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The impact of shipping emissions to urban air quality in Europe – Detailed port-city analysis

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The impact of shipping emissions to urban air quality in Europe - Detailed port-city analysis

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EXECUTIVE SUMMARY

Air pollutants concentrations have shown a declining trend over the last decades in Europe as a result of decreasing emissions in many sectors. However, the strong emission reductions in some sectors, such as traffic, have shifted the focus to other less strongly contributing sources, such as shipping whose emissions relative contributions increase, in order to further reduce air pollutant concentrations.

In this report the influence of shipping emissions on the air quality in European port cities is investigated with the chemical transport model LOTOS-EUROS. Using the model's source apportionment capabilities, the contribution of international and inland shipping emissions to atmospheric air pollutant concentrations in 19 European port cities is computed.

In the emission set used in this study, the shipping emission on seas are derived from Automatic Identification System (AIS) data of all ships sailing in the total geographic domain of the calculations. These emissions are higher than the emissions reported to the European Environment Agency (EEA) as a result of the restrictive definition of maritime emissions in the national inventories of the EU Member States which do not include any shipping emission outside the territorial waters of the Member States. The total European NO_x emissions used in this simulation are ~9.3 Mton for the simulation domain of which 64 kton (0.7%) originates from inland shipping and 2.2 Mton (23%) originates from international shipping emissions.

For the entire European domain, international shipping is predicted to contribute about 18% to the atmospheric surface concentration of NO_2 in 2018. This is the average contribution to the surface concentration in the entire simulation domain that includes sea covered areas. For SO_2, $PM_{2.5}$ and PM_{10} the contributions are at respectively about 11%, 5% and 3%. Inland shipping has only a minor contribution (<1%) for the average annual pollutant concertation for all investigated components.

Locally, shipping emissions contribute significantly to atmospheric pollutant concentrations in areas around big ports and port cities. For example, in the Rijnmond region around Rotterdam almost 30% of the NO_2 annual mean concentration in 2018 originates from a combination of international and inland shipping emissions. Similar relative contributions are found for other cities with large ports, while in some cases (e.g. Piraeus) the contribution of shipping emissions is predicted to be dominant compared to other sectors. For all the port cities examined, the relative contribution from international shipping was 22% on average, while the contribution is 28% on average when only sea ports are taken into account. This shows the significance of emissions from shipping on the local air quality in cities around big ports in Europe and indicates that mitigation policies aimed at reducing emissions from shipping can be effective for improving the air quality in port-cities.

Meteorological conditions play an important role in physical and chemical processes in the atmosphere and hence may influence pollutant concentrations. For port-cities a particular windspeed and -direction 'optimally' transport a pollutant with a given lifetime from the port into the city center and thereby cause most severe air quality deterioration attributable to the port activities.

KEYWORDS & ABBREVIATIONS

LOTOS-EUROS, Source Apportionment, International Shipping, Inland Shipping, NO_2, SO_2, PM_{10}, $PM_{2.5}$,

INTERNET

This report is available as an Adobe pdf file on the Concawe website (www.concawe.org).

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LIST OF ACRONYMS AND DEFINITIONS

ACRONYM	EXPLANATION
AIS	Automatic Identification System
CAMS	Copernicus Atmosphere Monitoring Service
CAMS-REG	Copernicus Atmosphere Monitoring Service REGional emissions
CDS	Climate Data Store
CLRTAP	Convention on Long-range Transboundary Air Pollution
CO_2	Carbon dioxide
CTM	Chemical Transport Model
DEPAC	DEPosition of Acidifying Compounds
EEA	European Environment Agency
ECMWF	European Centre for Medium-Range Weather Forecasts
EIONET	The European Environment Information and Observation Network
EMG	Exponentially-Modified Gaussian
ERA5	ECMWF ReAnalysis (generation 5)
GHG	GreenHouse Gas
LOTOS-EUROS	Long Term Ozone Simulation – EURopean Operational Smog model
MS	Mediterranean simulation
NO	Nitric Oxide
NO_2	Nitrogen dioxide
NO_X	The nitrogen oxides, the combination of nitric oxide and nitrogen dioxide.
NS	Northern European simulations
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter with a diameter smaller than 2.5 micron
PM_{10}	Particulate Matter with a diameter smaller than 10 micron
SA	Source Apportionment
SNAP	Selected Nomenclature for sources of Air Pollution
SO_2	Sulphur dioxide
TEU	Twenty-foot equivalent units
TNO	Dutch organisation for applied scientific research (Toegepast-Natuurwetenschappelijk Onderzoek)

Throughout this document technical terminology is used that we define in the table below for clarity.

DEFINITIONS	EXPLANATION
ATMOSPHERIC COMPONENT	A chemical constituent in the atmosphere. Not all of these constituents are modelled.
TRACER	Model equivalent to a chemical component present in the atmosphere, i.e. a modelled atmospheric component.
POLLUTANT	Atmospheric component with known harmful effects to human health and/or the environment, e.g. PM and NO_2.
ATMOSPHERIC CONCENTRATION	The concentration of an atmospheric component in mass per volume, often measured in $\mu g/m^3$.
ATMOSPHERIC SURFACE CONCENTRATION	The atmospheric concentration at 2.5 meter above ground level/earth surface.

1. INTRODUCTION

Fuels burnt by combustion engines of shipping vessels result in emissions of NO_x, SO_2 and particulate matter (PM) that have a negative impact on air quality for human health and ecosystem. This work aims to provide insights and enhance Concawe's understanding on this influence of shipping emissions on the air quality in cities with or near major ports. For this purpose, the chemical transport model LOTOS-EUROS is used to assess the contribution of both international and inland shipping emissions on the concentrations of major pollutants (NO_2, SO_2, $PM_{2.5}$, PM_{10}) in such cities.

1.1. AIM

The main focus of this work is to address the research question:

"How is the air quality influenced by shipping emission over port cities in comparison to other sectors?".

1.2. BACKGROUND

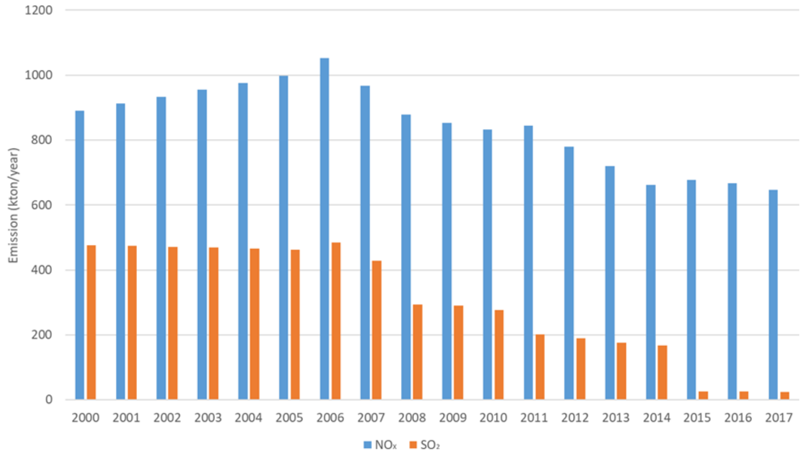
It is well known that elevated concentrations of atmospheric pollutants can lead to adverse effects on both human health and ecosystems. Epidemiological studies have shown that the exposure to pollutants such as fine particulate matter ($PM_{2.5}$) and nitrogen dioxide (NO_2) is associated with cardiovascular and respiratory diseases, leading to increased sickness, hospital admissions and premature death (Beelen et al., 2014). Moreover, nitrogen deposition in soils and water bodies leads to eutrophication and biodiversity loss, algae blooms and overall ecosystem damage and sulphur dioxide is a gas that together with other sulphur oxides can contribute to acidification which can harm sensitive ecosystems.

NO_x ($NO_x = NO + NO_2$) is formed in the combustion process due to the high temperatures and the naturally abundant nitrogen in the atmosphere. PM emissions primarily result from carryover of non-combustible trace constituents in fuels or formation from condensable gases released in the combustion process.

Over the past decades, legislation has been introduced to reduce emissions of these harmful pollutants. These efforts to reduce emissions in several sectors have resulted in a decrease in the atmospheric concentrations of $PM_{2.5}$, PM_{10}, NO_2 and SO_2. The most recognized example of successful emission reduction is in SO_2. Due to abatement measures in powerplants and desulphurization of fuels, the atmospheric SO_2 concentration in the European Union countries declined by around 70% between 2000 and 2017 (Colette & Rouïl, 2020) based on aggregated observations.

The shipping sector has seen less emission reductions compared to other sectors and, for example, its contribution for the Netherlands has been shown to have a growing significance with respect to other source sectors (Denier van der Gon et al., 2022; Jonson et al., 2015). In **Figure 1** it is visible that between 2000 and 2010 NO_x shipping emissions showed a decrease of ~4% whereas the reduction when taking all emission sources in Europe into account was about 7 times higher (-24%). In recent years (2010-2017) the reductions found in shipping NO_x emissions are more in line with other sectors which is the result of a more frequent use of cleaner engines and fuels (as a result of the designation of the North Sea as SECA as of 2006)). Shipping emissions are most relevant for cities with large ports and cities near important inland water ways (Monteiro et al., 2018).

Emissions are not the only factor that influence the atmospheric pollutant concentrations. Meteorological conditions, like precipitation, solar radiation, wind speed, temperature and relative humidity play an important role in atmospheric processes. Especially the height of the planetary boundary layer, that can vary between 100m and 2km, in which atmospheric mixing and hence dilution of pollutants is strong, has a large effect on surface concentrations.



	2000	2005	2010	2015	2017	Trend 2000–2010	Trend 2010–2017
CH_4	47 425	45 147	41 431	39 665	39 448	−13 %	−5 %
CO	58 235	49 792	43 261	35 885	35 299	−26 %	−18 %
NH_3	5877	5490	5261	5339	5410	−10 %	3 %
NMVOCs	15 805	13 532	11 377	9867	9757	−28 %	−14 %
NO_x	17 190	16 212	12 987	11 090	10 397	−24 %	−20 %
PM10	5465	5281	4854	4483	4436	−11 %	−9 %
PM2.5	3705	3560	3347	3044	3025	−10 %	−10 %
SO_2	16 110	12 665	8748	7482	6230	−46 %	−29 %

Figure 1 Figure based on Kuenen et al., 2021. The top panel shows a bar plot with the reduction in NOx and SO_2 emitted by shipping activities on the North Sea between 2010 and 2017. The bottom panel shows a table with the reduction trends in European total emissions for various pollutants (in kton) for selected years in the same period

1.3. APPROACH

In this study insight is gained in the contribution of shipping emissions to the air quality in Europe and major ports and cities using a chemical transport model (CTM) LOTOS-EUROS. This model computes air quality by taking into account emissions of pollutants, transport and chemistry in the atmosphere using meteorological data, land use and orographic information.

