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Modeling of air pollution due to marine traffic in Marseille

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HIGHLIGHTS

- Ship contribution to Pollution in Marseille area is estimated with WRF-Chem.
- A high ship traffic scenario analyzed under eight typical meteorological conditions.
- Relative ship contribution is much higher for NO₂ and SO₂ than for PM_{2.5} and PM₁₀.
- Under low-wind conditions, ship pollution is more widespread than in moderate wind.
- Sea-land breeze transitions seem to enhance PM_{2.5} accumulation above Marseille.

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ABSTRACT

Marine 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, PM_{2.5}), NO₂, SO₂ and ozone, are responsible for respiratory diseases such as airway irritation, cardiopulmonary and lung cancers. The aim of this study is to estimate the impact of maritime traffic on air quality in Marseille in case of high port occupancy. The same ship traffic emission scenario will be studied under a series of typical meteorological conditions selected on the basis of a statistical seasonal analysis. This approach therefore differs from studies based on annualized ship traffic scenarios, which do not capture worst-case pollution. 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 relative difference in concentration between a situation with and without ship traffic allows us to evaluate the influence of ships on air quality. The results show an average ship contribution of between 1.5% and 5.7% for PM_{2.5}, with some local maximum of about 25% near the port. Contribution levels for gaseous species are much higher, with values reaching 40% for SO₂ and 80% for NO₂. The analysis of various meteorological conditions has highlighted a significant influence of wind speed and sea-land breeze dynamic on ship contribution.

1. Introduction

The seaways are increasingly frequented, both for development of international trade and for tourism. Although maritime activity has experienced a recent slowdown due to COVID-19, projections for 2050 anticipate a growth in global international maritime trade, with estimates ranging from a 25% to 250% increase (Anon, 2022). Besides, 70% of emissions related to maritime transport occur within 400 km from the coast (Endresen et al., 2003). In fact, most cruise ships continue to run their engines at berth, directly affecting the health of populations living near port areas. Various studies have highlighted the adverse effects of ship emissions on public health (Corbett et al., 2007; Viana et al., 2020; Contini and Merico, 2021). Since 2020, the

International Maritime Organization (IMO) has implemented measures to curb ship fuel emissions under Annex VI of the MARPOL (Marine Pollution Convention) (Anon, 2016), imposing a sulfur content limit of 0.5% m/m (mass to mass). Despite these efforts to regulate fuel pollutant content, elevated levels of sulfur oxides (SO_x), nitrogen oxides (NO_x), and fine particles (PM₁₀ and PM_{2.5}) persist in ship emissions. The Mediterranean Sea is under consideration for designation as a Sulfur Emission Control Area (SECA) zone in 2025, which would lower the sulfur content limit down to 0.1% m/m. A recent study conducted in the context of the Baltic Seas, where the SECA is already in effect, assessed the benefits of adopting such a policy, resulting in an estimated reduction in premature deaths attributable to maritime traffic of about

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35% (Barregard et al., 2019). 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 impact of port activity on air pollution using comprehensive 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 (Miola and Ciuffo, 2011). 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 of identifying emission sources using statistical methods based on measurements from sensors. This approach, called Receptor Modeling, is frequently used to estimate the sources of fine particles and aerosols (Viana et al., 2008). However, it does not account for secondary pollutants resulting from chemical transformations and reactions. One alternative is the use of air quality models (AQMs), which provide an effective solution to this problem by incorporating these secondary components. Various AQMs have been applied worldwide to determine the impact of marine traffic on air quality: CALPUFF in Napoli (Murena et al., 2018; Toscano et al., 2021); TAPM in Hamburg (Ramacher et al., 2020); CAMx in Europe (Jiang et al., 2020); AERMOD in Turkey (Kuzu et al., 2021) etc... WRF-Chem has been used extensively to assess the impact of maritime traffic on air pollution and has demonstrated high efficiency. In China, WRF-Chem is commonly used in the recent studies for that purpose (Wang et al., 2019; Chen et al., 2018; Huang et al., 2022; Ma et al., 2022; Cheng et al., 2023). WRF-Chem was also applied to study maritime pollution in the Arctic seas by Marelle et al. (2016) and Raut et al. (2022). However, the application of WRF-Chem to estimate the impact of maritime traffic on air quality has not yet been implemented in the western Mediterranean. Toscano (2023) has recently produced a detailed review of the numerous studies on the contribution of ship emissions to air quality in the main ports in the Mediterranean sea. Among the 32 studies referenced in the review, only one is carried in France, indicating a lack of studies of this type in the country. As the port of Marseille (GPM) has the highest number of calls in France, it has been the subject of a few studies when it comes to its impact on the city's air quality. Project APICE in 2012 (Salameh et al., 2018) followed by Project CAIMANS in 2015 (Piga and Armengaud, 2015) produced a comprehensive report comparing the impact of ships on air pollution in the main Mediterranean ports, including GPM. However, simulations in these projects were based on annual emission inventories, and therefore does not capture high and short emission events. In 2020, a significant measurement campaign was carried out in Marseille as part of the SCIPPER project. The report also includes a numerical study with simulations performed using the CMAQ model coupled to the CityChem dispersion model (Oppo et al., 2023). However, this study only covers 4 months from July to October.

The study aims to quantify the contribution of ship traffic to air pollution in Marseille and its vicinity under typical seasonal meteorological conditions, utilizing the fully coupled chemistry model WRF-Chem, considering a single high ship traffic emission scenario. This should allow us to better understand the contribution of ships in the worst-case scenarios, which cannot be captured when using annual emission inventories. The main primary and secondary pollutants are analyzed, including SO₂, NO₂, PM_{2.5}, PM₁₀ and O₃. Special emphasis is given to PM_{2.5}, acknowledged as the main pollutant in Europe, resulting in 238000 premature deaths in 2020, as reported by the EEA (European Environment Agency, 2022). The following section presents the model setup as well as the methodologies involved, such as the calculation of ship emissions, the selection of the typical seasonal meteorological conditions and the model validation. The last section relates to the analysis of the results.

2. Methodology

2.1. Study area

The studied area is centered on Marseille, and includes the entire port of Marseille-Fos as depicted in Fig. 1. The port is divided into two basins. The EAST basin, located in the city of Marseille, welcomes cargo ships but particularly pleasure boats, cruise ships and ferries. The WEST basin constitutes the industrial port area of Fos-sur-Mer, located 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. approximately 80 × 80 km². A post-simulation sub-domain of about 23 × 20 km² (from 5.26°E to 5.51°E and from 43.18°N to 43.39°N) is defined in blue to specifically focus the analyses on Marseille.

2.2. Background emissions

In this study, a distinction is made between ship emissions and other anthropogenic emissions, referred to as background emissions. One of the major sources of uncertainty in air quality forecasting is the lack of detailed data on emissions. The Provence-Alpes-Côte-d'Azur (PACA) region, of which Marseille is the main city, benefits from the services of an AASQA (Association Agréée de Surveillance de Qualité de l'Air) called AtmoSud, which has produced a detailed inventory of regional emissions with a spatial resolution of 1 km². AtmoSud is acknowledged for sharing its regional emission inventory of 2017 (AtmoSud, 2017). Temporal profiles were applied to the yearly averaged emission to capture yearly, monthly, daily and hourly fluctuations. Emission fields are projected on the WRF grids of the three nested domains, described in the model setup section. Due to the lack of information concerning background emission stack heights, we assumed all sources to be at ground level. Fig. 2 represents background emissions at 9 AM projected onto the third and smallest domain. Yearly ship emissions were removed from the original dataset and replaced with the maritime emission scenario described below.

2.3. Ship emissions

Emissions from ships are mainly based on the methodology of the European Environment Agency (EMEP/EEA, 2009) from 2019, with some complementary tables taken from the EPA (2009) report of 2009. The method evaluates vessel emissions, based on two characteristics: the gross tonnage (GT), and the type of the boat. Correlations have indeed been established for each vessel type to determine the nominal power based on the GT (EMEP-Tables 3–12). From these data it is possible to compute emissions according to the following formula:

$$E_{i,b,m,p} = \sum_e P_{b,e} * LF_{b,e,p} * EF_{i,e,m} / S \quad (1)$$

with $E_{i,b,m,p}$ the emission flux (in g km⁻² h⁻¹) of the pollutant i from ship type b (Ro Ro Cargo; Bulk Carriers; Container; Passenger; General Cargo; Tugs; Tanker) consuming fuel type m (Residual Oil, RO; Marine Diesel Oil, MDO; Marine Gas Oil, MGO) during phase p (cruise; maneuvering; hotelling). $P_{b,e}$ is the nominal power (in kW), $LF_{b,e,p}$ is the load factor for engine type e (Propulsion; Auxiliary; Boiler), $EF_{i,e,m}$ is the emission factor (in g kWh⁻¹), and S the surface of a grid cell (in km²).

