 40 µg.m^{-3} (red and orange markers) and docked ships (yellow squares).

Site ID: Custoias

NOx concentrations

Year	Max	Mean
2016	145.85 µg/m³	45.85 µg/m³

Site ID: João Gomes Laranjo

NOx concentrations

Year	Max	Mean
2016	151.37 µg/m³	37.94 µg/m³

Figure 7. Contour map of the annual average NO_X concentrations obtained with C-PORT tool, comprising: the measured values at the distinct AQS locations (yellow triangles), the receptors with concentrations higher than the annual legal limit value of 40 $\mu g.m^{-3}$ (red and orange markers) and docked ships (yellow squares).

The highest PM10 concentrations simulated with the C-PORT tool were found within the Port of Leixões area, mainly in the South Container Terminal. The maximum value of PM10 concentrations of 263 $\mu g.m^{-3}$ (red marker) was recorded in the receptor located outside the port, first line of habitations. There were six receptors within the entire domain with concentrations higher than the annual legal limit value of 40 $\mu g.m^{-3}$ (orange markers), all of them located within the harbor, mainly in the container terminal and solid bulk conventional quays.

The maximum value of NO_X concentrations of 122 $\mu g.m^{-3}$ (red marker) was located near the entrance of the southern container terminal and highway. There were twenty-six receptors within the entire domain with concentrations higher than the annual legal limit value of 40 $\mu g.m^{-3}$ (approximately 21 ppb) (orange markers), located mainly at the quay and along the highway.

4.2. Influence of the meteorological conditions

Sensitivity tests were performed to assess the impact of the meteorological conditions (atmospheric stability, wind direction, sea-breeze circulation) on the pollutants' dispersion patterns, and to further identify the conditions that are responsible for worst-case pollution episodes.

Atmospheric stability condition was one of the key parameters influencing the dispersion phenomena. Therefore, distinct atmospheric stability conditions were tested with the C-PORT tool to determine the conditions more critical or favorable to promote pollutants dispersion over this study area, with particular attention to impacts in the surrounding urban area.

C-PORT simulations were performed for wind directions ranging from West-Southwest to West, corresponding to the typical average conditions of Summer season, corresponding to the typical average conditions of Summer season, considering all the point sources (i.e., the refinery and the docked ships).

Convective atmospheric stability conditions demonstrated that the refinery plume dispersion follows the horizontal direction as a result of high dispersion conditions and characterized by an intense vertical mixing. The convective stability class would be the best possible scenario (least pollutant concentration impacting the population) since it was characterized by a greater turbulence capable of dispersing the pollutants quicker, resulting in wider plumes, with lower ground-level concentrations along the average wind direction. On the opposite side, the stable class was characterized by a lower dispersion rate, and it produced greater ground-level concentrations near the emissions source and along the average wind direction.

Neutral atmospheric stability conditions represented the plume gradually expanding in the horizontal direction, symmetrically both to the left and right.

Based on results obtained with C-PORT, the atmospheric stability that potentiated higher concentrations, over the port and surrounding urban area, is the slightly stable condition. With the stable class simulation, the refinery plume was not visible, which is probably due to the stack height of 100 m; while hoteling ship emitted smoke at 20 m. Smoke emitted by the refinery was at the top of the Nocturnal Boundary Layer (NBL) or in the Residual Layer (RL), which under stable atmosphere conditions was rarely dispersed down to the ground because of the limited turbulence.

In coastal areas such as Port of Leixões, the dispersion of pollutants is mainly driven by the local maritime breeze system. There are several studies showing the important role of sea breezes on pollution dispersion (Damato et al., 2003, Ledoux et al., 2006; Bouchlaghem et al., 2007).

To evaluate the impact of the sea breeze circulation on the pollutant's concentration field, the different dispersion fields were simulated with C-PORT, taking into account all emissions inside harbor (i.e. area and point sources), for daytime (WSW direction) and nighttime (NE direction). All these simulations were performed for slightly stable conditions.

The influence of the sea breeze could be seen with the different spatial patterns of pollutant concentrations over the study area – pollutants emitted from the port during nighttime were expected to be dispersed and transported over the sea. Moreover, the rate of dispersion of pollutants emitted during nighttime and daytime periods was different due to the differences in wind speed and stability (wind speed was expected to be higher during daytime), as show in Table 2.

The highest PM levels were recorded during daytime sea breeze. The lowest NOx dispersion lead to hotspots close to the main sources of emissions. The stagnation of air masses over the area favored the accumulation of pollutants in the surrounding urban area.

4.3. Source contribution analysis

Together with the contour map, C-PORT tool also displayed relative contributions linked with the distinct source categories distributed over the domain, namely marine, land-based, roadways and refinery emissions, both for PM10 and NO_X concentrations.

Figures 8 and 9 show the short-term contributions of the different sources over the study area, to PM10 and NO_X concentrations, respectively, considering WSW wind conditions, daytime and slightly stable atmospheric class.