Besides the total pollutant concentrations in the atmosphere, it is relevant to assess the relative contributions from the various source sectors that cause them. Source Apportionment (SA) is applied both in the modelling and monitoring of air pollution. Various techniques exist to specify the sources that may cause the air pollution of interest. These techniques make it possible to estimate how much of an atmospheric concentration originates from a specific source (e.g., traffic, industry, etc.).

In modelling air quality with CTMs, two main approaches for source apportionment exist. A brute force approach that incrementally reduces the emissions from various source sectors that are fed as an input to the model. By extrapolating the effect on the resulting atmospheric concentrations of a certain percentage emission reduction to 100%, it is possible to derive contributions from these sectors to the concentration in a region or at a location of interest. The second method, which is used in this project, is the labelling approach. In this approach the chemical tracers receive a label based on the emission source that caused them. These labelled chemical pollutants are traced throughout the model to be able to monitor what sectors contributed to the surface concentration of that component at a region or location of interest.

The brute force approach is particularly useful to investigate the effects of emission reduction scenarios, taking into account non-linearities in modelled chemical and physical processes that make it hard to directly translate an emission reduction of a pollutant into an atmospheric concentration reduction. The brute force approach comes at the expense of more computational and memory costs with respect to the labelling approach, because it requires the performance of a large set simulations. For each additional label a new set of simulations needs to be performed. The labelling approach on the contrary uses a single simulation, also taking into account non-linearities and gives more accurate insight in a situation under consideration as the chemical regime remains unchanged, i.e. no changes in atmospheric concentrations are required to discern contributions from the various sectors. The labelling approach is less appropriate for scenario evaluations because non-linearities in the translation from emissions towards atmospheric concentrations can cause emission and concentration partitioning in various sectors to change in unanticipated ways. Since this study has a particular interest in accurately describing the current contribution from shipping emission to the air quality in port-cities the labelling is most suitable.

1.4. OUTLINE

The methodology used in the study is described in chapter 2. This chapter provides details on the model that is used and what data is taken as input to the model to perform the simulations of the atmospheric concentrations.

Chapter 3 presents the results of the study. The CTM provides labelled atmospheric concentrations over the simulation domain. Using the simulation results the contributions of various sectors to the air quality in port-cities of interest are computed.

Further discussions, implications and challenges are described in chapter 4 of the report and in chapter 5 the conclusions and recommendations from this study are given.

2. METHODS

Within this chapter a detailed description of the modelling approach is given. Firstly, the used CTM and its capabilities are introduced. Secondly, focus is given on project specific simulation settings and data usage. Lastly, the strategy of evaluating model results is described.

2.1. MODEL DESCRIPTION

LOTOS-EUROS is a 3D chemistry transport model. The off-line Eulerian grid model simulates air pollution concentrations in the lower troposphere solving the advection-diffusion equation on a regular latitude-longitude-grid with variable resolution over Europe (Manders et al., 2017; Schaap et al., 2008).

The vertical transport and diffusion scheme accounts for atmospheric density variations in space and time and for all vertical flux components. The vertical grid is based on terrain following vertical coordinates and when excluding stacked boundary layer on top extends to 5 km above sea level. The model uses a multilayer approach to determine the vertical structure where the vertical layers vary in space and time. The height of the layers on top of the 25 m surface layer is determined by heights in the meteorological input data.

In the model version exploited in this study 12 model layers are used (with 7 stacked boundary layers on top), leading to a resolvent of the first km in 7 layers (depending on meteorological conditions). The horizontal advection of pollutants is calculated applying a monotonic advection scheme developed by Walcek & Aleksic (1998). Gas-phase chemistry is simulated using the TNO CBM-IV scheme, which is a condensed version of the original scheme (Whitten, 1980). Hydrolysis of N_2O_5 is explicitly described following Schaap et al. (2004). LOTOS-EUROS explicitly accounts for cloud chemistry, computing sulphate formation as a function of cloud liquid water content and cloud droplet pH as described in Banzhaf et al. (2012). For aerosol chemistry the thermodynamic equilibrium module ISORROPIA2 is used (Fountoukis & Nenes, 2007). Dry Deposition fluxes are calculated using the resistance approach as implemented in the DEPAC (DEPosition of Acidifying Compounds) module (Zanten et al., 2010). Furthermore, a compensation point approach for ammonia is included in the dry deposition module (Wichink Kruit et al., 2012). The wet deposition module accounts for droplet saturation following Banzhaf et al. (2013).

In LOTOS-EUROS, the temporal variation of the emissions is represented by monthly, daily and hourly time factors that distribute the annual emission totals in time for each source category. For international shipping these time profiles are flat and activities are assumed to constantly occur at a fixed intensity. For other sectors, like traffic, the daily cycles can show rush hours with elevated activity, weekly cycles and seasonal trends in activity. The biogenic emission routine is based on detailed information on tree species over Europe (Köble & Seufert, 2001). The emission algorithm is described in Schaap et al.(2009) and is very similar to the simultaneously developed routine by (Steinbrecher et al., 2009). Sea salt emissions are described using Martensson et al. (2003) for the fine mode and Monahan et al. (1986) for the coarse mode. Dust emissions from agricultural activities and resuspension of particles from traffic are included following Schaap et al., (2009).

The model is part of the Copernicus Atmospheric Monitoring Service (CAMS) regional ensemble providing operational forecasts and analyses over Europe. In this context the model is regularly updated and validated using observations from ground and satellite observations. The model performance is also subject to numerous peerreviewed publications (Schaap et al., 2015; Escudero et al., 2019; Schaap et al., 2015; Skoulidou et al., 2021; Timmermans et al., 2022). For an overview the reader is referred to the model's website: www.lotos-euros.nl.

2.2. SOURCE APPORTIONMENT

The Dutch organisation for Toegepast-Natuurwetenschappelijk Onderzoek (Applied Scientific Research), TNO, has developed a system to track the impact of emission categories within a LOTOS-EUROS simulation (source apportionment) based on a labelling technique (Kranenburg et al., 2013). This technique provides more accurate information about the source contributions than using a brute force approach with scenario runs as the chemical regime remains unchanged. Another important advantage is the reduction of computational costs with respect to the brute force approach. The source apportionment technique has been previously used to investigate the origin of particulate matter (episodes) (Pommier, 2021; Timmermans et al., 2017, 2022), nitrogen dioxide and nitrogen deposition (Curier et al., 2014; Thürkow et al., 2023).

Besides the total pollutants' concentrations, the contributions of selected sources to these concentrations are calculated. The labelling routine is implemented for primary, inert aerosol tracers as well as for chemically active tracers containing a C, N (reduced and oxidized) or S atom, as these are conserved and traceable.

The source apportionment module for LOTOS-EUROS provides a source attribution valid for current atmospheric conditions as all chemical conversions occur under the same oxidant levels. For details and validation of this source apportionment module the reader is referred to Kranenburg et al., 2013.

The module is currently being further developed to also include source apportionment of ozone and methane.

2.3. MODEL SETUP

2.3.1. Meteorology

The LOTOS-EUROS model is run with ECMWF ERA 5 reanalysis meteorological data (2018). ERA5 provides hourly estimates of a large number of atmospheric, land and oceanic climate variables, that are necessary inputs for calculations of atmospheric concentrations. The ERA 5 data cover the Earth on a 30 km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80 km. Typical inputs required by LOTOS-EUROS are for example surface and air temperature, cloud cover, windspeed and direction, precipitation and relative humidity.

Quality-assured monthly updates of ERA5 (1959 to present) are published within 3 months of real time and are available through the Climate Data Store (CDS). Preliminary daily updates of the dataset are available to users within 5 days of real time.

2.3.2. Emissions

For anthropogenic trace gas emissions the CAMS-REG inventory emission data for the year 2018 version 5.1 REF2 (Kuenen et al. 2019) was used. This is the latest available data set, an update with more recent data is expected to be published in 2023. This emission dataset stays as close as possible to the emissions as officially reported and used in policy assessment. The inventory uses the officially reported emission data by European countries. However, for international shipping the dataset is replaced with emissions from the Finnish Meteorological Institute (FMI) STEAM model (Jalkanen et al., 2016). This dataset is described in more detail in section 3.1. This model is based on Automatic Identification System (AIS) data. For inland shipping the data is complemented by the same model, meaning that only the distribution of the emissions of STEAM model is used. The emission totals of inland shipping are based on the CAMS-REG inventory.

2.4. SIMULATION DESCRIPTION

Figure 2 shows the different domains which are part of the LOTOS-EUROS simulations. A coarse resolution (circa 25 x 25 km) simulation is performed over Europe (domain shown in blue). Results from this simulation are used as boundary condition for two nested simulations over the Mediterranean and a central part of Europe (domains shown in red) at a higher resolution (circa 6 x 6 km). These simulations will be referred to as MS (Mediterranean simulation) and NS (Northern Simulation). The high resolution would make a simulation over the large European domain too computationally demanding hence the strategy of nested simulations is applied.