As shown in the above equation, the total emission from a boat is the sum of the emissions from the Main (Propulsion), Auxiliary and Boiler engines. For propulsion engines, the nominal power is derived from EMEP Tables 3–12 functions, using the Mediterranean Sea fleet (2006). Tables 2–4 from EPA gives auxiliary to propulsion ratios for the nominal power.

The load factor depends on the engine type but also on the phase. LFs for Main and Auxiliary engines come from EMEP Tables 3–15

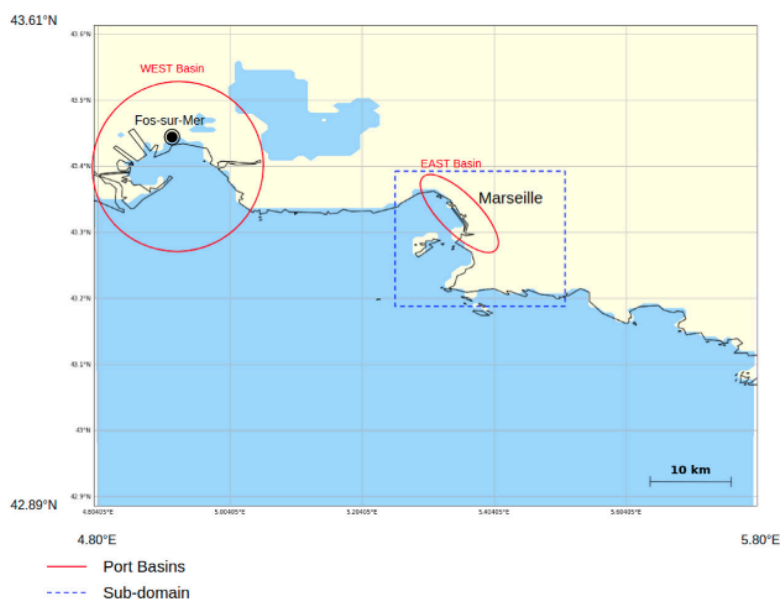


Fig. 1. Map of the study domain.

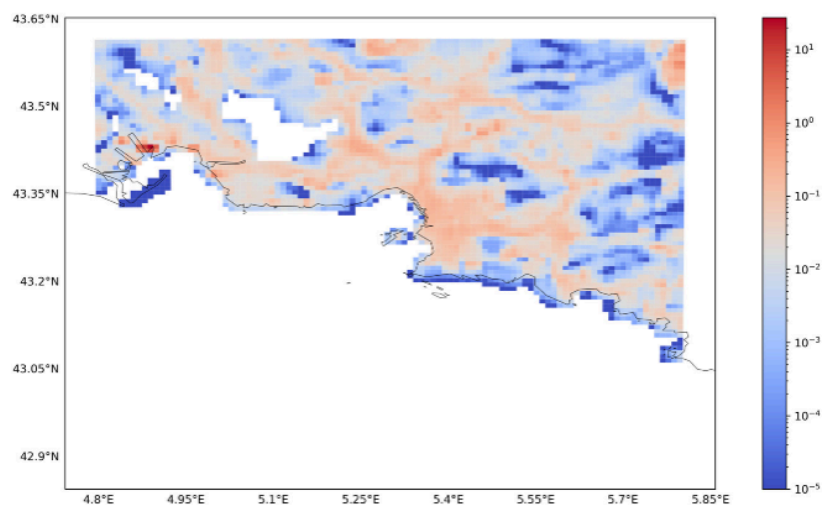


Fig. 2. 24-hour averaged $PM_{2.5}$ background emissions for 2021-04-22 in $\mu g m^{-2} s^{-1}$ (log scale). High emissions in the western port correspond to the refineries and chemical plants of Fos-sur-Mer.

and EPA Tables 2–7 respectively. For boilers, Tables 2–17 from EPA provides boilers power for each phase, which already includes the LF.

Emission Factors for Main Engines are taken from EPA Tables 2–9 combined with EMEP Tables 3–7 to take into account the different Propulsion engine sub-types (SSD, MSD, GT, ST). For Auxiliary Engines, Tables 2–16 from EPA provides EFs according to the fuel type. The EPA methodology assumes that Auxiliary Engines are using 29% of MGO and 71% of RO. However, regarding the regulations imposed by IMO in 2020, we assume that Auxiliary Engines use 100% of MGO with a sulfur mass content of 0.5% or less. EFs for boilers are taken from the ST (Steam Turbine) row of EPA Tables 2–9. Emissions are then converted to $\mu g m^{-2} s^{-1}$ for particles and $mol km^{-2} h^{-1}$ for gas-phase species.

The traffic scenario includes 45 boats per day with a GT ranging from 2158 to 235600. 28 incoming and 25 outgoing calls per day are modeled. This scenario, defined from observations using AIS data, represents a high occupancy of the port. Details of the average gross

tonnage per ship category are shown in Table 1. Cruising speeds depend on the boat type. They were taken from EPA Tables 2–6.

The height of ship emissions is defined at the second vertical level, i.e. 50 m above the ground. Due to the lack of information on maneuvering time and road layout, only the hotelling and cruising phases are taken into account for a matter of simplicity. Fig. 3 depicts an emission field of $PM_{2.5}$ used as an input for WRF-Chem. In the two basins, the isolated red dots represent emissions from boats during the hotelling phase. Additionally, the trails illustrate emissions from cruising boats.

Table 2 shows the annual emissions by sector taken into account in the simulations. Background emissions are taken from the AtmoSud 2017 inventory, while marine emissions are calculated and annualized on the basis of the high traffic scenario established in this study. The share of maritime emissions is greater for SO_x and NO_x compared to $PM_{2.5}$ and PM_{10} across the entire domain (26.4%, 30.3%, 11.7%, and

Table 1
Ship traffic scenario.

	Passenger	Cargo	Tanker	Container	Bulk	Tot.
No. of boats in WEST basin	0	1	16	6	1	24
No. of boats in EAST basin	15 ^a	4	0	2	0	21
Average GT	65 917	23 272	11 160	71 038	31 000	41 844
Average Hotelling time	10h30	19h00	15h30	10h00	10h45	13h08

^a 6 Cruises and 9 Ferries

Table 2

Yearly emissions by activity sector. All emissions are taken from AtmoSud emission inventory 2017 except for ship emissions that are based on the traffic scenario defined earlier. D3 was divided into two areas by a longitudinal line at 5.10°E. W3 and E3 zones are respectively to the west and east of the demarcation line.