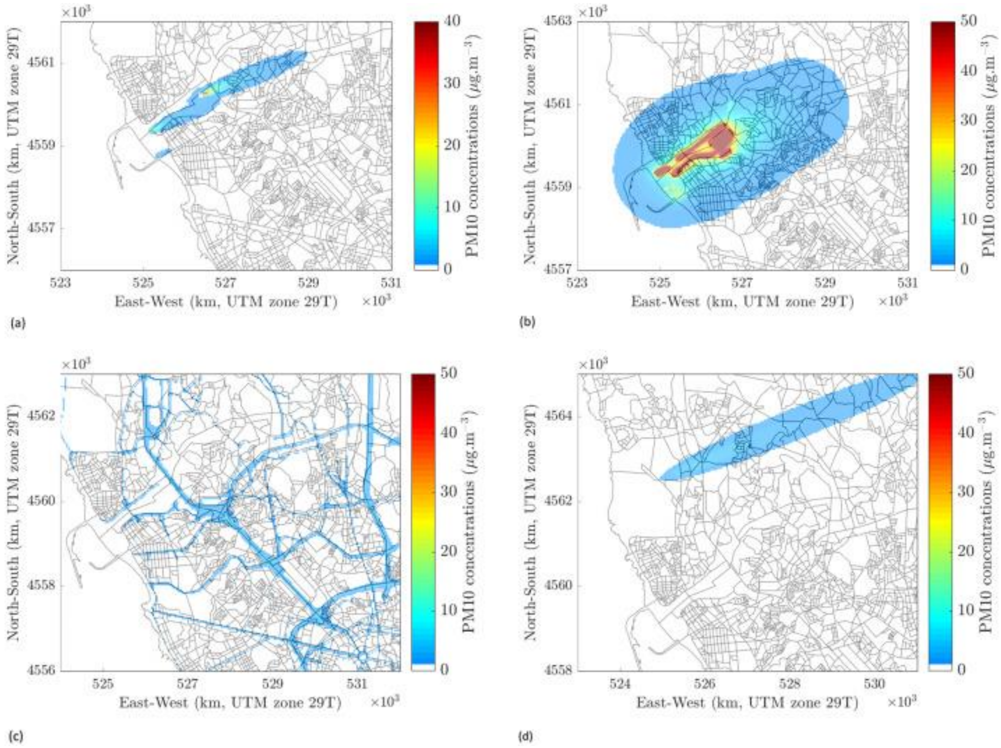


Figure 8. Short-term contributions of the different sources to PM10 concentrations estimated with C-PORT above regional background: a) marine emissions (including ship in transit and point source); b) land-based emissions; c) roadway emissions and d) refinery emission.

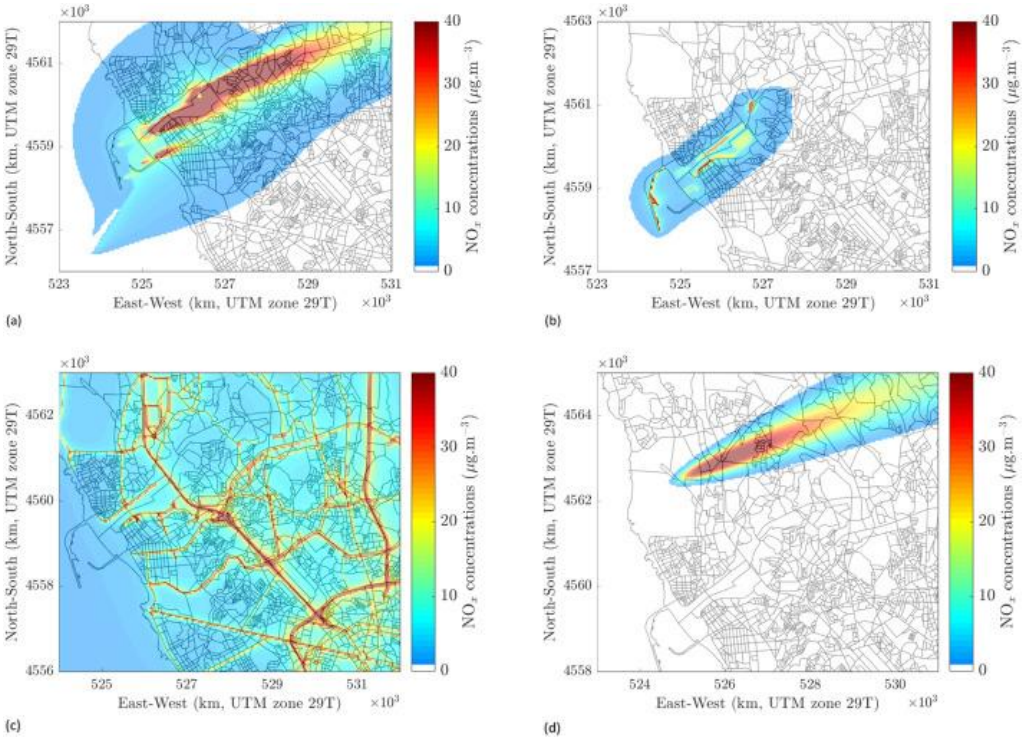


Figure 9. Short-term contributions of the different sources to NO_X concentrations estimated with C-PORT above regional background: a) marine emissions (including ship in transit and point source); b) land-based emissions; c) roadway emissions and d) refinery emission.