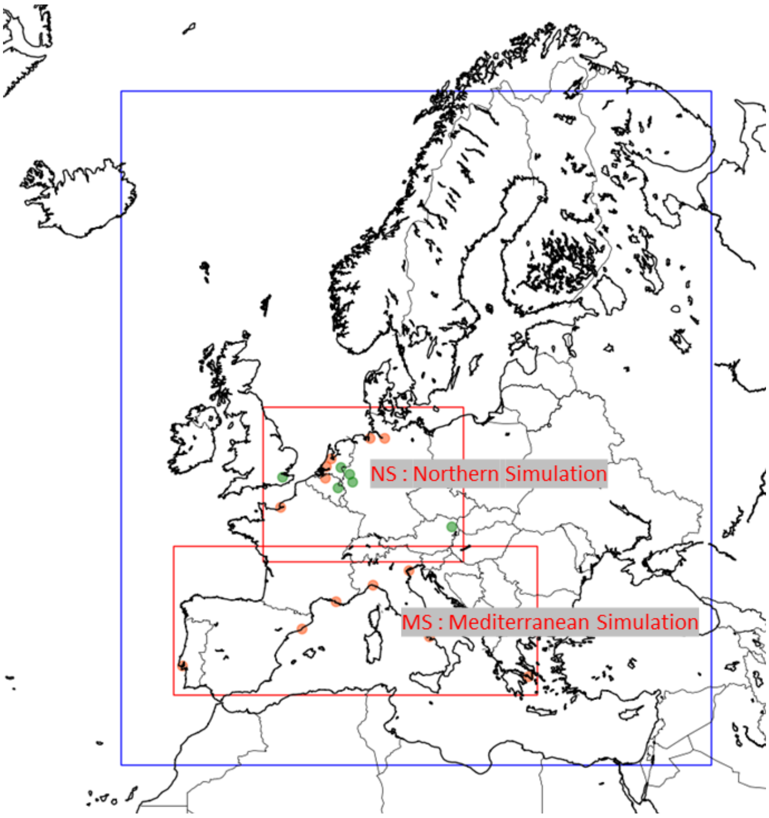


Figure 2 Display of the simulation setup domains. The port/cities of interest are displayed as dots on the map (orange for sea ports and green for inland ports)

2.4.1. Domains and resolution

A simulation across Europe (15°W, 40°E, 31°N, 69°N) at 0.4° longitude × 0.2° latitude (approximately 25 × 25 km2) resolution was performed, the results of which were used as boundary conditions for simulations at a resolution of 0.1° longitude × 0.05° latitude (approximately 6 × 6 km2) over Germany, the Benelux and the North Sea (1.5°W, 17.5°E, 46°N, 50°N) and the Mediterranean Sea (10°W, 24.5°E, 36.5°N, 47°N), covering the following major sea ports:

1. Rotterdam (NL)
2. Antwerp (BE)
3. Hamburg (DE)
4. Amsterdam (NL)
5. Marseille (FR)
6. Bremerhaven (DE)
7. Barcelona (ES)
8. Le Havre (FR)
9. Genoa (IT)
10. Piraeus (GR)
11. Lisbon (PT)
12. Naples (IT)
13. Venice (IT)

And inland ports:

1. Vienna (AU)
2. Liege (BE)
3. Duisburg (DE)
4. Nijmegen (NL)
5. London (UK)
6. Cologne (DE)

2.4.2. Included labels

The simulations were performed for the year 2018, since this is the most recent year for which the used emission dataset is available. Labels were applied to distinguish emissions sources from different sectors. A special split is made between international shipping and inland shipping. International shipping will include emissions from ships travelling in sea regions, whereas inland shipping will describe the emissions occurring on inland waterways. In some cases, significant contributions come from ships travelling on rivers flowing in or near these cities. This is categorized as inland shipping. The complete set of labels used in this study is as follows:

1. International shipping (all sea-going shipping)
2. Inland shipping (all river-going shipping)
3. Public Power
4. Refineries
5. Industry
6. Other Stationary combustion
7. Road transport exhaust
8. Road transport non-exhaust

9. Waste management
10. Aviation
11. Agriculture (Livestock and Manure management)
12. Biogenic [1]
13. Wildfires (GFAS -daily (Kaiser et al., 2012))
14. Sea salt (only contributes to PM)
15. Saharan dust (only contributes to PM)
16. Boundary [2]

These emission sources vary strongly in their influence on surface concentrations of $PM_{2.5}$, PM_{10}, NO_2 and SO_2. In the analysis throughout this report only significantly contributing sectors (>2%) are reported in graphs and tables for conciseness, with the exception of sectors of special interest (e.g., inland shipping, international shipping) that are always reported if they contribute. All less contributing sectors are aggregated and labelled as other.

2.5. EVALUATION OF MODELLED CONCENTRATIONS

The modelled atmospheric surface concentrations of pollutants $PM_{2.5}$, PM_{10}, NO_2 and SO_2 have been compared to measured concentrations from validated stationary air quality stations near or in port cities. The measurements used for verification are collected from the (Copernicus Atmospheric Monitoring Service) CAMS dataset of surface observations from the EEA/EIONET NRT database. This dataset from the European Environment Information and Observation Network (EIONET) is produced by a collaboration of the European Environment Agency (EEA) and its 38 member and cooperating countries. It contains validated surface observations for a large number of chemical tracers and pollutants including NO_2, SO_2, $PM_{2.5}$ and PM_{10}.

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[1] Biogenic emissions include isoprene and monoterpene from vegetation and soil NOx emissions.

[2] The label “Boundary” is used to describe contributions from the CAMS global simulation results that are used as a boundary condition to the simulation over the European domain.

3. RESULTS

Simulations with the chemical transport model LOTOS-EUROS have been performed to study the effect of shipping on air quality by modelling the atmospheric concentrations of NO_2, SO_2, PM_{10} and $PM_{2.5}$. This chapter presents the results of these calculations. Firstly, the emissions of shipping compared to the emissions from other sectors will be displayed. Secondly, the results of the European runs are presented. Finally, we zoom in the port cities and present comparisons of the results with nearby measurements.

3.1. EMISSIONS IN EUROPE

As mentioned in paragraph 2.3.2, the CAMS-REG inventory emission data for the year 2018 version 5.1 REF2 (Kuenen et al. 2019) was used in the air quality calculations. The year 2018 is the latest available data set, an update with more recent years is expected to be published in 2023. The CAMS-REG datasets are based on the officially reported emissions from the EU Member States.

It is important to mention that for the purpose of air quality calculations, a correct geographic distribution of the emissions is necessary. According to reporting conventions (UNECE, 2015) the inventory totals as reported by countries do not contain all shipping emissions (and they are not geographical referenced). Only the emissions from shipping between the national harbours are accounted for in the national emission totals. The emissions from seagoing shipping leaving or coming from another country are accounted for in so-called memo-item “International maritime navigation”. This “memo-item” is not included in the reported national total emission.

The emissions for the memo-item “International maritime navigation” are defined as: “Emissions from fuels used by vessels of all flags that are engaged in international water-borne navigation. The international navigation may take place at sea, on inland lakes and waterways and in coastal waters. Includes emissions from journeys that depart in one country and arrive in a different country. Excludes consumption by fishing vessels…” (EEA, 2019). These emissions (which are commonly calculated on bunker sales) cannot be attributed to a specific country as the emissions take place at sea in international waters. The emissions included in this memo item from national inventories cannot be used in air quality calculations as the location where the emissions occur is not known (not geographical referenced).

Therefore in the CAMS-REG dataset the emissions from all seagoing vessels as reported in the national inventories are replaced with emissions from the Finnish Meteorological Institute (FMI) STEAM model (Jalkanen et al., 2016). This model is based on actual ship movements as registered by the AIS data and moreover they are geographical referenced. This model gives the best geographical distribution of the shipping emissions on European seas (and the Atlantic). For inland shipping the data reported in the national inventories is complemented by the spatial distribution of the emissions as calculated by the STEAM model.

In order to illustrate the need for the changes made in the CAMS-REG dataset, **Table 1** shows the emissions as reported by the Member States surrounding the North Sea. These are compared to the emission at the North Sea from the CAMS-REG dataset.

Table 1 Comparison between national reported NOx emissions from seagoing vessel surrounding the North Sea and emission on the North Sea in the CAMS_REG dataset (for the year 2018 in kton). *I.E. stands for Included Elsewhere ‡N.O. stands for Not Occurring

From National inventories											From CAMS_REG	
NFR category	**Description**	**NLD**	**GBR**	**BEL**	**DNK**	**DEU**	**FRA**	**NOR**	**SWE**	**Total**	**Description**	
1A3di(ii)	**International inland waterways**	16.6	N.O.‡	2.1	0.0	I.E.*	0.8	N.O.‡	N.O.‡	19.4		
											Inland shipping	65.4
1A3dii	**National navigation (shipping)**	9.0	88.0	4.0	11.3	23.9	10.1	29.0	8.6	183.9		
1A4ciii	**Fishing: National fishing**	7.0	12.0	0.1	4.2	0.4	17.4	8.1	1.7	50.9		
MEMO	**International maritime navigation (bunkers)**	102.8	238.8	16.2	40.0	84.0	157.6	12.2	88.0	739.6		
Sum of seagoing emissions		118.9	338.8	20.3	55.5	108.2	185.1	49.3	98.3	974.4	**North Sea**	429.3

Table 1 illustrates that the emissions for inland shipping in CAMS-REG are higher than the estimates in the national inventories. This has two reasons:

- The methodology to calculate inland shipping in the different Member States is not harmonised, and thus not always comparable. In most countries it relies on national fuel statistics, which do not hold a distinction in fuel use for inland shipping and national seagoing shipping. In those cases, international inland shipping emissions might be included in National navigation or International inland waterways as the split between inland use and maritime use is not possible.
- The CAMS-REG data set is based on the emission estimates from the STEAM model (independent of the national inventories) and there is only a geographic distinction between ships at sea and ships on inland waterways. The split between these categories is made based on the layout of the seaports and or the location where the river flows into the sea. Therefore, the emissions from sea going ships sailing to an inland port are (partly) accounted for in the inland shipping emissions in the CAMS-REG dataset

For the emissions of seagoing vessels, **Table 1** shows that the sum of the reported emissions from the countries surrounding the North Sea are higher than the CAMS-REG dataset for the North Sea (which are based on actual ship movements determined from AIS data). The difference can be explained by the fact that the inventories calculate the emissions based on bunker sales (which will not only occur in the North Sea area but also on other seas covered by the total journeys until the next bunkering).

It should be noted that currently the CAMS-REG emission dataset is considered the best available dataset for the emissions from inland and seagoing shipping to be used in air quality modelling.

In **Table 2** the CAMS dataset and the EEA inventory data are compared to explain the differences in contribution of the specific source sectors (used in this study and by the EEA) to the total emission according to the respective definitions. The comparison is made for NOx as similar differences will be found for other air pollutants. It should be stressed that the emission data used in this study do include emissions on the sea outside the territorial waters of the individual Member States of the EU (which are not included in the EEA data). Furthermore, the emissions in this study cover all emission sources and are not limited as required by the reporting guidelines for national inventories (as in the EEA figures).

Table 2 Comparison between NOx emissions used in this study and reported by the EEA (In kton for the year 2018)

Source category		Emissions in 2018 (kton)		Contribution to total	
This study	**EEA32**	**This study**	**EEA32**	**This study**	**EEA32**
Energy Refineries Fuel prod.	Energy supply	1.767	1.469	19%	19%
Industry Solvent use	Manufacturing and extractive industry	1.064	1.034	11%	14%
Res. comb.	Residential	561	559	6%	7%
Road Transport	Road transport	2.876	2.787	31%	36%
Inland Shipping	National navigation	64	303	<1%	4%
International Shipping	International Shipping	2176	27	23%	<1%
Aviation	Domestic Aviation International Aviation	62	32 64	1%	<1% <1%
Mobile machinery	Other transport Railways	647	43 64	7%	<1% <1%
Waste	Waste	45	82	<1%	<1%
Livestock Manure and storage	Agriculture	53	1.182	<1%	15%
Wildfire	Not included	42	-	<1%	-
Total		9.360	7.645		

Note: EEA 32: EU 27, UK, Iceland, Liechtenstein, Norway and Switzerland. Also note that definitions differ and mobile machinery in this study largely falls under agriculture as per definitions used by the EEA.