Zone of Interest	Activity Sector	PM _{2.5} Ton	PM ₁₀ Ton	SO _x Ton	NO _x Ton
D3	Energy	177.58	246.24	8810.99	6243.41
	Industry	1620.83	2813.71	5323.33	9380.70
	Res./Com./Inst.	1028.08	1059.21	204.75	1734.40
	Non-maritime Transport	939.78	1472.68	57.06	12396.11
	Maritime Transport	635.75	692.25	5201.28	13257.61
	Agriculture	57.87	106.21	4.52	335.41
	Waste Management	4.58	6.28	22.07	46.73
	Biogenic	948.21	948.21	50.40	317.96
W3 (5.10°E to 5.80°E)	Energy	19.30	29.59	997.73	1046.91
	Industry	448.42	1105.24	1719.20	3173.76
	Res./Com./Inst.	898.23	925.82	180.15	1181.63
	Non-maritime Transport	842.15	1314.72	53.67	11189.15
	Maritime Transport	407.87	444.45	3349.30	9319.01
	Agriculture	37.08	74.80	3.44	252.37
	Waste Management	2.86	3.25	7.24	22.38
	Biogenic	822.40	822.40	43.72	267.80
E3 (4.80°E to 5.10°E)	Energy	158.28	216.65	7813.26	5196.50
	Industry	1172.41	1708.47	3604.13	6206.94
	Res./Com./Inst.	129.86	133.39	24.60	552.77
	Non-maritime Transport	97.63	157.97	3.39	1206.95
	Maritime Transport	227.88	247.81	1851.97	3938.60
	Agriculture	20.79	31.41	1.08	83.04
	Waste Management	1.72	3.03	14.83	24.35
	Biogenic	125.81	125.81	6.69	50.15

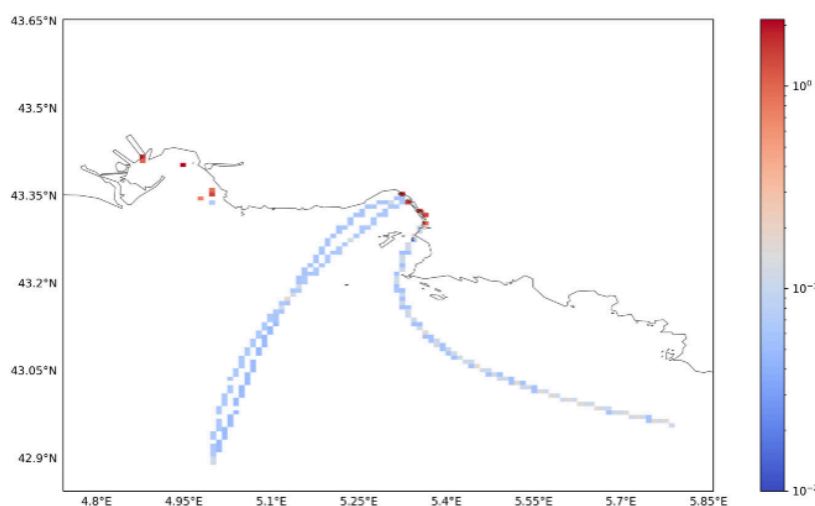


Fig. 3. 24-hour averaged PM_{2.5} estimated ship emissions for 2021-04-22 in $\mu\text{g m}^{-2} \text{s}^{-1}$ (log scale).

9.42% respectively). For all pollutants, we note a significant contribution from industrial sources in W3, mainly due to the high activity of chemical, oil and gas plants in Fos.

2.4. Model setup

The model WRF-Chem (Weather Research and Forecasting Chemical model, version 4.2) was used in this study to evaluate the impact of

maritime traffic on air pollution over Marseille and its surroundings. WRF-Chem performs online calculation of dynamical inputs (wind, temperature, boundary layer, and clouds), transport (advective, convective, and diffusive), dry deposition (Wesely, 2007), gas-phase chemistry, radiation, and photolysis rates (Tie, 2003). The following physical schemes are used in this study: the RRTM radiation scheme (Mlawer et al., 1997), the WSM-6 graupel microphysics scheme (Huang et al., 2015), the Bougeault and Lacarrère (1989) turbulent kinetic energy

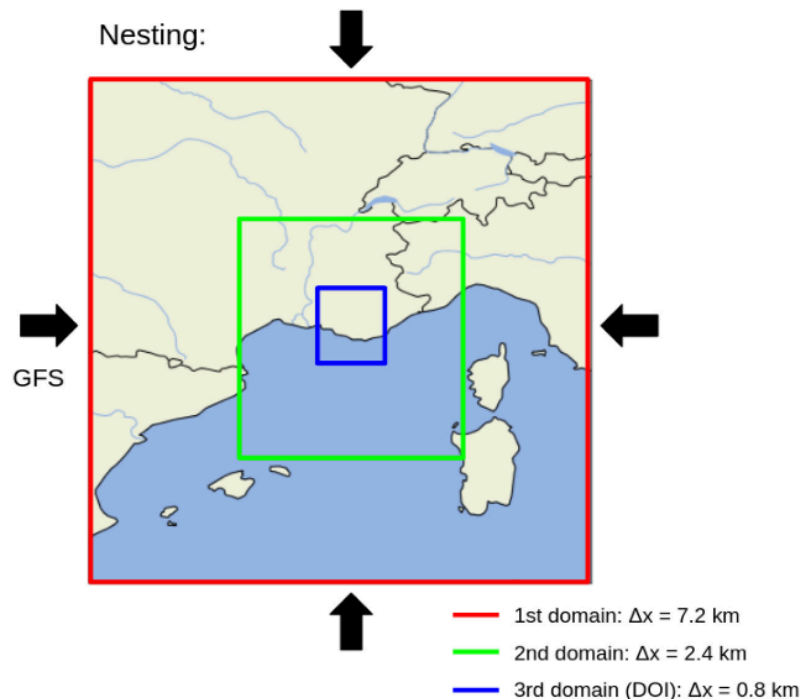


Fig. 4. Map of the three nested domains.

(TKE) planetary boundary layer (PBL) scheme, the Noah land surface model and the MM5 similarity surface layer scheme (Chen and Dudhia, 2001). Land use data, obtained from IGBP-Modified MODIS (2010), is presented in Appendix B along with its associated categories and parametric values, such as roughness length or albedo. As for chemistry, the chosen model MOZCART is a combination of two models: MOZCART-4 as a gas-phase mechanism and chemical transport model (Emmons et al., 2010), and GOCART as an aerosol transport model (Ginoux et al., 2001). Simulations are run with a three-level nesting, as shown in Fig. 4, with a final horizontal resolution of 0.8×0.8 km² on the DOI. The model contains 50 vertical levels defined according to the terrain-following η -coordinate system (see Skamarock et al. (2021) for more information). The distribution of vertical levels is detailed in Appendix A. The grid used by the solver is staggered both horizontally and vertically. The three components of the wind (U , V and W) are computed on the edges of the grid cells whereas the scalar variables are defined at mass points. The chemical variables discussed are calculated at mass points that lie between ground level and the first vertical layer, which is approximately 50 m above ground. Meteorological inputs for initial and boundary conditions are derived from the National Center for Atmospheric Research (NCAR) Final Analysis (GDAS/FNL) data, which were available at a resolution of $0.25^\circ \times 0.25^\circ$ and a temporal resolution of 6 h. Model of Emission Gases and Aerosols from Nature (MEGAN) allows the integration of biogenic isoprene emissions into WRF-Chem with a spatial resolution of 1 km² (Guenther et al., 2006).

2.5. Model validation

The meteorological part of the model has been compared with results from the operational forecast model Arome developed by Météo France. Arome provides hourly data with a resolution of $0.01^\circ \times 0.01^\circ$ (1.3 km²). Although the study focuses on the year 2021, the validation process uses data from 2022 due to restricted access to certain meteorological data. The period of comparison extends from 2022-09-05 to 2022-09-18, with a forecast of 23 h every day. WRF outputs were interpolated on Arome's horizontal grid using the cubic method of `scipy.interpolate` library on Python. The variables under comparison

Table 3
Comparison between WRF and Arome from 2022-09-05_00:00:00 to 2022-09-18_23:00:00.

Variable	T2 K	U m s ⁻¹	V m s ⁻¹	RH %	PS hPa
MAE	0.95	1.67	1.99	7.65	1.12
MBE	0.04	-0.37	0.40	0.74	-0.02
RMSE	1.26	2.14	2.54	9.70	2.01

are: temperature (T2) and relative humidity (RH) at 2 m, pressure at sea level (PS) and the two horizontal components of wind speed U and V at 10 m. Table 3 presents the differences between WRF and Arome. They are calculated according to the following three metrics: Mean Bias Error (MBE), Absolute Error (AE) and Root Mean Square Error (RMSE). The values in the table are the time-averaged metrics over 14 days of simulation. The differences on the domain are relatively small since the spatial average absolute temperature difference is 0.95 K. However, larger differences, approaching 7 K, are observed over some areas as shown in Fig. 5, which is a snapshot of the T2 Absolute Difference field from 2022-09-10 at 7 PM. These zones correspond to a high elevation of ground. The mismatch between the topology of the two models induces temperature differences. This also explains the high local differences on the surface pressure fields of approximately 24 hPa, although the RMSE over the entire domain remains low at 2.01 hPa. The models seem to differ more in terms of relative humidity, with a high RMSE of 9.70% and a low MBE of 0.74%, indicating high variability.