All the short-term simulations clearly point towards hoteling ship and refinery industry, indicating that PM10 emissions occurred in very narrow plumes from the stacks. This was due to the fact that the hoteling ship emitted at a higher altitude (up to 20 m above ground, depending on the stack height). The same behavior could also be seen in Figure 8d where the emission source (refinery) was emitted at a height of 100 m. As seen in Figure 8b, the dispersion does not point towards any specific direction, indicating that PM10 originate from several diffuse sources inside the harbor, including cargo-handling equipment, bulk material transport in trucks and trains and bulk material outdoor storage. All these sources emitted at ground level, causing low dispersion and high concentrations close to the emission sources – i.e. general cargo and solid bulk and container terminal. All short-term simulations for PM10 concentrations point out that area sources exhibited the highest impact over the study area.

Regarding NO_X, C-PORT results suggested that the marine emissions (Figure 9a) were the main contributors of NO_X. Although the European Air Quality Directive 2008/50/EC doesn’t establish any limit for NOx for human health protection, this emission source lead to the surpassing of the NO_2 hourly limit-value of 200 µg.m^{-3}, which may be used as a reference value (NO_2 is in average 60-70% of NO_X). NOx effects reached inland at a distance above 5 km from the container quay. The plumes released during docked ships were distinctly visible on NO_X, but the ship in transit inside the harbor had limited effects on NO_X.

The land based, roadway and refinery emissions respect the legal limit, showing maximum NO_X concentrations of 88 µg.m^{-3} (Figure 9b), 142 µg.m^{-3} (Figure 9c) and 56 µg.m^{-3} (Figure 9d).

Figures 10 and 11 show the annual contributions of the different sources over the study area to PM10 and NO_X concentrations, respectively, considering WSW wind conditions, daytime and slightly stable atmospheric class.

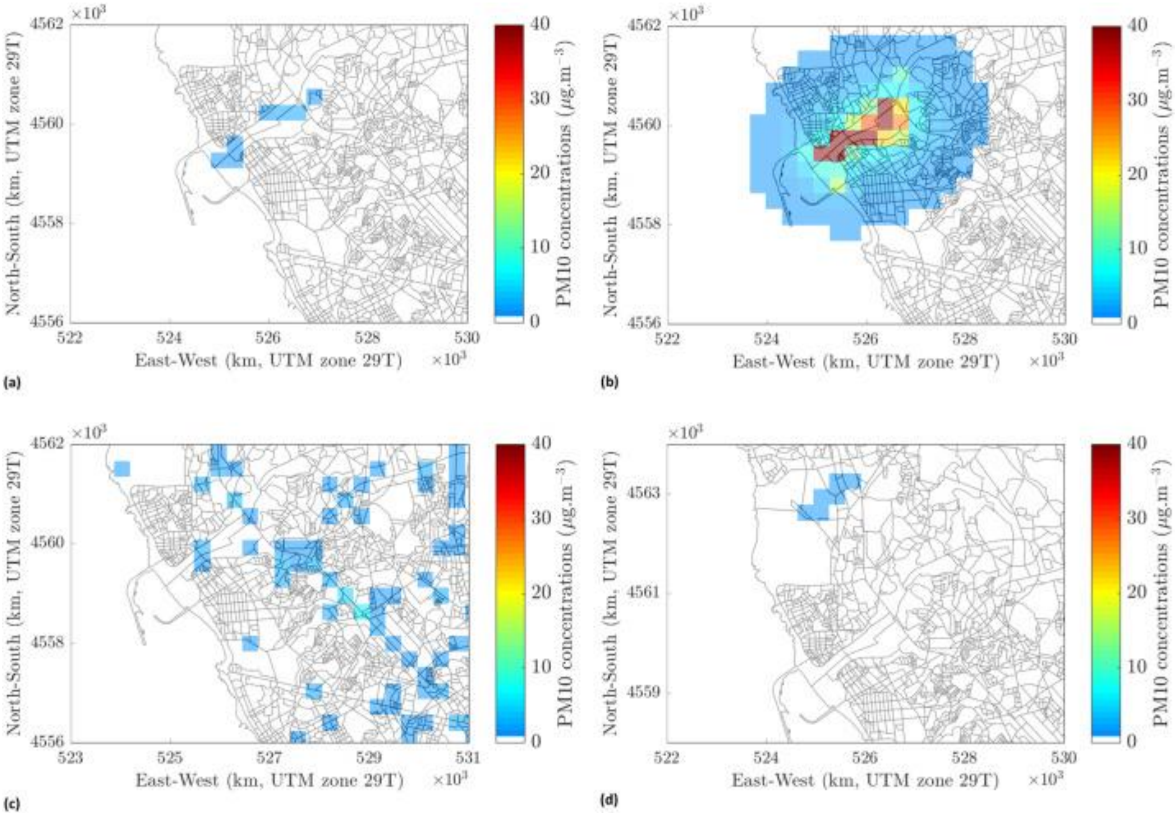


Figure 10. Annual average contributions of different sources to PM10 concentrations estimated with C-PORT above regional background: a) marine emissions (including ship in transit and point source); b) land-based emissions; c) roadway emissions and d) refinery emissions.

