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Modelling of air pollution due to marine traffic in Mediterranean coastal cities

E. Chevet, O. Boiron, F. Anselmet

Aix Marseille University, CNRS, Centrale Marseille, IRPHE, Marseille, France

Abstract

Maritime traffic is constantly increasing and is unlikely to decrease in the years to come. However, merchant and tourist ships still use fuels with a high pollutant content, particularly in the Mediterranean sea where regulations are more flexible than those applied in northern European waters. The pollutants of interest in this work, which include particulate matter (PM10, PM2.5), NO₂, SO₂ and ozone, are responsible for respiratory diseases such as airway irritation, cardiopulmonary and lung cancers. The purpose of this study is to estimate the impact of marine traffic on the air quality of Marseille in case of high occupancy scenarios of the port. In order to do so, we have parameterized the numerical weather forecasting model WRF (Weather Research and Forecasting) that allows the inclusion of chemistry and atmospheric transport equations. The chemical model takes yearly chemical emission data from EDGAR-HTAP inventory. Hourly coefficients are then applied accordingly to the method implemented by Crippa et al. [5]. For ship traffic, AIS data provides position, speed or time at berth of any given boat as well as its main features. Methodology to estimate ship emissions is derived from both EMEP/EEA [6] and EPA [8] reports. The relative difference in concentration between a situation with and without ship traffic allows us to evaluate the influence of ships on air quality. The effect of seasonality is also analyzed, by running 4 simulations of 72 hours for each season. When compared to the values presented in Viana et al. [22], the model seems to underestimate the contribution of the shipping sector to urban pollution for gas species, estimated around 1% for SO₂, NO₂ and O₃. However, PM10 and PM2.5 contribution levels are consistent with previous studies, with values ranging from 3.5% to 12.8%.

Keywords: *Atmospheric Pollution, Ship Traffic, Numerical Weather Prediction, Chemical Emissions*

1 Introduction

The seaways are more and more frequented, both for development of international trade and for tourism. Over the past 40 years, world seaborne trade and maritime tourism in cruises have grown by an average of +3% [19] and +7% each year respectively. Besides, 70% of the emissions related to maritime transport occur within 400 km of the coast. In fact, most cruise ships continue to run their engines at dockside in port, directly impacting the health of populations near the port area. It has been estimated that fine particles emitted by ships close to the coast are responsible for 60000 premature deaths per year [4]. Although measures have been established by the International Maritime Organization (IMO) to regulate the pollutant content of the fuels consumed, they remain very rich in sulfur oxides (SO_x), nitrogen oxides (NO_x) and fine particles (PM10 and PM2.5). Since 2020, ship fuels are limited to a mass sulphur content of 0.5% in the Mediterranean, compared to 0.1% in Northern Europe, which is still 1000 times higher than in the diesel for cars. The proximity of large ports to densely populated areas makes these emissions a real threat to the health of the many residents of these port cities. Controlling pollution from maritime transport in port cities is therefore of utmost importance, hence the significance of building a model capable of accurately estimating the contribution of port activity to air pollution based on complete and reliable data. Concerning the data on ship emissions, the "bottom-up" approach has been adopted. Indeed, the "top-down" method consisting in estimating the emissions of the ships from the total fuel consumption was found to be less efficient [14]. Traffic data are usually derived from the Automatic Identification System (AIS), which provides real-time information for all sorts of ships worldwide. Given the type, the size and the operating state of a single boat, it is possible to estimate its proper emission. There are two main methods to estimate the impact of anthropogenic emissions of a sector on air quality. The first method consists in identifying by statistical methods the sources of pollutant emissions based on measurements from sensors. This approach, called Receptor Modelling, is frequently used to estimate