The models were then compared to observations from the meteorological station Marignane over the same period, located at (43.44°N, 5.23°E). The station provides data on the same variables as seen above. The trends of the predicted variables over the 24-hour simulation period are found to be close to the station measurements, according to the time series on Fig. 6. Analysis on the 14-day period is summarized in Table 4. Temperature is slightly overestimated by both WRF and Arome, with average errors of 0.22 and 0.35 K respectively. WRF performs better for wind speed, although both models underestimate

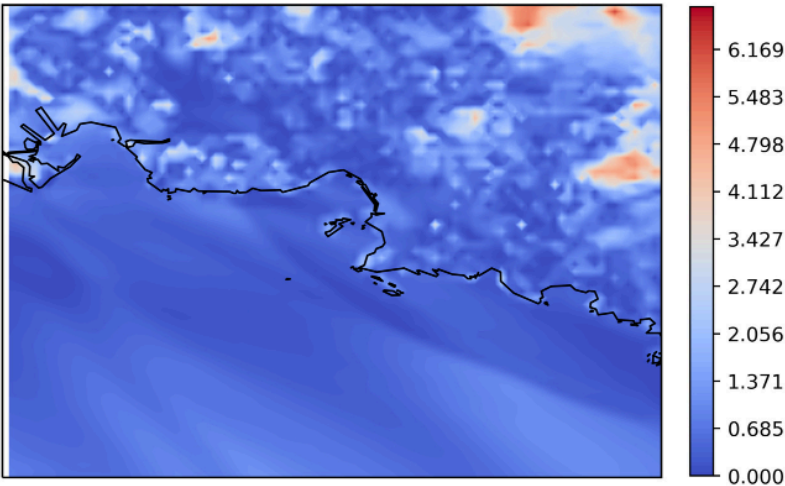


Fig. 5. T2 absolute difference between WRF and Arome for 2022-09-10 at 7 PM (UTC+2).

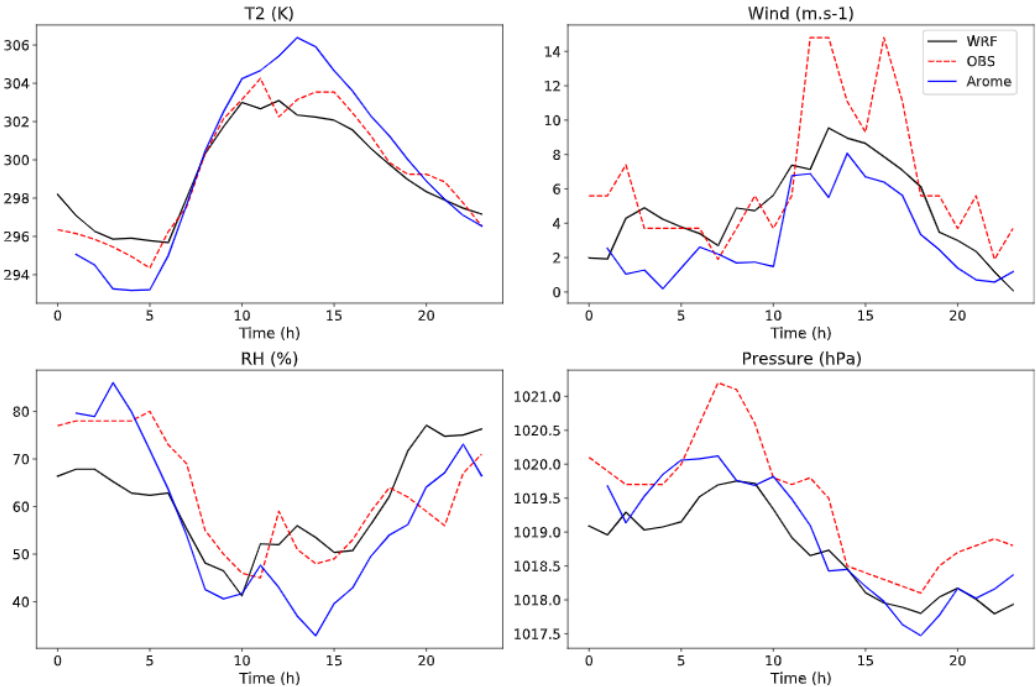


Fig. 6. Time series of WRF, Arome and Observations from Marignane for 2022-09-05. ($Wind = \sqrt{U^2 + V^2}$).

wind speed by approximately 4 m s^{-1} . Arome has better results regarding relative humidity in Marignane. Both pressure surfaces RMSE are smaller than 1 hPa, which we believe to be accurate. Figures from both Tables 3 and 4 confirm that WRF and Arome provide forecasts with similar errors over the DOI. Therefore, the results obtained in this section allow us to consider that the meteorological predictions of the WRF model are sufficiently consistent and reliable for this case study.

2.6. Time slot selection

In order to capture the behavior of boat pollution under various meteorological conditions, two 72-hour statistically significant time slots per season were considered. The selection of these time slots was based on a statistical study of observations from the meteorological station of Marignane for the full year 2021 with a 3-hour time interval. Observations are first filtered and split in two categories of wind speed,

Table 4
Errors of WRF and Arome with respect to observations from Marignane from 2022-09-05 to 2022-09-18.

Variable		T2	Wind Speed	RH	PS
Unit		K	m s^{-1}	%	hPa
WRF	MBE	0.22	-3.96	-5.38	-0.58
	RMSE	1.35	5.15	9.73	0.79
AROME	MBE	0.35	-4.91	-2.37	-0.38
	RMSE	1.01	5.80	7.82	0.62

defined from the Beaufort scale (bf). The wind is considered weak between 0.3 and 3.4 m s^{-1} (1–2 bf) and moderate from 3.4 to 7.9 m s^{-1} (3–4 bf). For each season, one time slot with weak wind and one time slot with moderate wind are selected. Seasonal averages of the 2 m temperature and nebulosity were calculated and used as criteria

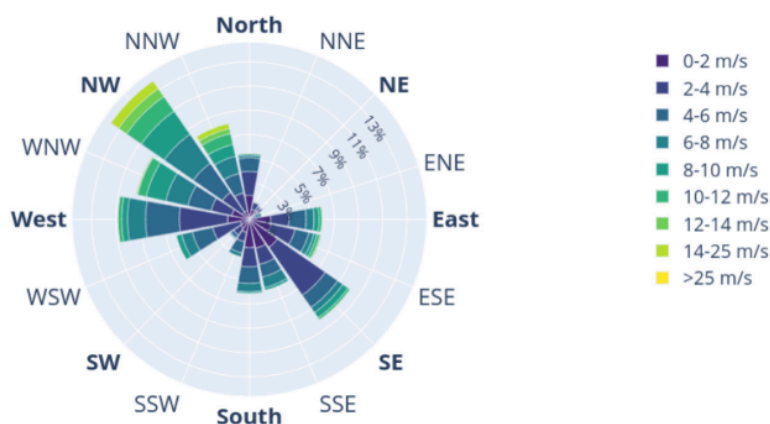


Fig. 7. Windrose of 2021 from Marignane meteo station.

Table 5
Weather conditions for each time slot over 2021.

	Start/end dates	Wind speed m s ⁻¹	Wind direction	Temperature K	Nebulosity Octas
Winter	03 – 02/03 – 05 (W1)	1.48	SE	282.5	4.04
	01 – 23/01 – 26 (W2)	5.68	NW	281.4	3.42
Spring	04 – 22/04 – 25 (Sp1)	2.71	S	288.1	1.16
	05 – 03/05 – 06 (Sp2)	4.35	W	288.8	1.21
Summer	07 – 19/07 – 22 (Su1)	2.68	NW	300.0	0.91
	08 – 28/08 – 31 (Su2)	5.40	NW	295.0	0.83
Fall	11 – 19/11 – 22 (F1)	1.19	SE	283.5	1.79
	11 – 06/11 – 09 (F2)	3.98	N	283.8	2.00

for selecting the time slots. Wind has a strong advective effect on the chemical species present in the atmosphere. The location of the areas most impacted by pollution is therefore strongly dependent on wind direction. As discussed in Ma et al. (2022), a sea breeze can significantly enhance the transport of pollutants from shore to land. Fig. 7 shows the annual distribution of wind direction measured at the station of Marignane during 2021. Three main directions have been identified: North-West, West, and South-East, which align with the local winds known as the Mistral, the Tramontane, and the Marin, respectively. The selection, presented in Table 5, was made so that each one of these three winds are dominant during at least one of the time slots.