Table 2 shows difference in the source coding as used in this study and as reported by the EEA on their website (Air pollutant emissions data viewer (Gothenburg Protocol, LRTAP Convention) 1990-2020 — European Environment Agency (europa.eu)). This is not a problem for the non-maritime sectors, but for the shipping emissions there is a clear difference. The EEA source description is following the reporting guidelines whereas in this study the geographic position of the emissions is used. This study includes (a part) of the memo items “Bunker emissions” as reported in the MS inventories which are not included in the EEA32 data in **Table 2**.

International shipping in this study means: all actual emissions (geographical located) on the sea due to shipping. Inland shipping means in this study: all emissions (geographical located) on inland waterways (Both taken from the CAMS geographical referenced data set). This difference is clearly shown in the comparison of the emissions. The emissions from shipping in this study are more than 80 times higher than reported by the EEA, as the latter do not include the emissions from seagoing shipping which are included in the memo item Bunker emissions. These differences also result in different contributions of the shipping emissions to the total emissions.

From these differences it can be concluded that when analysing the contribution of maritime emissions to air quality such analysis cannot directly be related to the contribution of maritime emissions to the total emission as reported by the EEA. The actual emissions on sea (including those (partly) covered by the memo item Bunker emissions in the national inventories) should be taken as a basis for such analysis.

3.2. CONTRIBUTION OF SHIPPING EMISSIONS TO AIR QUALITY IN EUROPE

3.2.1. NO_2

In **Figure 3** the total yearly averaged surface concentration of NO_2 in 2018 for the European domain is shown (left panel) together with the source apportionment results of the whole domain (right panel). The source attributed relative contributions include aquatic areas, like the North Sea and Mediterranean Sea. It is computed by summing the total surface concentration resulting from the emissions in a certain source sector over the entirety of the simulation domain and dividing this value by the total summed surface concentration with the contributions from all the sectors.

On the left side highest NO_2 concentration values are calculated in the central part of Europe (Benelux, Germany, UK) and in the Po Valley (north of Italy). The biggest contributions to the atmospheric NO_2 concentration in the displayed domain are Road Transport – exhaust and International Shipping. Road transport is known to be a large contributor to the NO_2 concentration over land. Because a large part of the chosen domain covers seas, it is also logical that international shipping has a relatively large contribution. The relative contribution of inland shipping is < 0.5% and therefore forms a small contribution in the whole European domain.

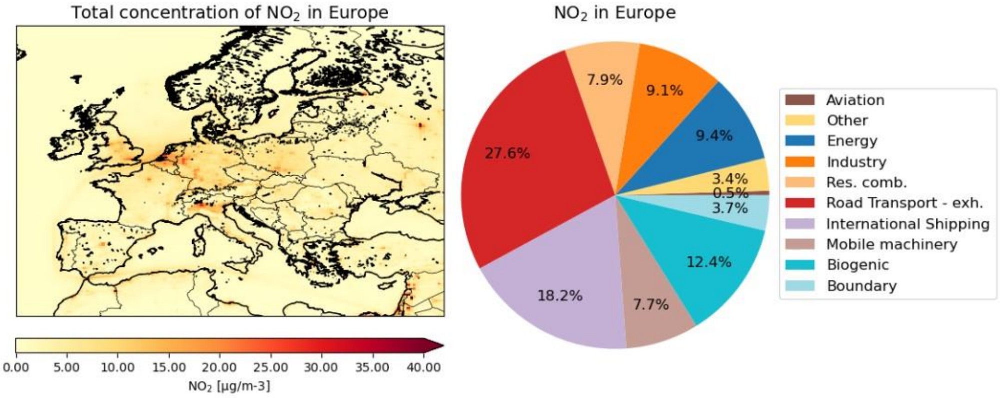


Figure 3 The annual average NO_2 surface concentration for 2018 in the simulation domain of the coarse (25x25km) resolution LOTOS-EUROS simulation (left panel). The relative contributions from the various labelled sectors to the surface concentration of NO_2 for the entire simulation domain (right panel)

In **Figure 4**, the absolute contribution of international shipping (left side) and inland shipping (right side) to the NO_2 surface concentration in Europe is shown. In the left image the busy shipping lanes on the North Sea, along the coast of Portugal and in the Mediterranean Sea are clearly visible with contributions up to 10 $\mu g/m^3$ (circa 25-90%). For inland shipping the relatively small contribution along the Rhine-Main-Danube canal of up to 5 $\mu g/m^3$ (circa 8%) is the only shipping route with a discernible contribution from inland shipping. It is apparent from these results that international shipping is overall a larger contributor to the NO_2 concentration than Inland shipping. Both sources have a highly local effect on NO_2 concentrations and their influence on air quality is only seen in relatively close vicinity (<50km) to waterways and shipping lanes which is to be expected for a short-lived component.

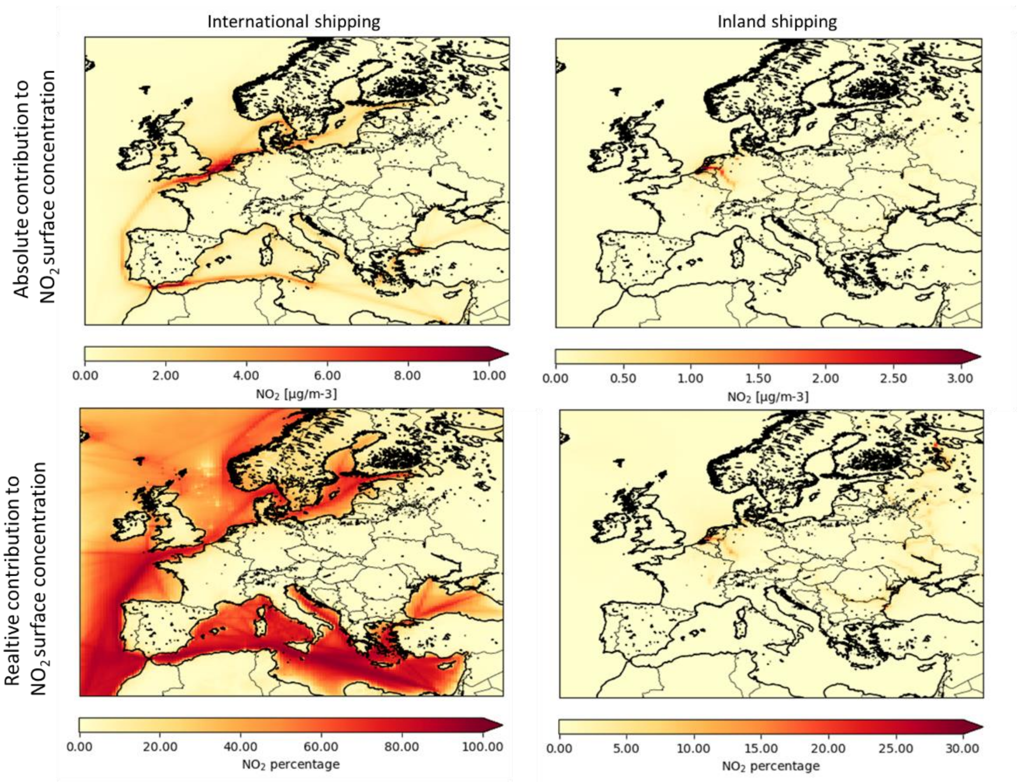
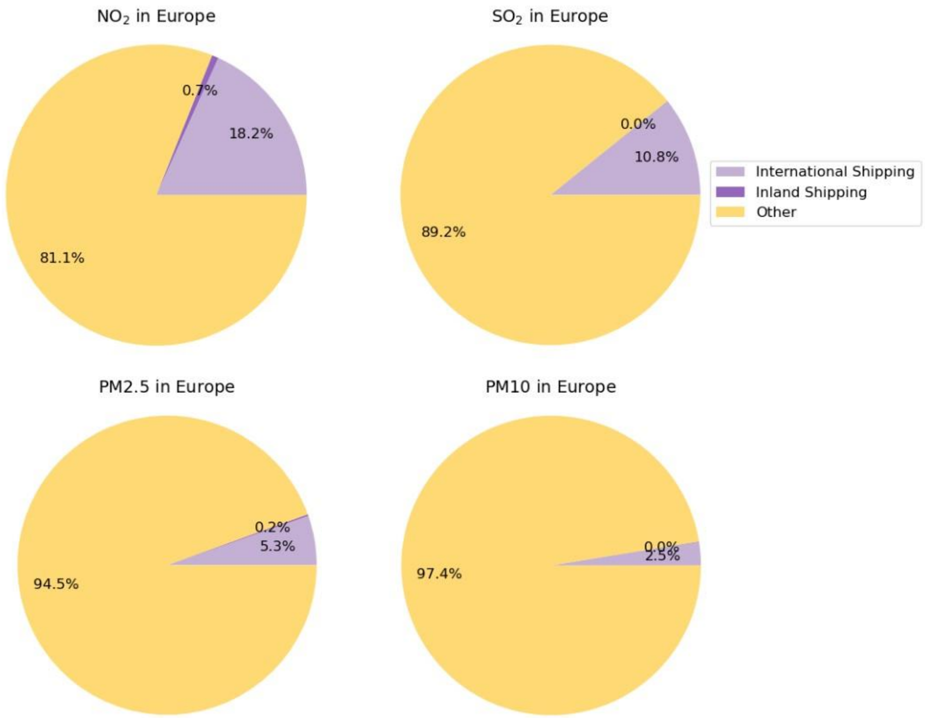


Figure 4 The absolute contribution from international shipping (top left panel) and inland shipping (top right panel) to the annual average NO_2 surface concentration in Europe in 2018. The corresponding relative contributions are shown in the bottom panels. Note that the range of the colorscales are different because inland shipping on average has a smaller contribution than international shipping

3.2.2. Other components

The results presented in the previous sub section show that shipping appears to have a relatively large contribution to the NO_2 concentrations in the European domain. In **Figure 5**, the contributions of the different sectors for four different types or air pollutants (i.e. NO_2, SO_2, $PM_{2.5}$, and PM_{10}) are compared for the European domain.

From these pie charts it is apparent that for all considered pollutants, shipping has the largest relative contribution for NO_2. For SO_2 a significant contribution from international shipping is still present (11%). Because the highest contribution of shipping is found for NO_2, the main part of the report focusses to explore the effect of shipping emissions to NO_2 concentrations in the selected ports/cities. NO_2 furthermore has a relatively short lifetime compared to PM and SO_2 and hence will show local effects most clearly. Results on SO_2, $PM_{2.5}$ and PM_{10} are included in the **APPENDIX**. For all the pollutants in general, it can be concluded that on average in Europe, inland shipping is a small contributor to the atmospheric pollutant concentrations.