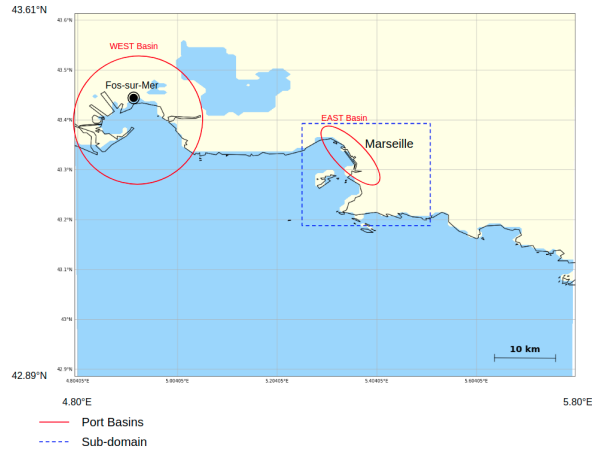


Figure 1: Map of the study domain

the sources of fine particles and aerosols [21]x. However, it does not account for secondary pollutants, those resulting from chemical transformations and reactions. One alternative is the use of air quality models (AQMs), which provide an effective response to this problem while including these secondary components. Various AQMs have been applied worldwide to determine the impact of marine traffic on air quality: CALPUFF in Napoli [16]; TAPM in Hamburg [18]; CAMx in Europe [12] etc... WRF-Chem has been utilized several times to determine the impact of maritime traffic on air pollution and has proven to be very efficient for that purpose (Marelle et al. [13], Wang et al. [23], Chen et al. [2]). These studies are regional with a horizontal resolution ranging from 3 to 15 km. While the port of Marseille (GPMM) has the highest number of calls in France, few studies are focusing on the impact of its activity on the air quality of the city. Project CAIMANS has produced a detailed report in 2015 in which the main Mediterranean ports, including GPMM, have been compared regarding their impact on air pollution [17]. However, this project focuses on annual analysis, and therefore does not capture high emission events. The aim of this work is to quantify the contribution of ship traffic on the air pollution of Marseille and its surroundings using the fully coupled chemistry model WRF-Chem. Main primary and secondary pollutants are analysed, including SO₂, NO₂, PM_{2.5}, PM₁₀, and O₃. The "bottom-up" method is applied using AIS data in order to define a scenario of high occupancy of the harbor. Seasonal variations and their impact on local meteorology are then investigated by running the same scenario over different periods of 72 hours.

2 Methodology

2.1 Study area

The studied area is centered on Marseille, and includes the entire port of Marseille-Fos as represented in fig 1. The port is divided into two basins. The EAST basin, located in the city of Marseille, welcomes cargo ships, but especially pleasure boats, cruise ships and ferries. The WEST basin constitutes the industrial port area of Fos-sur-Mer to the WEST of Marseille. It is mainly used by vessels specialized in the transport of petroleum chemicals and container ships. The domain of interest (DOI) extends from 4.80°E to 5.80°E and from 42.89°N to 43.61°N, i.e. about 80*80 km². A sub-domain in blue is defined post-simulation to focus the analyses on Marseille.

2.2 Ship emissions

Emissions from ships are mainly based on the methodology of the European Environment Agency [6], with some updated tables taken from the EPA [8] report. The method evaluates vessel emissions, based on two characteristics: the gross tonnage (GT), and the boat type. Indeed, for each type was defined laws

were defined to determine the nominal power of the vessel given the GT. From these data it is possible to compute emissions according to the following formula:

$$E_{i,b,m,p} = \sum_e P_b * LF_{e,b,p} * EF_{i,e,m} / S$$

with $E_{i,b,m,p}$ the emission flux of the pollutant i from ship type b (Ro Ro Cargo; Bulk Carrier; Container; Passenger; General Cargo; Tug; Tanker) consuming fuel type m (Residual Oil, RO; Marine Diesel Oil, MDO; Marine Gas Oil, MGO) during phase p (cruise; manoeuvring; hotelling). P_b is the nominal power, $LF_{e,b,p}$ is the load factor for engine type e (Propulsion; Auxiliary; Boiler), $EF_{i,e,m}$ is the emission factor, and S the surface of a grid cell. This methodology is therefore applied to every boat included in the considered traffic scenario, which includes 42 boats at berth and 8 arrivals and departures per day with a GT ranging from 6680 to 157000. The height of naval emissions is defined at the second vertical level, i.e. 50m above the ground. Only cruise and hotelling phases are considered for a matter of simplicity.

2.3 Model setup

The model WRF-Chem (Weather Research and Forecasting Chemical model, version 4.2) has been applied in this study to evaluate the impact of maritime traffic on air pollution over Marseille and its surroundings. WRF-chem does online calculation of dynamical inputs (winds, temperature, boundary layer, and clouds), transport (advective, convective, and diffusive), dry deposition [24], gas-phase chemistry, radiation, and photolysis rates [20]. The following physical schemes are used in this study: the RRTM radiation scheme [15], the WSM-6 graupel microphysics scheme [11], the Bougeault and Lacarrère [1] turbulent kinetic energy (TKE) planetary boundary layer (PBL) scheme, the Noah land surface model and the MM5 similarity surface layer scheme [3]. As for chemistry, the chosen model MOZCART is a combination of two models: MOZART-4 as a gas-phase mechanisms and chemical transport model [7], and GOCART as an aerosol transport model [9]. Simulations are run with a three-level nesting, with a final horizontal resolution of $0.8*0.8 \text{ km}^2$ on the DOI. Meteorological inputs for initial and boundary conditions are derived from the National Centers of Atmospheric Research (NCAR) Final Analysis (GDAS/FNL) data, which were available at a $0.25^\circ \times 0.25^\circ$ resolution and a temporal resolution of 6 h. Anthropogenic emissions are taken from the EDGAR/HTAP annual emission inventory, to which hourly coefficients from Crippa et al. [5] were applied. Model of Emission Gases and Aerosols from Nature (MEGAN) allows the integration of biogenic isoprene emissions into WRF-Chem with a 1 km^2 spatial resolution [10].