For each time slot, two simulations, with and without ship emissions considered, are performed with the same conditions otherwise. The difference between the two outputs is used to calculate the contribution of ship emissions to the concentration levels of the analyzed species. This approach is known as the “zero-out method”.

3. Results and discussion

Figs. 8 and 9 show time-averaged contribution of boats to PM_{2.5} for time slots corresponding to weak and moderate wind speeds respectively. Comparing the two figures, one can notice that under weak wind conditions, the contribution of boats is more spread out and lower than for moderate wind conditions. High contribution values are observable as red spots on Fig. 9. The contribution of boats in these areas ranges between 20 and 25%. The location of these hot spots corresponds to the positions of the docked vessels. Plumes oriented in the direction of the prevailing winds are clearly observed, especially for time slots Su2 and F2 where the wind direction was less fluctuating. Contributions to NO₂ and SO₂ are provided in Appendix C. Table 6 presents the contribution for each pollutant. %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 level only (see Appendix A). Ships appear to have a larger impact on gas-phase species concentration than on aerosol concentration. Boats contribute to approximately 1.48 to 7.6% of the particulate matter concentration, while their contribution to SO₂ and NO₂ concentrations is higher, accounting for over 30%. PM_{2.5} and PM₁₀ ship contribution levels are consistent with the results summarized in Viana et al. (2014) (1%–14% and 1%–7% respectively). However, NO₂ levels are higher (~70%) than those presented in the study (7%–24%). “The Scipper Project”, a recent campaign aimed at evaluating ship pollution, conducted assessments in various port cities, including Marseille. The findings indicate that boats in Marseille contribute an average of 31% to NO₂ levels, while in Gothenburg and Kiel, the contributions reach 73% and 75% respectively (Oppo et al., 2023). The elevated levels of NO₂ contribution observed from the WRF-Chem simulations can be attributed to the specific conditions considered in this study, which include a high occupancy scenario at the port and weak or moderate wind conditions. PM_{2.5} and SO₂ contribution levels are in line with the Scipper Project values for Marseille (i.e. 3% and 34% respectively). 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 0.47 µg m⁻³ on the domain against 1.56 µg m⁻³ over Marseille on average for time slot Su1. It is observed that in most cases, the contribution of ships to ozone is negative. This is primarily due to the complex chemical process involved in ozone formation in the atmosphere. The emission of nitrogen oxide (NO) by ships enhances a specific chemical reaction, resulting in a decrease in ozone concentration. The reaction can be represented as:



The results discussed here are obtained without considering the maneuvering phase, as indicated earlier. However, emission factors associated with this phase are typically greater than those for the hotelling phase. This suggests that the values presented here might

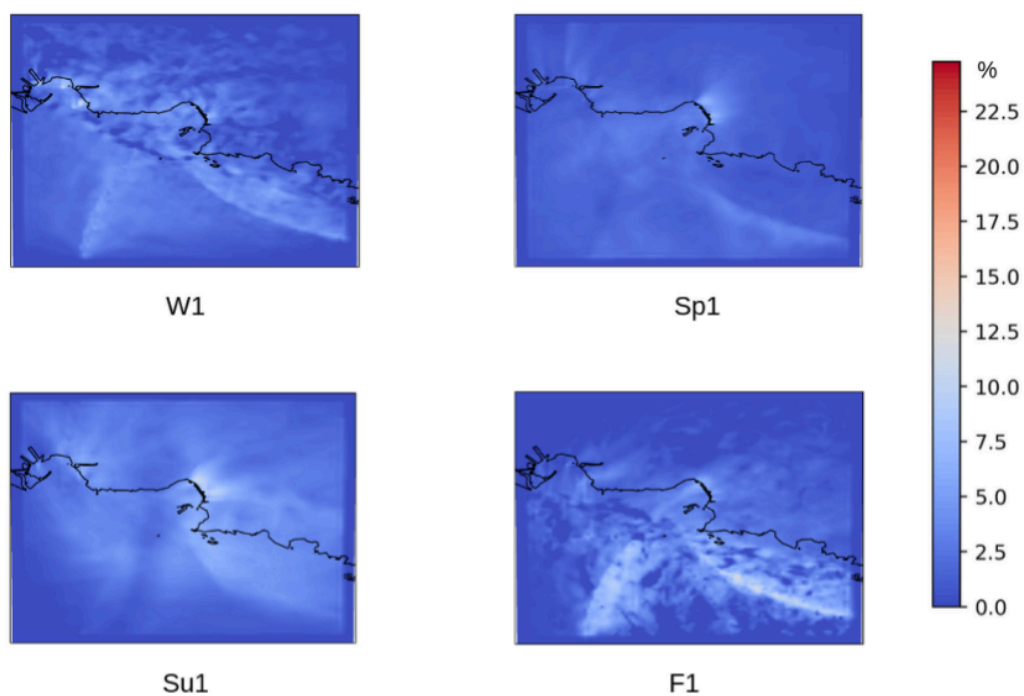


Fig. 8. 72-hour averaged contribution of ships to $PM_{2.5}$ concentration in % for weak winds.

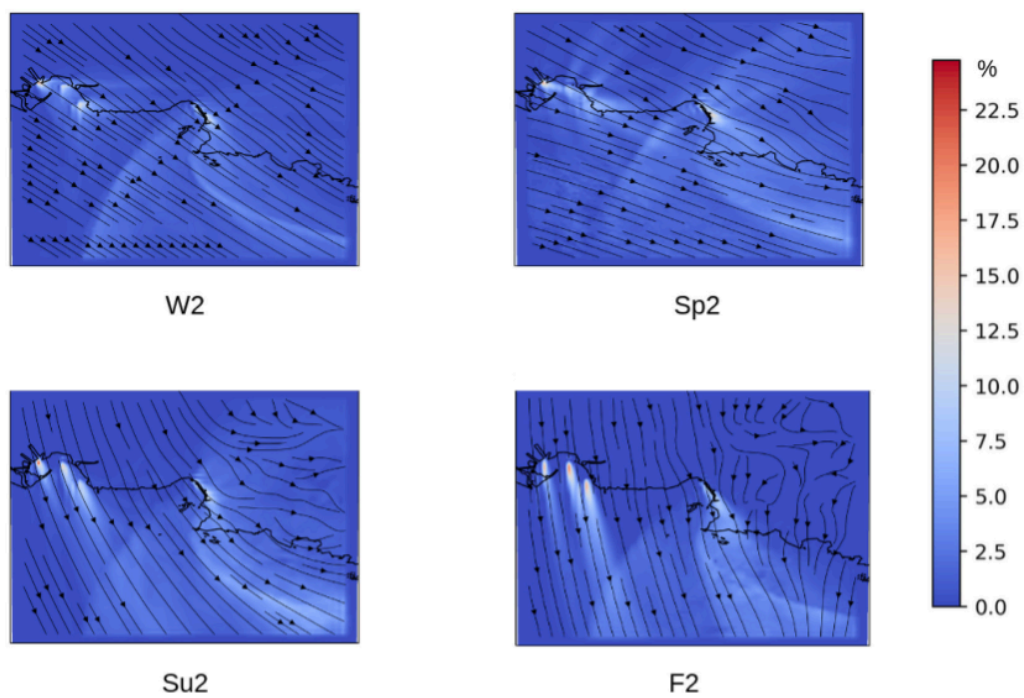


Fig. 9. 72-hour averaged contribution of ships to $PM_{2.5}$ concentration in % for moderate winds.

underestimate the actual contributions and concentrations. Considering all phases would provide a more comprehensive representation of maritime pollution.