NO$_2$ in Europe

SO$_2$ in Europe

PM2.5 in Europe

PM10 in Europe

Figure 5 The predicted relative contribution from international and inland shipping to various air pollutant annual surface concentrations over Europe in 2018

3.3. CONTRIBUTION OF SHIPPING EMISSIONS FOR EACH PORT

In this section the results of the calculated shipping contribution to NO_2 levels near the ports will be presented and discussed. Not all ports will be presented in detail; for a similar detailed (graphic) analysis for other ports that are not discussed in the main text, as well as the analysis for the other air pollutants SO_2, $PM_{2.5}$, and PM_{10}, we refer to the **APPENDIX**. For the analyses, a representative central location for the port and the city centre was determined for the selected cities. The city centre locations are represented as blue dots and the port locations as green dots in **Figure 6-Figure 11**. For these locations of interest, the concentration fields were calculated as a weighted average of the 4 nearest grid point in the simulation domain (inversely with distance from the grid point to the coordinates of the location of interest).

3.3.1. Rotterdam

The port of Rotterdam is the 10th largest port of the world and the largest port of Europe based on throughput volume for 2019 (https://www.worldshipping.org/top-50-ports). In **Figure 6** the distribution of the contribution of international shipping to the annual average NO_2 surface concentration in the Rotterdam area for 2018 is shown. The pie chart is showing the relative contributions from all labelled source sectors at the main container terminal of the port (bottom right) and in the city centre of Rotterdam (bottom left). The average annual absolute contribution of international shipping is 16 $\mu g/m^3$ (60%) at the port entrance at sea (green dot in **Figure 6**). It should be noted that this is a distance weighted average of the 4 surrounding grid values. Clearly the relative contribution from shipping on sea (also caused by a dominant prevailing West to South West wind as can be seen in **Figure 21**) can go up to 100%, but still even above the city centre of Rotterdam (blue dot), considerable contributions are found of 3.7 µg/m^3 (13%). The distance between the international shipping port (Maasvlakte) and the city is 30 km. Therefore, the absolute contribution decreases between the port and the city center due to dilution upon transport and the lifetime of NO_2.

Contrarily, the absolute contribution from inland shipping is larger in the city center than at the port location (respectively 8.1 (29%) vs 1.1 (4%) µg/m^3) and inland shipping is calculated to be the most dominant source in the city center together with exhaust emissions from the road transport sector. The river Rhine (which is the major inland waterway linking the North Sea with industrial areas in Germany and its eastern neighbours via the Rhine-Main-Danube canal) ends in Rotterdam. This leads to the significant contribution from inland shipping to the air quality in Rotterdam city.

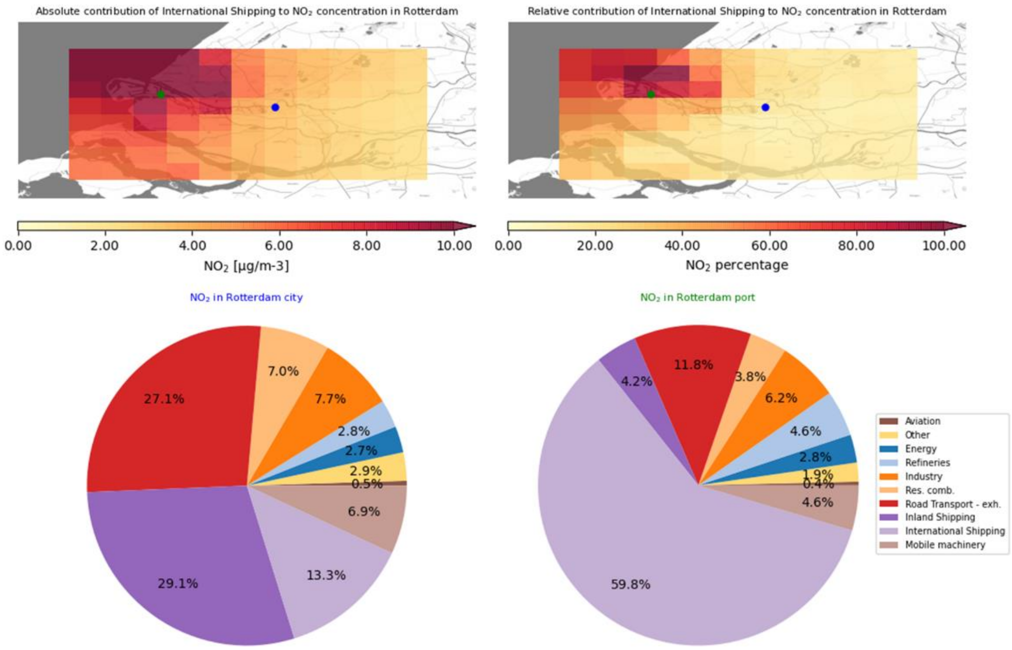


Figure 6 The computed absolute (top left panel), relative contributions (top right panel) of international shipping to the surface annual average NO_2 concentration in the Rijnmond area in the Netherlands in 2018. The pie charts in the bottom panels shows the contribution from all labelled sectors to the NO_2 concentration in the city centre (bottom left panel) and port respectively (bottom right panel)

3.3.2. Le Havre

Le Havre is the second-largest commercial port in France in terms of overall tonnage after Marseille. It is the largest container seaport, with three sets of terminals and over 6 kilometres of docks. In addition to this, it is also a major cruise port that can accommodate all sizes of world cruise liners and forms a ferry link to Portsmouth, England (Leriche et al., 2015).

In **Figure 7** the predicted contribution of international shipping to the NO_2 concentration in Le Havre is shown. The absolute contribution of international shipping is predicted to be 7.5 µg/m^3 (53%) in the port itself. International shipping in the displayed area in **Figure 7** is on average the main contributor to the NO_2 concentrations reaching a fraction of up to a 100%. With the city centre closed to the north side of the port, the international shipping contributes similarly (7.0 µg/m^3 or 51%) in the city centre to the NO_2 concentration thereby having a significant influence on the air quality in the city.

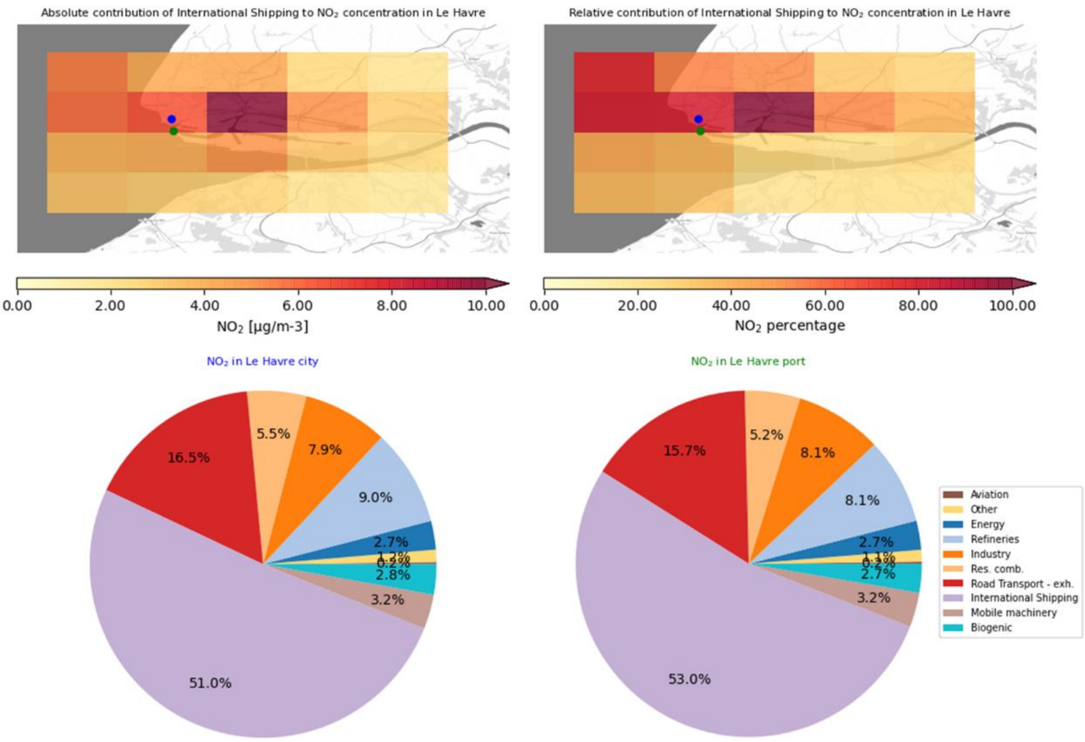


Figure 7 The calculated absolute (top left panel) and relative (top right panel) contributions of international shipping to the surface NO_2 concentration in Le Havre in France in 2018. The port is closed to the city centre so the pie charts corresponding to the respective locations are very similar. Inland shipping is not displayed in the pie charts as there is no contribution from this sector around le Havre

3.3.3. Antwerp

Antwerp is by far the biggest Belgian (sea)port, accounting for approximately 74% of the total Belgian maritime traffic in tonnage in 2017 (Vanelslander, 2022). It is located at the river Scheldt which also features the port of Ghent closer to the sea. It plays an important role in the connection between the port of Hamburg and Le Havre in nearly all major traffic flows.

In **Figure 8** the contribution of international shipping to the NO_2 concentration in Antwerp is shown. The absolute contribution of international shipping at the port of Antwerp (green dot in **Figure 8**) located at the delta of the Scheldt river is 16 µg/m^3 (47%). The relative contribution from international shipping can go up to 70% following the Scheldt river further downstream. The concentration in the port is predicted to receive contribution from emissions from ships at berth in the port. This also influences the air quality in the city centre of Antwerp situated to the southeast of the port (blue dot). Here international shipping contributes 5.8 µg/m^3 (24%) and inland shipping contributes 1.0 µg/m^3(4.0%).