Two 72-hour time slots per season are considered as presented in table 1. One for which the average wind is low and the other corresponding to an average wind with respect to the observations of the given season. These latter are taken from the meteorological station of Marignane for the year 2021 with a 3-hour time interval. For each time slot, two simulations, with and without ship emissions, are performed with the same conditions otherwise. The comparison of the two outputs enables to calculate the contribution of ship emissions on the concentration fields of the different species analyzed here.

Table 1: Weather conditions for each time slot over 2021

	Start/end dates	Wind speed $m.s^{-1}$	Wind direction $^\circ$	Temperature K	Nebulosity $Octas$
Winter	03 – 02/03 – 05	1.48	135	282.5	4.04
	01 – 23/01 – 26	5.68	315	281.4	3.42
Spring	04 – 22/04 – 25	2.71	180	288.1	1.16
	05 – 03/05 – 06	4.35	292.5	288.8	1.21
Summer	07 – 19/07 – 22	2.68	315	300.0	0.91
	08 – 28/08 – 31	5.40	315	295.0	0.83
Fall	11 – 19/11 – 22	1.19	135	283.5	1.79
	11 – 06/11 – 09	3.98	0	283.8	2.00

3 Results and Discussion

The difference between the output fields of the simulations with and without boat emission allowed us to determine their contributions for the different pollutants. Figure 2 shows time-averaged contribution of boats in PM 2.5 for time slots corresponding to typical wind speeds observed in each season. The areas with the highest contribution (between 35 and 50%) are located close to the docked vessels' positions. Plumes oriented in the direction of the prevailing winds are clearly observed, especially for time slots 20210828 and 20211106 where the wind direction was less fluctuating.

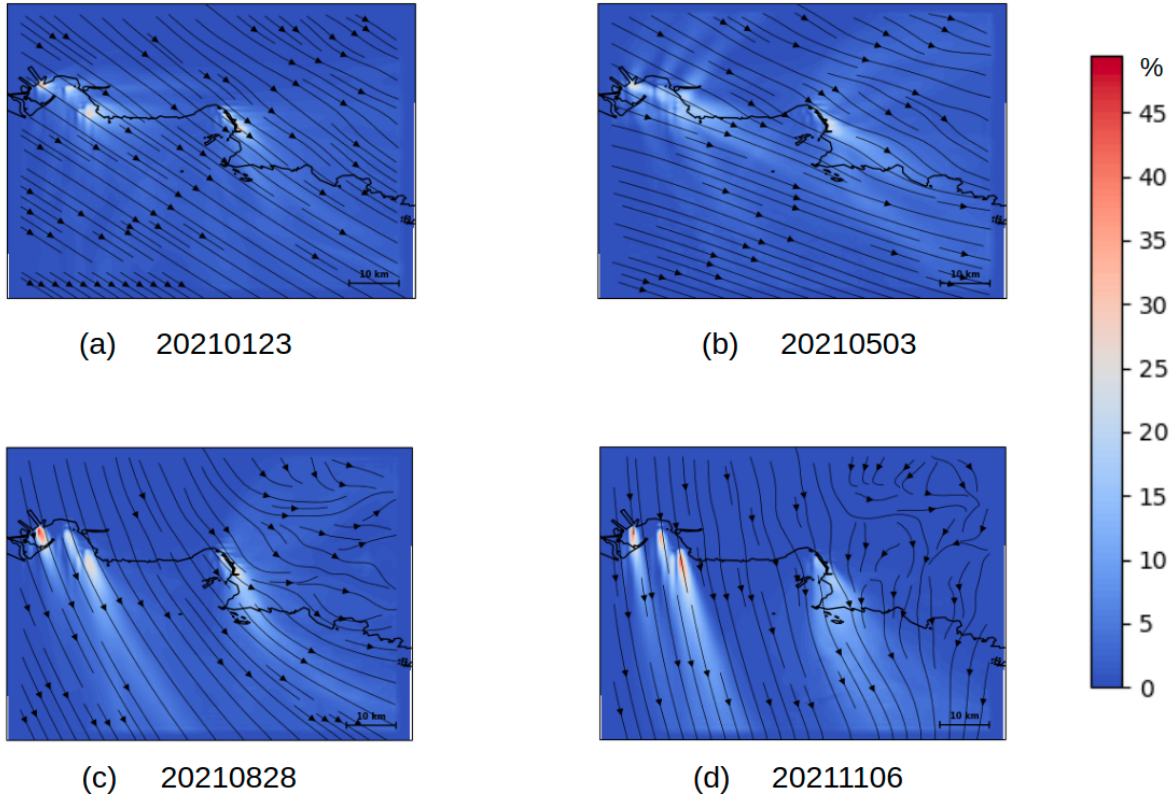


Figure 2: Contribution of ships to mean PM2.5 in %.
20210123 (a); 20210503 (b); 20210828 (c); 20211106 (d)