Only the relative contribution of ships to total pollution has been discussed so far. These graphs do not provide information on the meteorological conditions that lead to the highest concentration values. Fig. 10 aims to compare the time slots in terms of concentration of ship-emitted $PM_{2.5}$. It was obtained by subtracting the time-averaged concentration values of W2 (corresponding to the lowest $PM_{2.5}$ values) from all time slots. As expected, weak winds (first row) lead to higher differences than moderate winds (second row). Highest values of concentration in $PM_{2.5}$ are mostly located over Marseille. For the same traffic scenario, the time-averaged $PM_{2.5}$ concentration can vary by $3 \mu g m^{-3}$ locally from one meteorological condition to another. In every case, the difference is stronger above Marseille. For slot F1, the average difference is $0.22 \mu g m^{-3}$ for the entire domain and reaches $2.55 \mu g m^{-3}$ over the city.

Total pollution was analyzed along shorelines defined at a certain distance from the coast, as represented in the upper half of Fig. 11. Given the higher contribution from ships for Su1, our focus for this analysis will be on the corresponding time slot. Outside of Marseille and Fos, $PM_{2.5}$ concentration does not seem to depend on the distance from the coast. However, for longitudes crossing Marseille, the shorter the distance, the higher the concentration. Indeed, Table 7 emphasizes a stronger gradient in Marseille than outside its borders. This was observed for all time slots, meaning that the meteorological conditions do not explain this correlation between distance from the shore and concentration. Since boats are the main source of pollution on the coast of Marseille, it seems legitimate to believe that the main cause of this concentration gradient is the presence of hotelling boats. The pollution in the Fos area is mainly caused by the presence of chemical plants near the shore. The influence of ships in this area is therefore difficult to identify from this figure. We note that the WHO guideline for $PM_{2.5}$ defined as $15 \mu g m^{-3}$ 24-hour average is far exceeded in Fos-sur-Mer and Marseille close to the shoreline, where concentration reaches $66.3 \mu g m^{-3}$ and $27.7 \mu g m^{-3}$ respectively.

When the wind is weak, the sea–land breeze dominates, establishing an onshore wind during the morning that persists throughout the day, referred to as the diurnal breeze. In the evening, an inversion occurs, leading to the observation of a nocturnal offshore wind. These inversions occur when the land warms up (in the morning) or cools down (in the evening). Moreover, the sea breeze is expected to be more intense in spring and summer when temperatures reach higher values during the day, as opposed to the land breeze, which are more intense in Winter and Fall (Federico et al., 2010). To analyze this phenomenon, we introduce the breeze vector, defined as a unit vector oriented inland along the normal to the Marseilles coastline. We then calculate the scalar product between the breeze vector and each of the normalized wind vectors over the Marseilles sub-domain. Thus, the scalar product equals 1 when the wind is onshore and perfectly aligned with the breeze vector. To better understand the effects of this phenomenon on maritime pollution, Fig. 12 shows the time series of the average scalar product superimposed on the average $PM_{2.5}$ concentration attributed to ship emissions over Marseille for each time slot of weak wind. Generally, an onshore wind is observed during the day and offshore at night. Morning inversions take place between 8 and 11 AM, while evening inversions occur between 6 and 9 PM. As the time slots are chosen according to each season, it is coherent to note that the inversion takes place earlier in the morning and later in the evening during summer, effectively prolonging the onshore period. Consequently, maritime pollution is carried towards the city for a longer period compared to other seasons. Additionally, it is observed that for Su1, a south wind neutralizes the offshore regime, and no predominant wind direction is observed at night. This seems to be even more conducive to the accumulation of $PM_{2.5}$ above the city, as it is no

Table 6
Contribution of ships to pollutants concentration.

Time slots		$PM_{2.5}$ $\mu g m^{-3}$	PM_{10} $\mu g m^{-3}$	SO_2 $\mu g m^{-3}$	O_3 $\mu g m^{-3}$	NO_2 $\mu g m^{-3}$
W1	%_Max	13.7%	15.3%	69.6%	11.1%	70.0%
	%_Avg_Mrs	2.25%	2.91%	39.7%	−9.86%	68.0%
W2	%_Max	16.2%	15.7%	88.0%	9.79%	93.7%
	%_Avg_Mrs	2.34%	2.74%	34.2%	4.14%	68.9%
Sp1	%_Max	9.47%	12.1%	57.4%	3.58%	57.9%
	%_Avg_Mrs	3.21%	4.41%	43.2%	−19.7%	64.7%
Sp2	%_Max	17.1%	16.3%	71.9%	12.0%	81.8%
	%_Avg_Mrs	3.13%	3.68%	33.1%	−5.83%	75.0%
Su1	%_Max	11.2%	14.1%	60.8%	3.31%	76.3%
	%_Avg_Mrs	5.69%	7.60%	39.3%	−31.5%	79.1%
Su2	%_Max	23.8%	24.9%	80.5%	1.13%	79.6%
	%_Avg_Mrs	2.33%	2.88%	33.9%	−11.6%	49.9%
F1	%_Max	12.4%	14.6%	54.6%	3.26%	57.0%
	%_Avg_Mrs	3.71%	5.23%	39.4%	−55.2%	50.7%
F2	%_Max	20.4%	25.5%	61.7%	5.88%	87.4%
	%_Avg_Mrs	1.48%	2.06%	25.5%	−14.5%	36.4%

Table 7
 $PM_{2.5}$ Concentration levels along distances from shore for time-slot Su1 in $\mu g m^{-3}$. Tot. is for total domain. Marseille and Fos are splitting shorelines in longitude according to the borders represented in Fig. 11. Outside refers to the remaining longitudes of the domain.

	Marseille	Fos	Outside	Tot.
1 km	14.06	22.15	10.84	13.91
3 km	12.50	14.41	9.15	11.04
5 km	11.31	11.28	8.22	9.61
10 km	9.95	8.78	8.69	9.04
20 km	8.19	6.52	5.26	6.19

longer swept by the land breeze. For these two reasons, the configuration appears highly unfavorable in terms of maritime pollution. Indeed, Su1 is the period during which the maritime contribution in $PM_{2.5}$, PM_{10} , and NO_2 is the strongest in Marseille (Table 6). The fact that the maritime emission scenario remains the same for each simulated day reinforces our interpretation, as inter-seasonal variations cannot be explained by emission variations. The inversion of the wind regime appears to have a significant impact on the concentration of $PM_{2.5}$. In most cases, a concentration peak is observed during wind regime transition phases. This phenomenon seems clearer for Sp1, which can be explained by a greater amplitude of wind direction oscillation.

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 impact of ships are becoming more and more present worldwide, few have been conducted in the city of Marseille. In this work, we developed a city-scale model using WRF-Chem that allows us to estimate the contribution of boats to air pollution for the major pollutants. The contribution of boats was estimated at over 5% and 7% for $PM_{2.5}$ and PM_{10} respectively in the worst-case scenarios. For SO_2 and NO_2 , contributions reach higher values (40% and 80%). The O_3 contribution is negative in most cases. The analysis of typical seasonal meteorological conditions for the same ship traffic scenario enabled us to examine the impact of wind on ship pollution. Comparing different time slots revealed that the dispersion of ship-induced pollution is significantly influenced by wind speed, displaying a more pronounced effect during periods of low wind speed. Additionally, there appears to be a significant influence of the sea breeze, as indicated by the occurrence of peaks in maritime pollution during sea–land breeze inversions.

As the study is not based on a real case scenario, but on the same shipping traffic scenario under different weather conditions, the

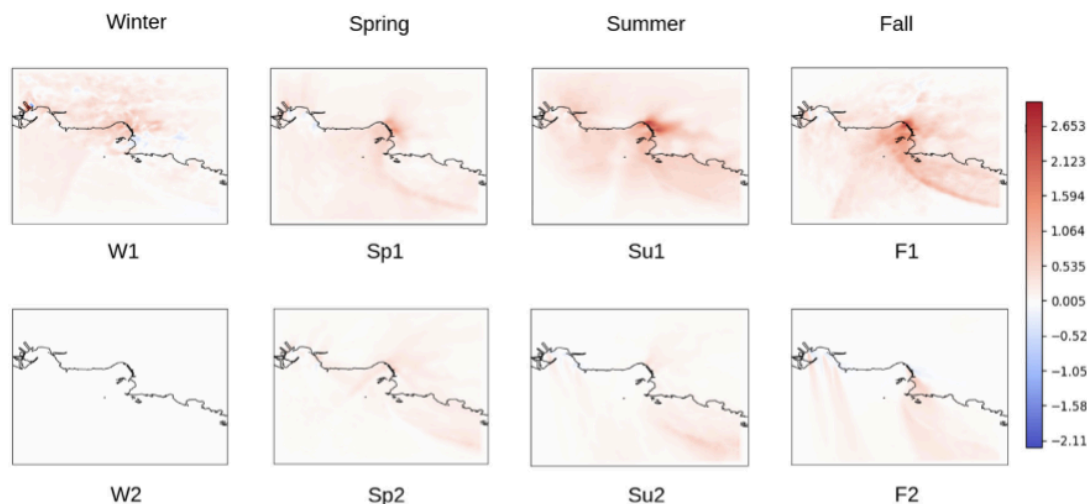


Fig. 10. Differences between all time slots and W2 in ship-emitted $PM_{2.5}$ concentration in $\mu g m^{-3}$. First and second rows correspond to weak and moderate winds respectively.