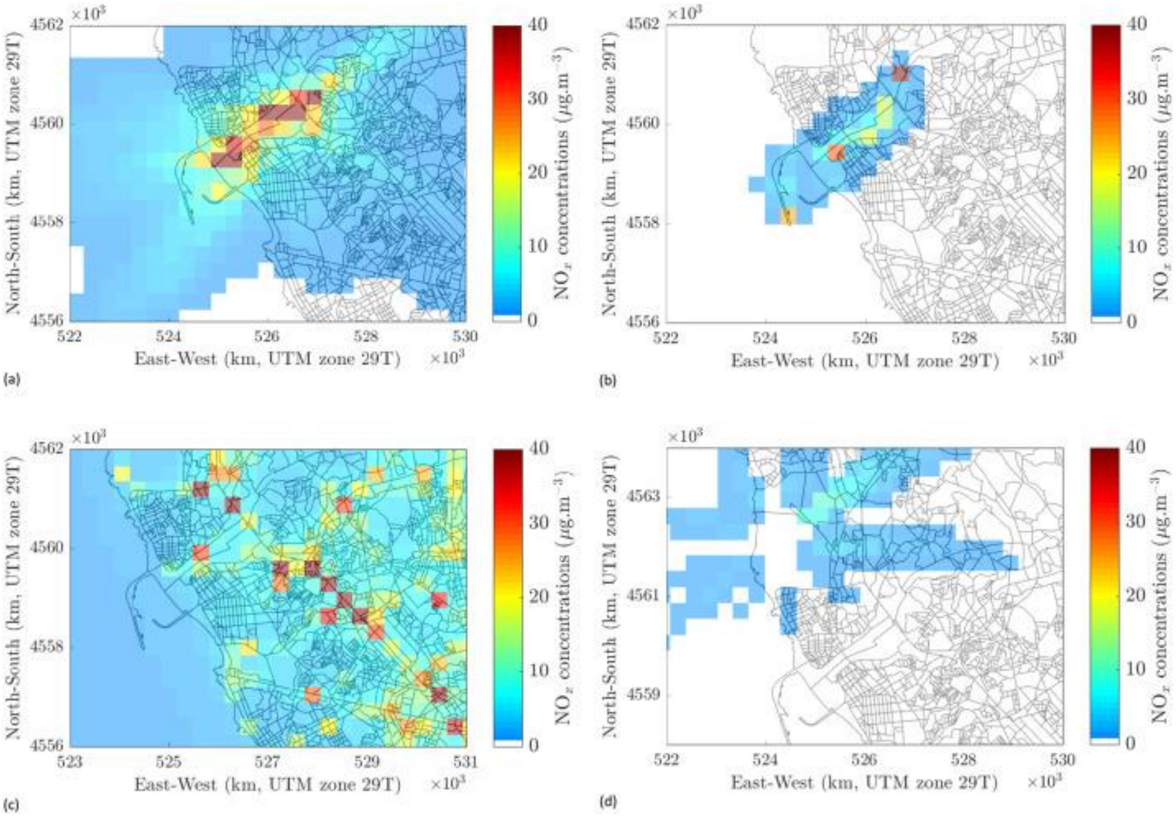


Figure 11. Annual average contributions of different sources to NO_X concentrations estimated

with C-PORT above regional background: a) marine emissions (including ship in transit and point source); b) land-based emissions; c) roadway emissions and d) refinery emissions.

From the annual average concentration patterns obtained in Figure 10, C-PORT tool identified the land-based emission sources as the main ones contributing for the total PM10 concentrations, with an estimated contribution of 76-84 %. Roadway and refinery (located close to the port) contributed 3-4 % and <1 %, respectively. Marine activities had a negligible contribution of 27 % from docked ships and < 1 % from ships in transit.

Model results pointed out that these land-based emissions (Figure 10b) contributed to a maximum value of PM10 around 260 µg.m^{-3}, with five receptors registering a concentration above the legal limit value of 40 µg.m^{-3}, established by the European Air Quality Directive 2008/50/EC. While, both the marine activities and the refinery had a negligible contribution for the PM10 concentrations in the study area. The marine emissions (Figure 10a) led to a maximum of 2.4 µg.m^{-3} of PM10 concentrations, while the refinery (Figure 10d) led to a maximum of 1 µg.m^{-3} of PM10. Regarding the roadway contribution (Figure 10c), model results exhibited a maximum value of PM10 concentrations around 6 µg.m^{-3}, close to the main routes.

Regarding the NOx concentrations modeled for 2016, docked ships were the main contributors to the higher NOx concentration (55-73 %), followed the by roadway emissions with a contribution between 20-35 %. Ships in transit contributed with less than 1 %, which could be justified by the extended hoteling time while the ships were docked. The maximum NOx concentration of 93 µg.m^{-3} was linked with marine emissions (Figure 12a). This value was due to the high number of ships docked in the south container terminal. Figure 11a presents 4 receptors over mainly the channel leading to the Port of Leixões with a concentration above the legal NO_2 annual limit value of 40 µg.m^{-3}, once again used as reference in the absence of a NOx limit value. The maximum concentrations from the land-based sources (Figure 11b) were about 66 µg.m^{-3}.