Table 2 presents the contribution for each pollutants. $\%_{Max}$ is the spatial maximum observed over the time-averaged contribution field whereas $\%_{Avg_Mrs}$ is the mean contribution over the rectangular sub-domain focused on Marseille represented in Fig.1. Calculations are done on the first simulated vertical domain only. Ships seem to play a greater role in aerosol concentration than in gas-phase species concentration. Indeed, boats are responsible for 3.5 to 12.8% of the concentration of particulate matter against about 1% for SO₂, NO₂ and ozone. This is partly due to the stack height of boats, emitting at 50m above ground. Gaseous species are much more volatile than aerosols and will tend to stay at the same level, while aerosols are subject to gravitational settling. PM2.5 and PM10 ship contribution levels are consistent with the results summarized in Viana et al. [22], (1-7% and 1-14% for PM10 and PM2.5 respectively). However, NO₂ levels are lower ($\sim 1\%$) than those presented in the study (7-24%). These low levels can also be explained by the fact that emissions during manoeuvring are not considered in the estimation of ship emission. In the CAIMANs report [17], emissions from manoeuvring phase are found to be much higher than those from hosteling phase, especially for SO₂. For all time slots and for every species, we note that the mean contribution of boats is higher over Marseille than over the whole domain. For instance, as it is for PM10, pollution from boats stands for $0.69 \mu g.m^{-3}$ on the domain against $2.83 \mu g.m^{-3}$ over Marseille on average for time slot 20210422. Regarding seasonal variations, the differences

from one season to another are not significant enough to conclude with such a small sample of days. However, it seems that the contribution of boats on ozone is higher in winter, when the nebulosity is at its highest level.

Table 2: Contribution of ships to pollutants concentration

Time slots		PM2.5 $\mu\text{g.m}^{-3}$	PM10 $\mu\text{g.m}^{-3}$	SO2 $\mu\text{g.m}^{-3}$	O3 $\mu\text{g.m}^{-3}$	NO2 $\mu\text{g.m}^{-3}$
03 – 02/03 – 05	%_Max	19.5%	21.8%	6.0%	9.3%	3.1%
	%_Avg_Mrs	3.5%	4.2%	0.6%	0.9%	1.1%
01 – 23/01 – 26	%_Max	35.2%	37.7%	10.4%	2.7%	5.0%
	%_Avg_Mrs	5.5%	6.2%	0.8%	1.3%	1.0%
04 – 22/04 – 25	%_Max	16.5%	18.3%	3.3%	5.0%	2.9%
	%_Avg_Mrs	6.1%	7.5%	0.9%	0.4%	1.1%
05 – 03/05 – 06	%_Max	29.2%	31.5%	5.6%	6.1%	3.2%
	%_Avg_Mrs	6.4%	7.4%	0.7%	0.5%	0.7%
07 – 19/07 – 22	%_Max	21.1%	24.2%	2.7%	3.5%	2.1%
	%_Avg_Mrs	10.7%	12.8%	1.0%	-0.1%	0.8%
08 – 28/08 – 31	%_Max	45.4%	50.7%	5.5%	7.2%	2.4%
	%_Avg_Mrs	5.9%	7.0%	0.7%	6.0e-3%	0.5%
11 – 19/11 – 22	%_Max	14.5%	15.0%	3.4%	10.3%	5.1%
	%_Avg_Mrs	7.55%	9.3%	1.0%	1.1%	1.5%
11 – 06/11 – 09	%_Max	40.6%	43.5%	8.6%	3.4%	3.0%
	%_Avg_Mrs	4.6%	5.7%	0.8%	0.34%	0.5%

4 Conclusions and future research

Air pollution from ships is still a major problem in Mediterranean coastal cities, since maritime traffic is constantly increasing and restrictions on the fuel used in this area are not sufficient. While studies on the impacts of ships are becoming more and more present worldwide, few have been conducted on the city of Marseille. In this work, we built a city-scale model using WRF-Chem that allows us to estimate the contribution of boats to air pollution for the major pollutants. The results showed higher contribution for PM10 and PM2.5, reaching about 13% in the worst case. However, the model seems to underestimate the contribution to gas-phase species concentration. Emissions from maneuvering phases are being considered for inclusion to correct this effect in the future. We also intend to analyze the influence of onshore power supply and a change in fuel quality. Finally, we are planning a full year study to better understand the effects of seasonality. Centre de Calcul Intensif d’Aix-Marseille is acknowledged for granting access to its high performance computing resources.

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