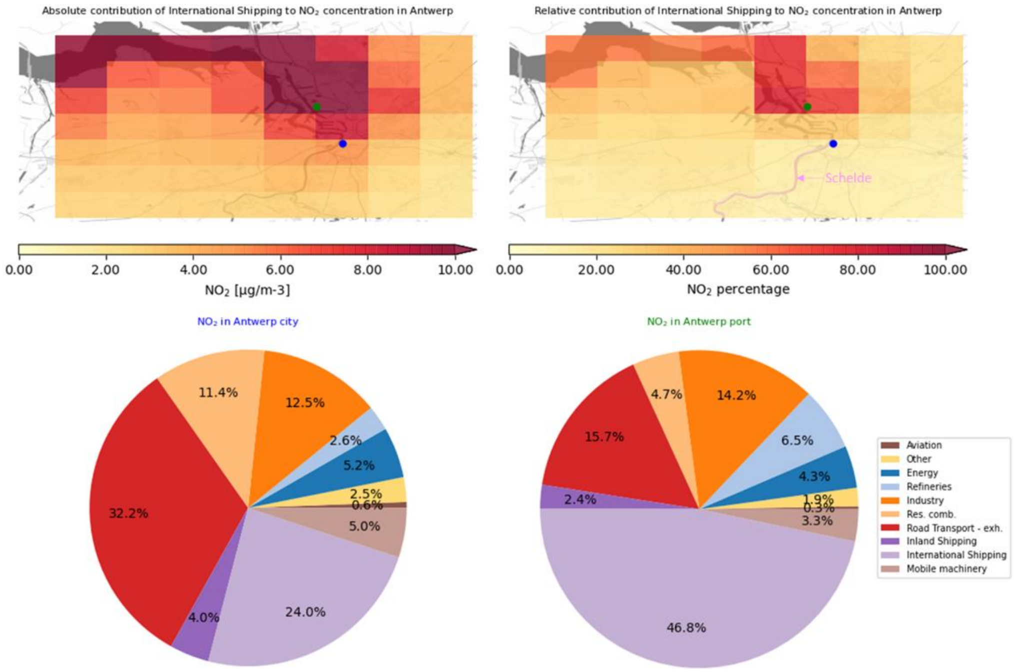


Figure 8 The calculated absolute (top left panel) and relative (top right panel) average contributions of international shipping to the surface NO$_2$ concentration in Antwerp in Belgium in 2018. The relative contributions of various sectors to the NO$_2$ concentrations in the port (bottom right panel) and city centre (bottom left panel) of Antwerp are shown in the bottom right and left panel respectively

3.3.4. Piraeus

Piraeus is one of the largest ports in the Mediterranean Sea. It acts as a connecting port between northern Africa and the south of Europe. It is the largest passenger port in Europe and one of the largest passenger ports in the world with 15.5 million passengers in 2017. It is also one of the largest ports in terms of freight throughput (4.9 million TEUs (Twenty-foot Equivalent Units) in 2017) [2017 annual financial report]. In **Figure 9** the absolute and relative contribution of international shipping can be seen. On the top left panel, it can be seen that the absolute contribution of international shipping is exceeding 5 µg/m^3 in most of the surrounding areas, and can reach up to 10 µg/m^3 or higher at the sea part. The port is located at the city centre which causes the green and blue dots in the top panels to coincide and the associated pie charts to be the same. International shipping is predicted to contribute 12 µg/m^3 (34%) to the annual average surface NO$_2$ concentration in Piraeus being the dominant source closely followed by exhaust emissions from the transport sector.

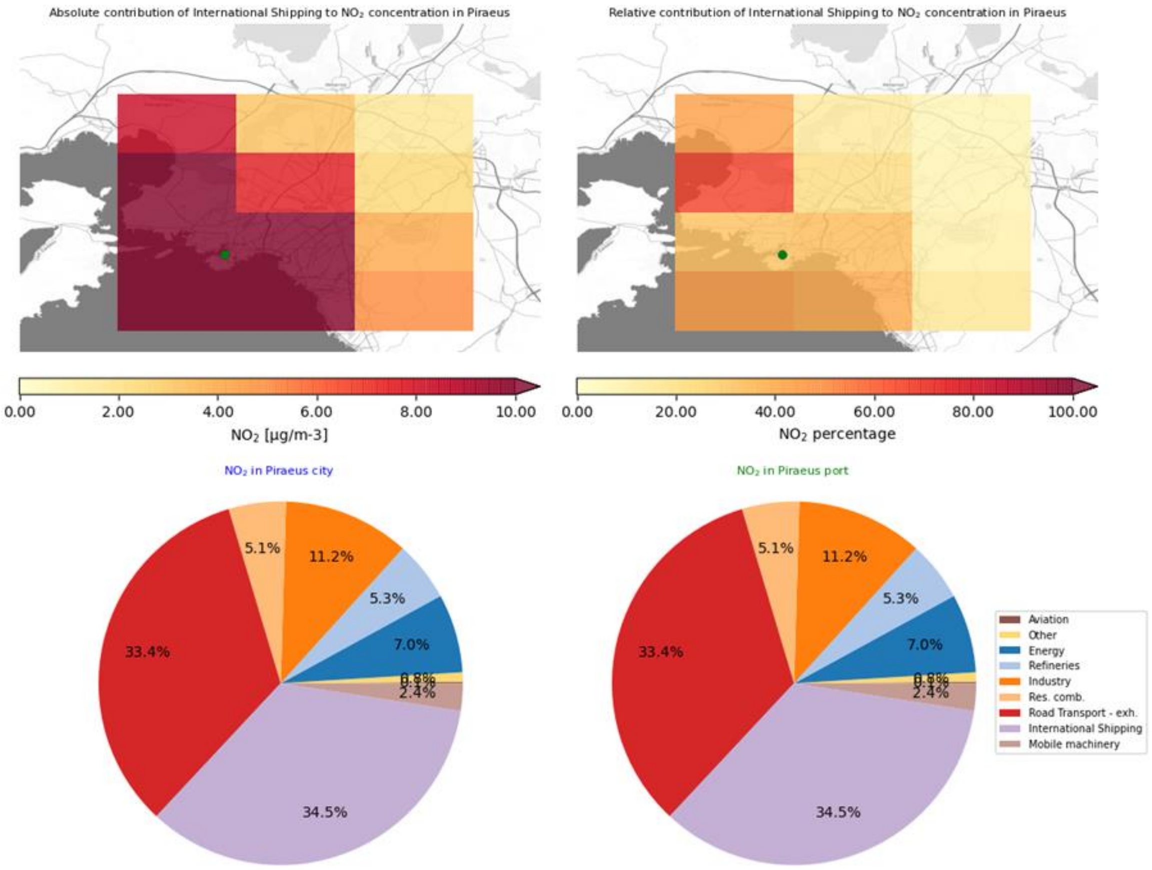


Figure 9 The calculated absolute (top left panel) and relative contributions (top right panel) of international shipping to the surface NO_2 concentration in Piraeus in Greece in 2018. The pie charts for the city centre and the port are the same since the port essentially forms the city centre. Inland shipping is not shown in the pie charts as there is no contribution from this sector around Piraeus

3.3.5. Naples

The port of Naples is a large port in the Mediterranean Sea and situated almost in the centre of the city. In **Figure 10** the estimated absolute (top left panel) and relative contributions (top right panel) of international shipping to the surface NO_2 concentration in Naples are shown. In both panels it can be clearly seen that at the location of the port (and therefore also in the city centre) both absolute and relative contributions of shipping emissions are high. For Naples, the NO_2 concentration in the port and city centre originating from international shipping emissions are 8.4 $\mu g/m^3$ (31%) and 4.8 $\mu g/m^3$ (19%) respectively. Inland shipping has a negligible contribution for the port and city centre of $7.1*10^{-4}$ $\mu g/m^3$ and $2.6*10^{-5}$ $\mu g/m^3$ respectively.

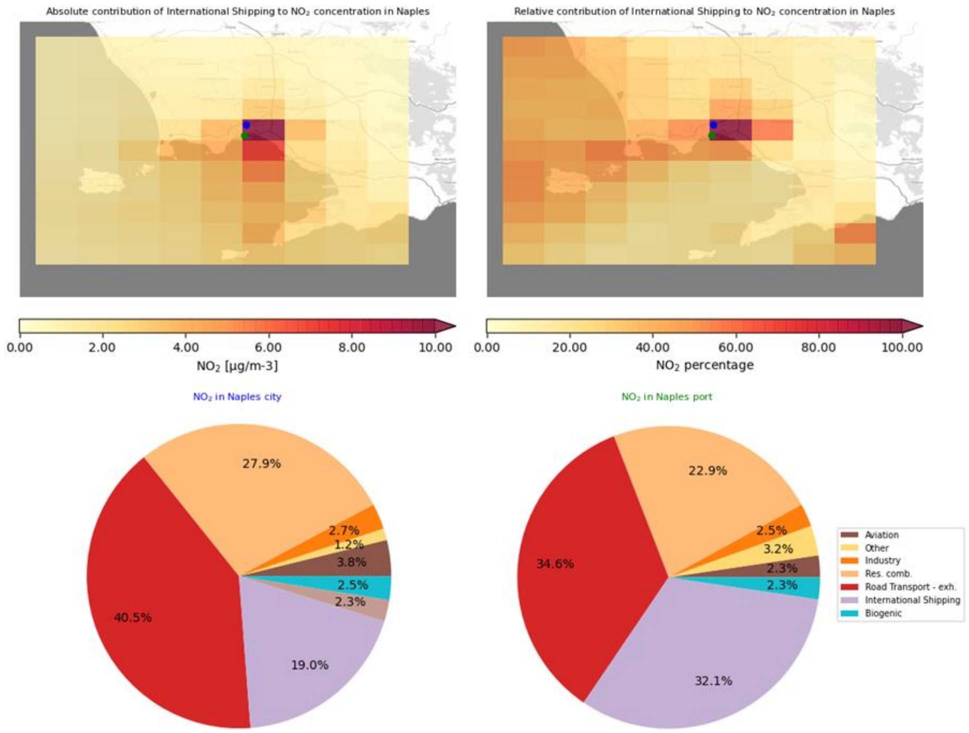


Figure 10 The predicted absolute (top left panel) and relative (top right panel) average contributions of international shipping to the surface NO_2 concentration in Naples in Italy in 2018. The relative contributions of the labelled sectors to the NO_2 concentrations in the port (bottom right panel) and city centre (bottom left panel) of Naples are shown in the bottom right and left panel respectively. Inland shipping is not shown in the pie charts as there is no contribution from this sector around Naples

3.3.6. Venice

In contrast to the majority of the cities/ports examined, the calculated absolute NO_2 concentration due to international shipping in Venice is lower. This is a reflection of the relatively small size of the port in term of throughput. The nominal capacity of the port was 800 kTEU in 2014 (Twrdy & Batista, 2014) which for example is ~17% of the 4.7 mTEUs nominal capacity of Piraeus in same year (Glyniadakis, 2016). However, in relative terms, international shipping is still, an important contributor to NO_2 concentrations, compared to other sectors (28 %). Also shipping in the Canal Grande, denoted as a pink line in the top right panel of **Figure 11**, is expected to cause NO_x emissions, but this is not reflected in **Figure 11**. This can have three reasons. Firstly and most importantly the resolution of the simulation is not fine enough to accurately discern the Canal Grande and secondly the CAMS-REG emission inventory might not have a proper representation of the activity of all the sea services like gondolas, ferries and other vessels navigating the Canal Grande. Lastly, emissions from small boats navigating Canal Grande are much smaller than emissions from container ships. In general >60% of total NO_x emissions are caused by container ships (Nunes et al., 2017; Toscano & Murena, 2019). Still relatively international shipping is one of the main contributors to the NO_2 concentration in the port and city of Venice, with contributions of respectively 26% and 28%. Strikingly the main waterways that connect the main container terminal and the Adriatic Sea also run close to Venice old town (where the blue dot is located in **Figure 11**). This might partially explain why relative international shipping contributions in the city centre are similar (and even slightly higher) than in the port location