Regarding land-based emissions source, Figure 11b highlights the existence of two hotspots, in the entrances of the harbor (waterway and terrestrial). Highest land-based emissions sources in this region were centered on the trucks’ entrance, used by approximately 830,000 trucks in 2016. Road-traffic (Figure 11c) presented a strong influence in the area as an emission source, leading to high values of NOx concentrations close to the main roads. The maximum value of NOx concentration was recorded southeast the port area over the main motorway (A28) and was higher than 90 µg.m^{-3}. Figure 11c presents four receptors over the main motorway with a concentration above the NO_2 annual limit value for human health protection (40 µg.m^{-3}) and over 8 receptors inside the study domain. Finally, the annual average plume from the refinery (Figure 11d) had a maximum value of 10 µg.m^{-3}.

4.4. Population exposure

The population exposure was estimated considering the annual average concentrations of PM10 and NO_X, and the local population distribution by each computational grid cell. The study domain included a total of 374,144 residents.

Figure 12 and 13 show the average population potentially affected by concentrations above 40 $\mu g.m^{-3}$ for both PM10 and NO_x. Black squares represent the grid cells with concentration above the respective annual limit values.

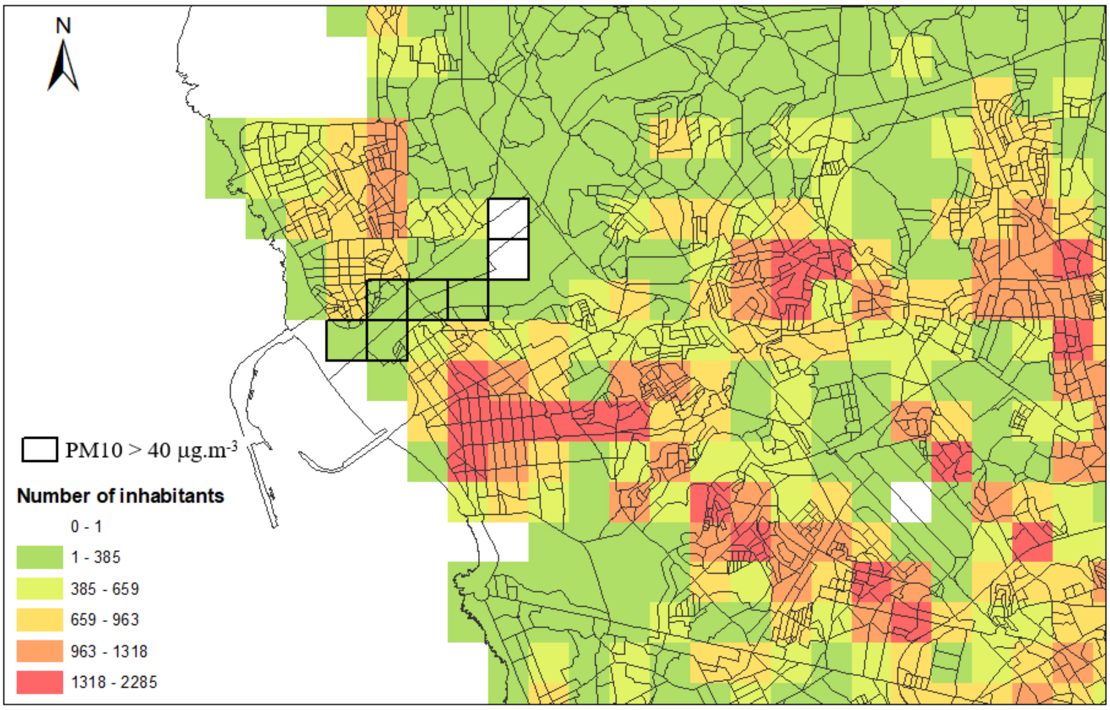


Figure 12. Number of inhabitants and annual average population potentially affected by contributions of all port-related sources of PM10 (marine emissions; land-based emissions; roadway emissions and refinery emissions).