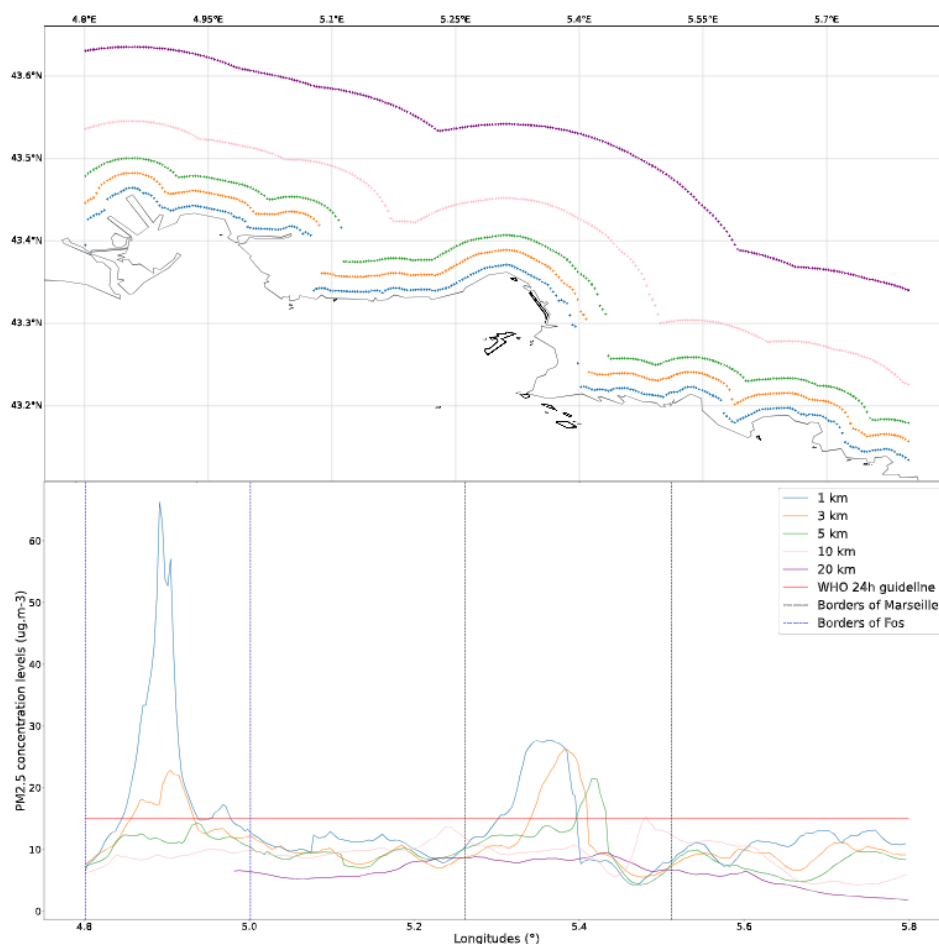


Fig. 11. Top: map of the 5 shorelines; Bottom: 72-hour averaged $PM_{2.5}$ concentration levels along the shorelines for time-slot Su1. Borders of Fos: 4.80°E to 5.00°E; Borders of Marseille: 5.26°E to 5.51°E.

contribution values for ships are not intended to be representative of a situation that might have occurred in the past. Forthcoming access to GPMM maritime traffic data will enable us to compare model results with observations and incorporate real case studies in our next article.

Onshore power supply is increasingly seen as an effective way to reduce emissions from ships at berth. GPMM authorities have announced

the installation of 12 possible connections by 2025 in addition to the 4 already installed in 2017. We are planning to quantify the air quality benefits of such installations.

Another solution would be to improve the fuel quality by using liquid natural gas (LNG) instead of heavy fuel oil (HFO). The methodology

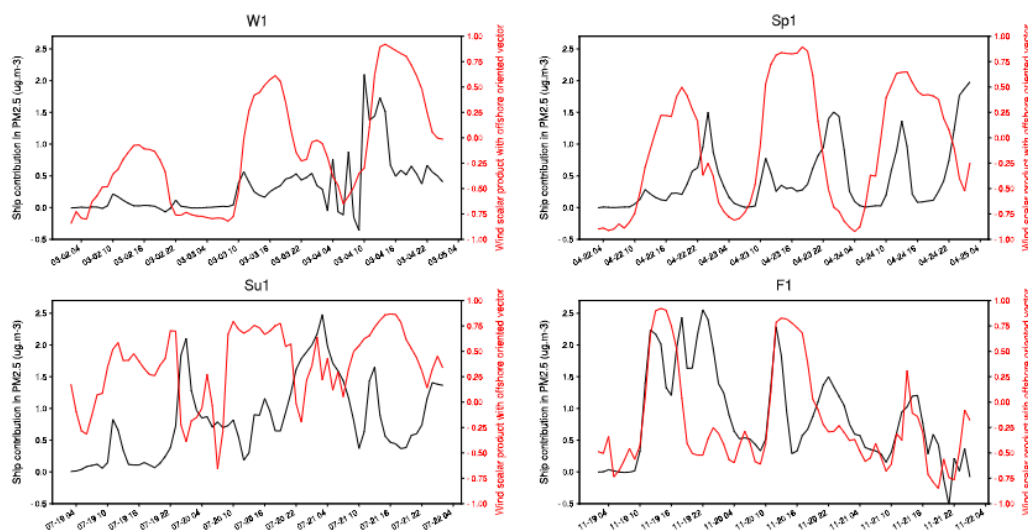


Fig. 12. In black: Time series of $PM_{2.5}$ ship-emitted average concentration over Marseille; In red: Time series of average scalar product between the sea-breeze vector and wind direction over Marseille.

presented in this article can easily include these changes by modifying the emission factors according to the solutions considered.

Finally, we are considering a full year study to better understand the effects of seasonality.

CRedit authorship contribution statement

E. Chevet: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **O. Boiron:** Writing – review & editing, Supervision, Project administration, Methodology. **F. Anselmet:** Writing – review & editing, Supervision, Methodology, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Centre de Calcul Intensif d'Aix-Marseille is acknowledged for granting access to its high performance computing resources.

AtmoSud is acknowledged for providing the detailed 2017 regional emission inventory from the CIGALE database.

Appendix A. WRF-CHEM vertical levels

See [Figs. A.1 and A.2](#).

Appendix B. IGBP-Modified MODIS land use

See [Fig. B.1](#).

Appendix C. Ship contribution to NO_2 and SO_2

See [Figs. C.1–C.4](#).

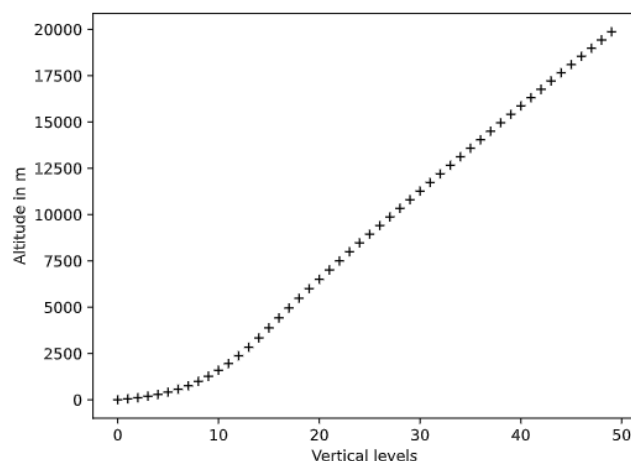


Fig. A.1. Mean elevation of vertical levels.