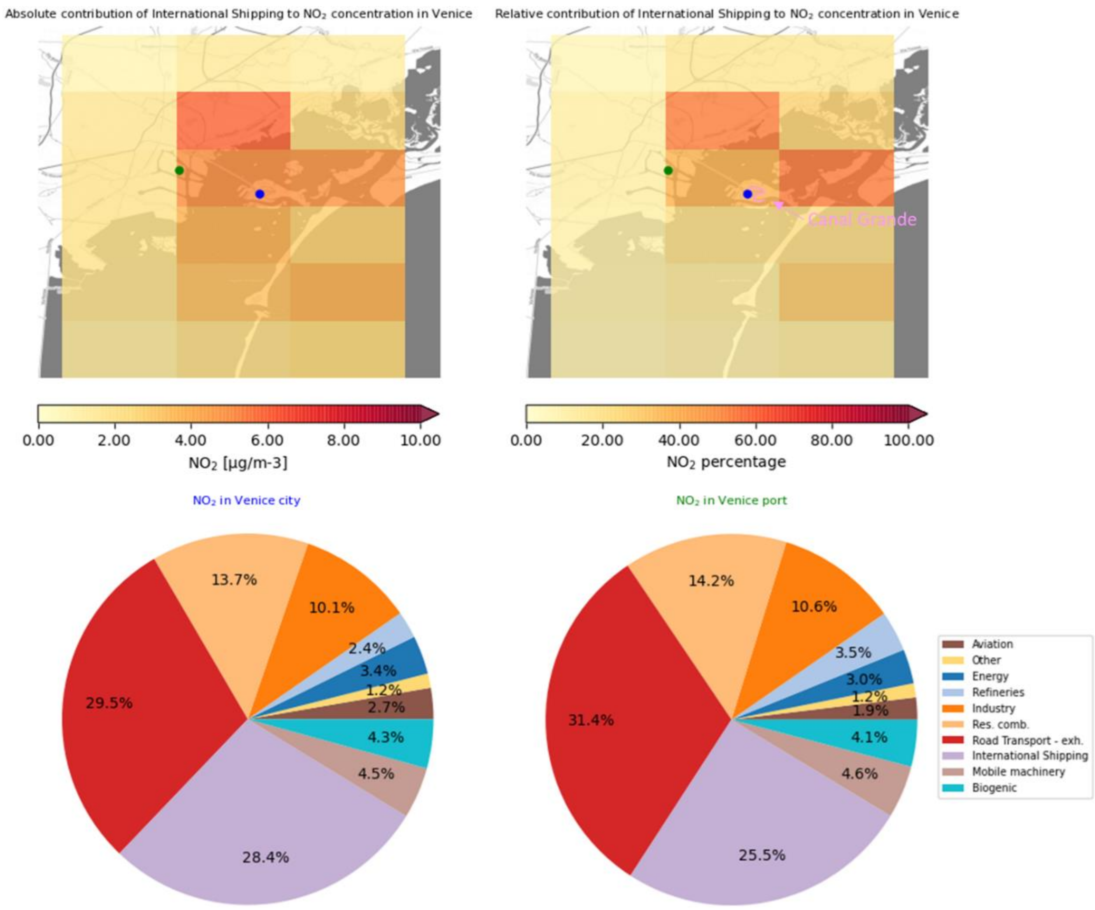


Figure 11 The calculated absolute (top left panel) and relative (top right panel) average contributions of international shipping to the surface NO_2 concentration in Venice in Italy in 2018. The relative contributions of the labelled sectors to the NO_2 concentrations in the port (bottom right panel) and city centre (bottom left panel) of Venice are shown in the bottom right and left panel respectively. Inland shipping is not present in the pie charts as there is no contribution from this sector around Venice

3.3.7. Overview of all port cities

The results presented above are illustrative examples of port cities showing representative pollutant concentration distributions and sector contributions for other port cities of interest. Detailed results for all ports/cities can be found in the **APPENDIX**. Results for all ports are summarized in **Table 3**. This table gives an overview of the contribution of shipping emissions to the NO_2 concentration for all the city centres of the port cities of interest. The city centres of Le Havre, Bremen, Genoa and Piraeus seem to be influenced most heavily in a relative sense by emissions from shipping. This has to do with the fact that the ports are relatively close to the city centre and absolute contributions from other usually important sectors like road transport and industry are relatively small compared to other port cities. On average, international shipping contributes for 22% and inland shipping for 5% to the NO_2 concentration in the investigated domains as shown in **Table 3**. If we only take sea ports into account international shipping contributes for 28% to the surface concentration. For some cities with big ports, e.g. Rotterdam, Piraeus, Bremen and le Havre, contributions from shipping (inland and international) form the largest contribution to NO_2.

Table 3 The relative contribution of international shipping (%) to the annual average concentration of NO_2 in the city centres close to the explored major ports

	Annual average NO_2 concentration [µg/m^3]	Inland shipping contribution (%)	International shipping contribution (%)	Domain size [10^3 km^2]
	Sea Ports			
Rotterdam	28	29	13	3.4
Antwerp	24	4.0	24	2.2
Amsterdam	22	16	13	0.9
Hamburg	23	4.0	26	2.6
Bremerhaven	21	1.3	59	3.7
Marseille	14	0.0	29	0.9
Barcelona	32	0.0	20	0.8
Le Havre	14	0.3	51	0.8
Genoa	19	0.0	48	0.6
Piraeus	34	0.0	34	0.6
Lisbon	15	0.0	15	2.0
Naples	25	0.0	19	4.6
Venice	16	0.0	28	0.8
Average	*22*	*4.2*	*28*	*1.8*
	Inland Ports			
Vienna	18	1.6	0.3	1.4
Liege	18	2.7	2.8	0.6
Duisburg	27	8.7	2.0	0.3
Cologne	26	8.6	1.6	0.9
Nijmegen	17	13	6.5	0.2
London	26	0.2	5.5	2.8
Average	*22*	*5.8*	*3.1*	*1.0*

A total overview of the absolute contributions from the labelled sectors to both the port and city centre locations is given in **Figure 12**. In more detail **Table 8** in the **APPENDIX** shows the absolute contributions in numbers to the city centres. The highest concentrations from international shipping occurs for the city centre of Piraeus (12 µg/m^3) and Bremen (12 µg/m^3). From **Figure 12** it is clear that in cities where the port is located far from the city centre, the respective international shipping contribution is heavily reduced, but still remains significant. The city centres of Le Havre, Bremen, Marseille and Genoa again stand out because of the relatively small absolute cumulative contribution from “Energy”, “Refineries”, “Industry”, “Residential combustion” and “Road Transport”. The contributions from different sectors will be presented in the next section.

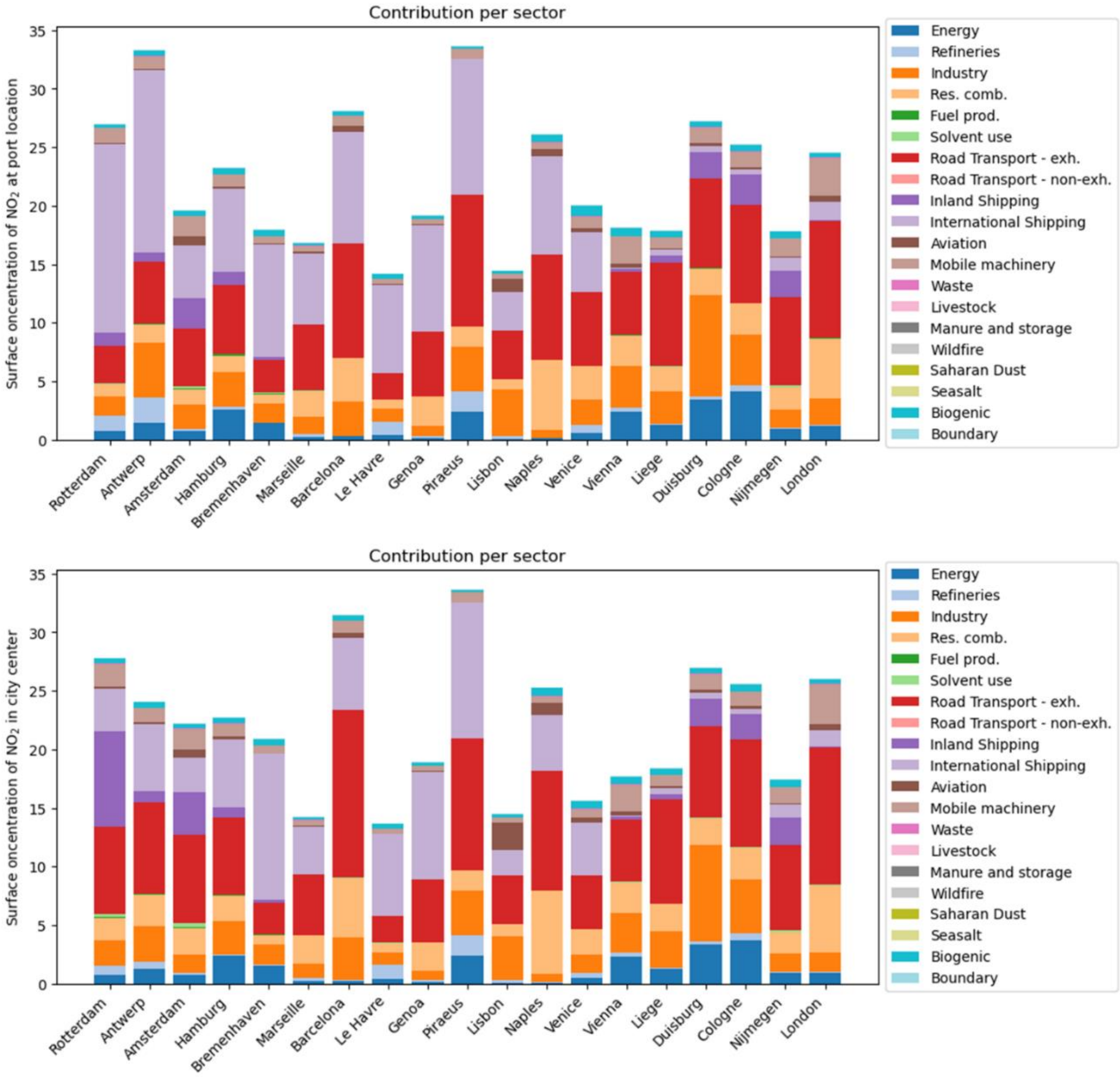


Figure 12 Stacked bar plot showing the predicted absolute contributions from the various labelled sectors to the annual average surface NO$_2$ in 2018 for the port cities of interest in the port/main container terminal location (top panel) and in the city center (bottom panel)

3.4. CONTRIBUTION OF SHIPPING EMISSIONS COMPARED TO OTHER SECTORS

The results of the study have shown that international shipping causes a significant part of the atmospheric NO$_2$ concentration in many port areas with average contribution of 22% in the harbour cities. Other sectors that are major contributors are listed in **Table 4** which shows the average sector contribution of the 5 sectors with the largest contributions (based on data in **Table 8** in the **APPENDIX**) for the port cities of interest. Besides international shipping, the most dominant sectors are exhaust emissions from road transport, residential combustion and industry. The 5 sectors together are responsible for 86% of the surface NO_2 concentration in the domains of interest.