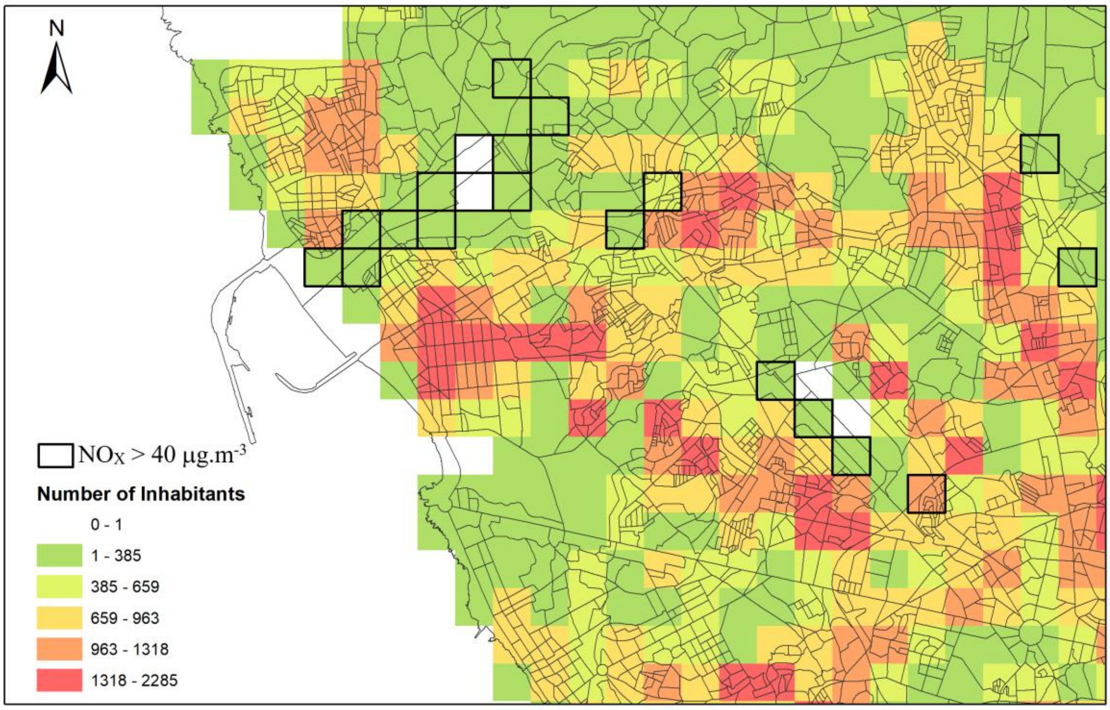


Figure 13. Number of inhabitants and annual average population potentially affected by contributions of all port-related sources of NO_x (marine emissions; land-based emissions; roadway emissions and refinery emissions).

As expected, there were low exposure values for both PM10 and NO_X, since the majority of the cells that exceeded the legislated limit value were located where there was little population. The population potentially affected by PM10 concentrations above the EU limit value accounted for 567 inhabitants. On the other hand, the population potentially affected by NO_X concentrations above 40 $\mu g.m^{-3}$ accounted for 5657 inhabitants. For both pollutants, cells with concentrations greater than 40 $\mu g.m^{-3}$ were located mainly in the port terminals (Figure 12 and Figure 13).

5. SUMMARY AND CONCLUSIONS

The Port of Leixões, near the city center of Porto’s metropolitan area, is the largest port infrastructure in the Northern Region of Portugal and one of the most important in the country. The impact on Port of Leixões’ air quality was investigated with particular emphasis on the population of the surrounding urban area.

The C-PORT air quality modeling platform, designed to study urban-scale air pollution due to port-related sources, was developed by UNC-IE and U.S. EPA, based on dispersion modelling algorithms and optimized for rapid execution through an intuitive web-based interface. We expanded C-PORT for a first application outside the U.S., to Port of Leixões in Portugal, characterizing local-scale air quality in and around the port, and performing source apportionment to understand dominant source sectors. First, the impact of different meteorological conditions and the influence of wind directions/sea breeze on local air quality were assessed. Results pointed out that air pollutant dispersion is dependent on meteorological conditions, with slightly stability atmospheric conditions exhibiting the most critical situation for PM10 and NO_X dispersion. The dominant wind direction, a diurnal sea breeze from WSW is responsible for the transport of pollutants over the surrounding urban area. During nighttime periods, the dispersion pattern is completely different and promotes the accumulation of pollutants over the port area.

The C-PORT modelling tool was also applied to estimate the relative contributions of various source sectors to outdoor air quality concentrations, including port (terminals, ships, and roads), roadway traffic, and industrial (refinery) sources that potentially affect the port vicinity, including the local urban community.

The land-based emission sources, (including trucks, railways, cargo handling equipment and bulk material stored) at the Port of Leixões exhibit the highest contribution (approximately 80 %) to the levels of PM10 concentrations in the study area. Marine activities and the refinery (located close to the port) have a negligible contribution. Regarding NOx, the docked ships are the main source with a contribution above 50 % for NOx concentration values, with ships in transit contributing below 1 %, justified by the extended hoteling time while the ships are docked.

Future work will include the computational fluid dynamics (CFD) based modelling of microscale air quality in which the dispersion of the air pollutants will be computed applying a Lagrangian approach. This will identify the obstacles that lead to the formation of additional hot spots from the rearrangement of vertical flow structures, and for a better understanding of the air quality problem in urban hot spots in the immediate vicinity of the harbor.

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REFERENCES

AAPA, 2016. Ports' Value to the U.S. Economy. http://www.aapa-ports.org/advocating/content.aspx?ItemNumber=21150 (accessed in 21 November 2017).

Alastuey, A., Moreno, N., Querol, X., Viana, M., Artíñano, B., Luaces, JA, Guerra, A. (2007). Contribution of harbour activities to levels of particulate matter in a harbour area: Hada Project-Tarragona Spain. Atmos. Environ. 41, 6366–6378. https://doi.org/10.1016/j.atmosenv.2007.03.015.

Arunachalam, S., Brantley, H, Barzyk, T., Hagler, G., Isakov, V., Kimbrough, S, Naess, B., Rice, N., Snyder, M., Talgo, K., Venkatram, A., 2015. Assessment of port-related air quality impacts: geographic analysis of population. Int. J. Environ. Pollut. 58, 231-250. http://dx.doi.org/10.1504/IJEP.2015.077455.

Barzyk, T., Isakov, V., Arunachalam, S., Venkatram, A., Cook, R., Naess, B., 2015. A Near-Road Modeling System for Community-Scale Assessments of Mobile-Source Air Toxics: The Community Line Source (C-Line) Modeling System. Environ. Modell. Softw. 66, 46-56. https://doi.org/10.1016/j.envsoft.2017.09.004.