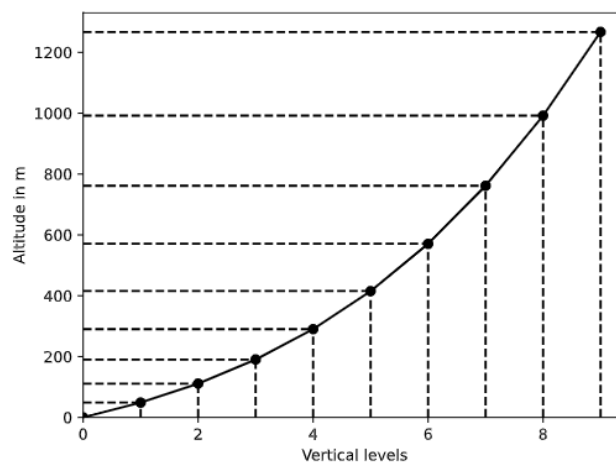


Fig. A.2. Mean elevation of the first 10 levels.

Class No.	Class name	Roughness length (m)	Albedo (%)	Building height (m)
1	Evergreen needleleaf forest	0.50	12	—
2	Evergreen broadleaf forest	0.50	12	—
3	Deciduous needleleaf forest	0.50	14	—
4	Deciduous broadleaf forest	0.50	16	—
5	Mixed forests	0.50	13	—
6	Closed shrublands	0.05	22	—
7	Open shrublands	0.06	20	—
8	Woody savannas	0.05	22	—
9	Savannas	0.15	20	—
10	Grasslands	0.12	19	—
11	Permanent wetlands	0.30	14	—
12	Croplands	0.15	17	—
13	Urban and built-up	0.80	15	—
14	Cropland/natural vegetation mosaic	0.14	18	—
15	Snow and ice	0.001	55	—
16	Barren of sparsely vegetated	0.01	25	—
17	Water	0.0001	8	—
18	Wooded tundra	0.30	15	—
19	Mixed tundra	0.15	15	—
20	Barren tundra	0.10	25	—
31	Low-intensity residential	0.80	10	5.0
32	High-intensity residential	0.80	10	7.5
33	Industrial or commercial	0.80	10	10.0

Fig. B.1. 20-category IGBP-Modified MODIS Land Use.

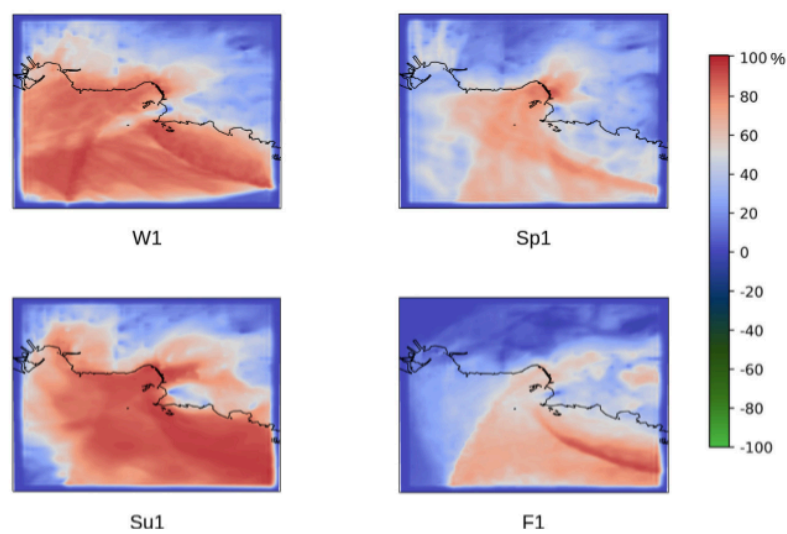


Fig. C.1. 72-hour averaged contribution of ships to NO₂ concentration in % for weak winds.

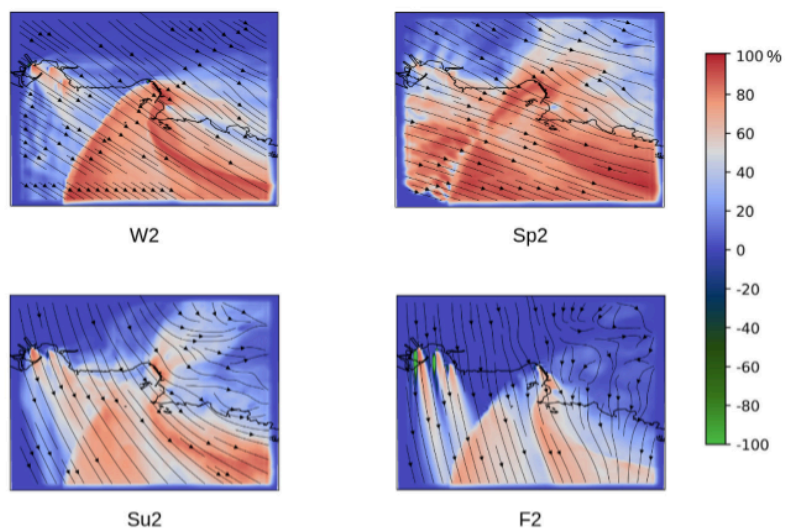


Fig. C.2. 72-hour averaged contribution of ships to NO_2 concentration in % for moderate winds.

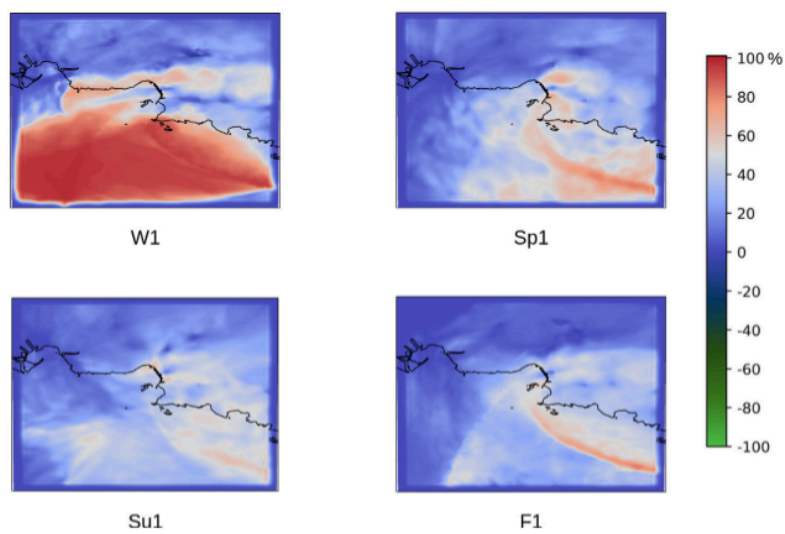


Fig. C.3. 72-hour averaged contribution of ships to SO_2 concentration in % for weak winds.

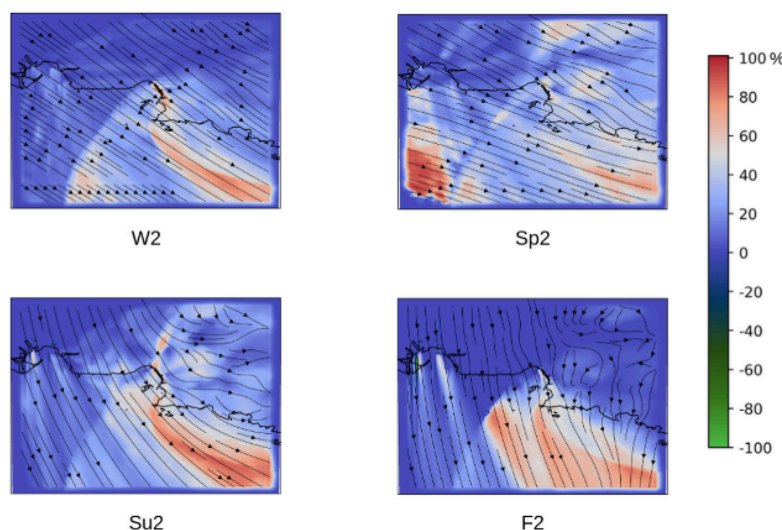


Fig. C.4. 72-hour averaged contribution of ships to SO_2 concentration in % for moderate winds.

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