Baumgardner, D., Raga, GB, Grutter, M., Lammel, G., 2006. Evolution of anthropogenic aerosols in the coastal town of Salina Cruz, Mexico: Part I particle dynamics and land–sea interactions. Sci. Total Environ. 367, 288–301. https://doi.org/ 10.1016/j.scitotenv.2005.11.013.

Borrego, C., Tchepel, O., Salmim, L., Amorim, JH, Costa, AM, Janko, J, 2004. Integrated modelling of road traffic emissions: application to Lisbon air quality management. Cybernet. Syst. 35, 535-548. https://doi.org/10.1080/0196972049051904.

Borrego C., Costa A. M., Amorim J., Santos P., Sardo J., Lopes M., Miranda A. I., 2007. Air quality impact due to scrap-metal handling on a sea port: a wind tunnel experiment. Atmos. Environ. 41, 6396-6405. https://doi.org/10.1016/j.atmosenv.2007.01.022.

Borrego, C., Carvalho, A., Sá, E., Sousa, S., Coelho, D., Lopes, M., Monteiro, A., Miranda, A.I., 2011. Air Quality Plans for the Northern Region of Portugal: Improving Particulate Matter and Coping with Legislation, Advanced Air Pollution, Farhad Nejadkoorki (Ed.), ISBN: 978-953-307-511-2, InTech.

Borrego C., Sá, E., Carvalho, A., Sousa, J., Miranda, A.I., 2012a. Plans and Programmes to improve air quality over Portugal: a numerical modelling approach. Int. J. Environ. Pollut. 48, 60-68. https://doi.org/10.1504/IJEP.2012.049652.

Borrego C., Monteiro A., Sá E., Carvalho A., Coelho D., Dias D., Miranda A.I., 2012b. Reducing NO2 Pollution over Urban Areas: Air Quality Modelling as a Fundamental Management Tool. Water Air Soil Poll. 48, 60-68. https://doi.org/10.1007/s11270-012-1281-7.

Cesari, D., Genga, A., Ielpo, P., Siciliano, M., Mascolo, G., Grasso, F.M., Contini, D., 2014. Source apportionment of PM2.5 in the harbor-industrial area of Brindisi (Italy): identification and estimation of the contribution of in-port ship emissions. Sci. Total Environ. 497-498, 392-400. https://doi.org/10.1016/j.scitotenv.2014.08.007.

Chang, SY, Vizuete, W., Valencia, A., Naess, B., Isakov, V., Palma, T., Breen, M., Arunachalam, S., 2015. A modeling framework for characterizing near-road air pollutant concentration at community scales, Sci. Total Environ. 538, 905–921. https://doi.org/10.1016/j.scitotenv.2015.06.139.

Cimorelli, A., Perry, S., Venkatram, A., Weil, J., Paine, R., Wilson, R., Brode, R., 2005. AERMOD: A dispersion model for industrial source applications. part I: General model formulation and boundary layer characterization. J. Appl. Meteorol. 44, 682-693. https://doi.org/10.1175/JAM2228.1.

Contini, D., Gambaro, A., Belosi, F., De Pieri, S., Cairns, WRL, Donateo, A., Zanotto, E., Citron, M., 2011. The direct influence of ship traffic on atmospheric PM2.5, PM10 and PAH in Venice. J. Environ. Manag. 92, 2119-2129. https://doi.org/10.1016/j.jenvman.2011.01.016.

Corbett, JJ, Winebrake, JJ, Green, EH, Kasibhatla, P., Eyring, V., Lauer, A., 2007. Mortality from ship emissions: a global assessment. Environ. Sci. Technol. 41, 8512-8518. https://doi.org/10.1021/es071686z.

Diesch, J.M., Drewnick, F., Klimach, T., Borrmann, S., 2013. Investigation of gaseous and particulate emissions from various marine vessel types measured on the banks of the Elbe in Northern Germany. Atmos. Chem. Phys. 13, 3603-3618. https://doi.org/10.5194/acp-13-3603-2013.

European Parliament and Council, 2008. *Article 13, Annex XI* of Council Directive/50/EU.

Donateo, A., Contini, D., Belosi, F., 2006. Real time measurements of PM2.5 concentrations and vertical turbulent fluxes using an optical detector. Atmos. Environ. 40, 1346-1360. https://doi.org/10.1016/j.atmosenv.2005.10.026.

EC, 2005. Economic Instruments for Reducing Ship Emissions in the European Union. Nera, London.

EEA, 2013. EMEP/EEA Air Pollutant Emission Inventory Guidebook 2013: Technical Guidance to Prepare National Emission Inventories. EEA Technical report No 2013, European Environment Agency.

EEA, 2016. EMEP/EEA air pollutant emission inventory guidebook 2016 – Update May 2017. EEA Technical report No 4/2017, European Environment Agency.

EPA, 1995. Compilation of air pollutant emission factors, AP-42, vol. 1, fifth ed. Stationary Point and Area Sources. US Environmental Protection Agency (US EPA), Office of Air Quality Planning and Standards, Research Triangle Park, NC.

ESPO, 2013. Top Environmental Priorities of European Ports for 2013. An Analysis Taking Port Size and Geography into Consideration. ESPO, Brussels.

Gariazzo, C., Papaleo, V., Pelliccioni, A., Calori, G., Radice, P., Tinarelli, G., 2007. Application of a Lagrangian particle model to assess the impact of harbor, industrial and urban activities on air quality in the Taranto area, Italy. Atmos. Environ. 41, 6432-6444. https://doi.org/10.1016/j.atmosenv.2007.06.005.

Hagler, G., Gagliano, P., Kimbrough, S., Barzyk, T., Isakov, V., Bailey, C., D'Onofrio, D., Bergin, M., 2013. Panama Canal Expansion Illustrates Need for Multimodal Near-Source Air Quality Assessment. Environ. Sci. Technol. 47, 10102–10103. https://doi.org/10102–10103. 10.1021/es403145x.

HIP, 2010. Los Angeles and Long Beach Maritime Port HIA Scope. Prepared for the United States Environmental Protection Agency. Working Draft (accessed 17 May 2010).

Isakov, V., Barzyk, T., Smith, E., Arunachalam, A., Naess, B., Venkatram, A., 2017. A web-based screening tool for near-port air quality assessments. Environ. Modell. Softw. 98, 21-34. https://doi.org/10.1016/j.envsoft.2017.09.004.

Isakson, J., Persson, T., Selin Lindgren, E., 2001. Identification and assessment of ship emissions and their effects in the harbor of Göteborg, Sweden. Atmos. Environ. 35, 3659–3666. https://doi.org/10.1016/S1352-2310(00)00528-8.

Kilic, A., Tzannatos, E., Song, S., Schembari, C., Cavalli, F., Cuccia, E., Citron, M., 2007. Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. Atmos. Environ. 41, 186–198. https://doi.org/10.1016/j.envpol.2010.02.013.

Kozawa K.H., Fruin S.A., Winer A.M., 2009. Near-Road Air Pollution Impacts of Goods Movement in Communities Adjacent to the Ports of Los Angeles and Long Beach. Atmos. Environ. 43, 2960–2970. https://doi.org/10.1016/j.atmosenv.2009.02.042.

Sharma, DC. 2006. Ports in a Storm. Environ. Health Persp. 114, A224-A226. https://doi/pdf/10.1289/ehp.114-a222.

Lonati, G., Cernuschi, S., Sidi, S., 2010. Air quality impact assessment of at-berth ship emissions: Case-study for the project of a new freight port. Sci Total Environ. 409, 192–200. https://doi.org/10.1016/j.scitotenv.2010.08.029.

Marmer, E., Dentener, F., Van Aardenne, J., Cavalli, F., Vignati, E., Velchev, K., Hjorth, J., Boersma, F., Vinken, G., Mihalopoulos, N., Raes, F., 2009. What can we learn about ship emission inventories from measurements of air pollutants over the Mediterranean Sea?. Atmos. Chem. Phys. 9, 6815-6831. https://doi.org/10.5194/acp-9-6815-2009.

Matsuoka, M., Hricko, A., Gottlieb, R., and DeLara, J., 2011. Global Trade Impacts: Addressing the Health, Social and Environmental Consequences of Moving International Freight through Our Communities. http://scholar.oxy.edu/uep_faculty/411, (accessed 15 November 2017).

Merk O., Shipping Emissions in Ports, International Transport Forum, 2014. Vol. 20. Paris, 37, 2014

Monteiro A., Miranda A.I., Borrego C., Vautard R., 2007. Air quality assessment for Portugal. Sci Total Environ. 373, 22-31. https://doi.org/10.1016/j.scitotenv.2006.10.014.

Pérez, N., Pey, J., Reche, C., Cortés, J., Alastuey, A., Querol, X., 2016. Impact of harbour emissions on ambient PM10 and PM2.5 in Barcelona (Spain): Evidences of secondary aerosol formation within the urban area. Sci Total Environ. 571, 237–250. https://doi.org/10.1016/j.scitotenv.2016.07.025.

Relvas, H., Miranda, A. I., Carnevale, C., Maffeis, G., Turrini, E., & Volta, M., 2017. Optimal air quality policies and health: a multi-objective nonlinear approach. Environ Sci Pollut R. 24, 1-13. https://doi.org/10.1007/s11356-017-8895-7.

Rosenbaum, A., Hartley, S., Holder, C., 2011. Analysis of diesel particulate matter health risk disparities in selected US harbor areas. Am. J. Public Health. 101, S217-23. https://doi.org/10.2105/AJPH.2011.300190.

Sorte S., Rodrigues V., Ascenso A., Freitas S., Valente J., Monteiro A., Borrego C., 2018. Numerical and physical assessment of control measures to mitigate fugitive dust emissions from harbor activities. Air Qual Atmos Hlth. 11, 493-504. https://doi.org/10.1007/s11869-018-0563-7.

Viana, M., Amato, F., Alastuey, A., Querol, X., Saúl, G., Herce-Garraleta, D., Fernandez-Patier, R., 2009. Chemical tracers of particulate emissions from commercial shipping. Environ. Sci. Technol. 43, 7472-7477. https://doi.org/10.1021/es901558t.

Zhou, Y. and Levy, J., 2007. Factors influencing the spatial extent of mobile source air pollution impacts: a meta-analysis. BMC Public Health. 7, 7-89. https://doi.org/10.1186/1471-2458-7-89.