As mentioned before, inland shipping contributes 3% to the total NO_2 surface concentration in the investigated cities. The total contribution from the industry (including refineries) is 14%.

Table 4 The 5 strongest contributing sectors and their relative contribution to the NO_2 concentration in the 19 harbour cities under consideration

Sector	Contribution (%)
Road Transport – exhaust	33
International Shipping	22
Industry (incl. refineries)	14
Residential combustion	12
Energy	5.9

3.5. MODEL RESULTS COMPARED TO OBSERVATIONS

An evaluation of the model results against selected measurement stations near or in port cities is made to give an indication of the accuracy of the modelled concentrations. This will help put the discussion into perspective. A vast network of monitoring sites from which data is freely available exist in Europe as can be seen in **Figure 13**. In this figure all EIONET stations with at least 50% temporal coverage in hourly NO_2 observations in 2018 are shown and a selection is made to only compare with (urban) background stations.

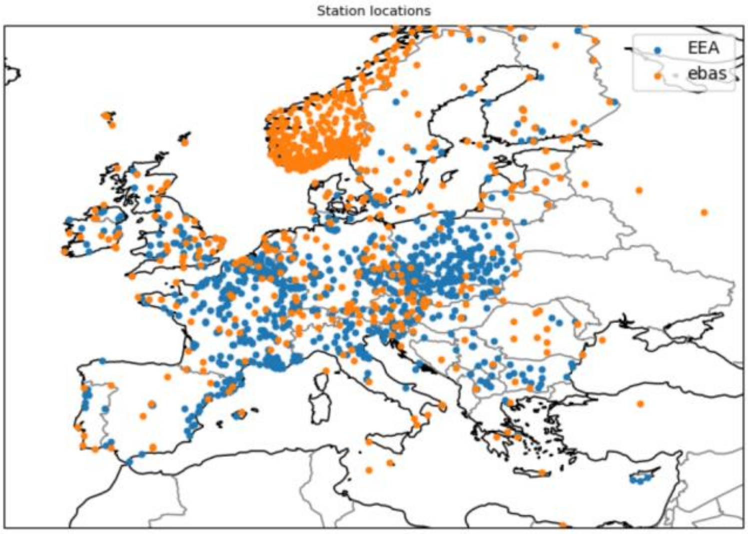


Figure 13 All the sites in the EIONET measurement network with data coverage for at least 50% of the days in 2018

A relatively strong agreement is found as can be seen in **Figure 14** when comparing the annual mean concentrations of NO_2 from all stations in the network (meeting the criterion of >= 50% coverage) with the simulated concentrations that are collocated in space and time. The Pearson correlation between the observations and the modelled station averages is 0.77 and 0.73 for the NS (Northern Simulation) and MS (Mediterranean Simulation) respectively. The blue dots show how well the coarse European run corresponds to the observed mean concentrations for all the stations in **Figure 14**. The same can be seen for the Mediterranean (green dots) and North Sea (red dots) zoom runs for all stations that were covered by these simulations. It is clear that the higher resolution generally improves the simulation results with respect to the measurements since the linear relation fitted through the station averages in **Figure 14** lies closer to the 1-to-1 line. Especially for stations with high concentrations the model results show an underestimation of the annual average concentration.

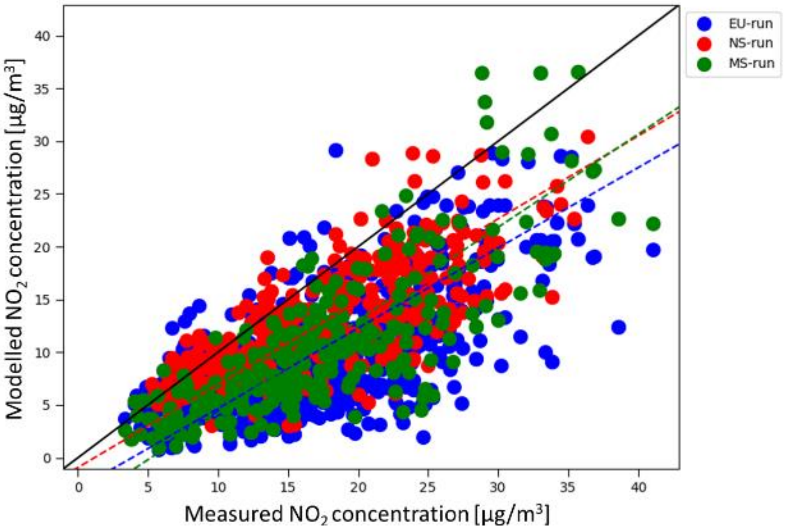


Figure 14 Annual mean NO_2 concentration measured in each station of the network shown in Figure 13 compared to the simulated concentrations that are collocated in space and time. The three simulations (the coarse European run and the two zoom runs) are separately compared with the measurement results

A selection based on location closest to the ports of interest is made to compare simulation results with observations. An overview of the selected measurement stations for the ports of interest is given in **Table 5**.

Overall, reasonable agreement between measurements and simulation results is found. For **Figure 15** (Rotterdam) and **Figure 20** (Venice) the coarse and the high resolution runs show similar performance in terms of orthogonal regression. This is expected when regional background measurement stations are selected. Since the focus is at stations near cities one would intuitively expect that the increased resolution will improve correlations. Looking at the concentration as function of time for Venice we however, see that some high concentrations that are measured in the beginning of the year (Jan-Feb) are (regardless of resolution) not found in the model results. This is clearly not a matter of resolution and hence will not be resolved by adding more spatial detail. For Rotterdam the correlation is already high (0.73) in the coarse simulation indicating that the emission sources are already depicted accurately. Hence, adding more detail will not lead to further improvements. Furthermore, for a comparison based on hourly concentrations, timing mismatches in emissions due to daily shifts in rush hours caused by accidents and other unpredictable events are inevitably present and improvements in correlations beyond the values reported here are hard to achieve without the use of activity/real-time data to improve emission timings. Looking at daily averaged or weekly averaged concentrations reduces this mismatch drastically.

For **Figure 16** (Antwerp) the higher resolution leads to a better matching between model and simulation results both in terms of orthogonal regression (0.38 vs 0.58) and slope (1.24 vs 1.20). This shows that the higher resolution can clearly improve model performance in some cases.

For **Figure 17** (Le Havre) no improvement in agreement with observations is found looking at orthogonal regression (0.38 for both resolutions) but a clear performance improvement is found with respect to the slope using the increased resolution. The fact that correlations do not improve, indicate that the timing of the emission sources might not reflect reality well for this particular location (e.g., the flat emission profiles for international shipping).

For **Figure 18** (Piraeus) and **Figure 19** (Naples) the orthogonal regression does not improve when the resolution is increased. For Piraeus the slope shows that the underestimation of NO_2 concentration decreases when the resolution is increased (with a slope of 0.74 vs a slope of 0.97 from for the European and Mediterranean simulation respectively). For Naples such an improvement is not seen. The higher resolution does lead to a higher NO_2 concentration, however the agreement with measurements is not improved due to this change. The increased resolution will generally increase peaks and decreases smearing of concentrations. For Piraeus the concentration increases with the higher resolution indicating the station is in the vicinity of an emission source or at least in an area of elevated NO_2 concentrations. The increased resolution improves the slope. The fact that the regression does not improve indicates that the temporal profile of this nearby emission source might not capture the actual emission profile in full detail. For Naples we see both an increase (in summer) and a decrease (in spring) in the concentration. It can be seen in the **APPENDIX** that industry also plays a role around Piraeus. If the temporal profile of this emission sector is not accurately represented for the activities around Piraeus, an increase in the resolution will not improve agreement between modelled and observed concentration.

An overview of the statistics between model results and measurements is given in **Table 6**. The linear regressions lines from the high resolution simulations lie closer to the 1-to-1 line for all stations except Piraeus. The stations on average show a moderate correlation. For all stations the average orthogonal correlation coefficient is 0.51, similar to performances found in other studies (Bessagnet et al., 2016). As mentioned before it should be noted that hourly correlations are negatively affected by unsystematic activities like traffic jams, construction works, road works, etc. because these are not reflected in the general time profiles that are used for the emissions. These time profiles have an averaged daily and weekly and annual course based on averaged activities. Next to that even a validated set of measured concentrations come with an uncertainty so both in the model result and the measurements, misrepresentations are present at these high temporal scales. For statistics on the comparison of modelled and measured surface concentrations for the other pollutants we refer to **APPENDIX 7.4**.

Table 5 The overview of the measurement stations that were selected for the comparison with simulation results

	Rotterdam	Antwerp	Le Havre	Piraeus	Naples	Venice
Measurement station	NL0091R	BETR820	FR05078	GR0031A	IT1497A	IT0963A
Longitude	4.50	4.44	0.14	23.65	14.26	12.26
Latitude	52.30	51.32	49.49	37.94	40.86	45.50
Elevation (m)	4	11	3	20	145	1

Table 6 The statistics between measurement stations and model results

	Rotterdam	Antwerp	Le Havre	Piraeus	Naples	Venice
Slope (EU run)	1.03	1.24	0.58	0.90	0.74	0.59
R (EU run)	0.73	0.39	0.38	0.49	0.37	0.58
Slope (HR run)	1.08	1.20	0.88	1.29	0.94	0.78
R (HR run)	0.71	0.58	0.38	0.48	0.36	0.56

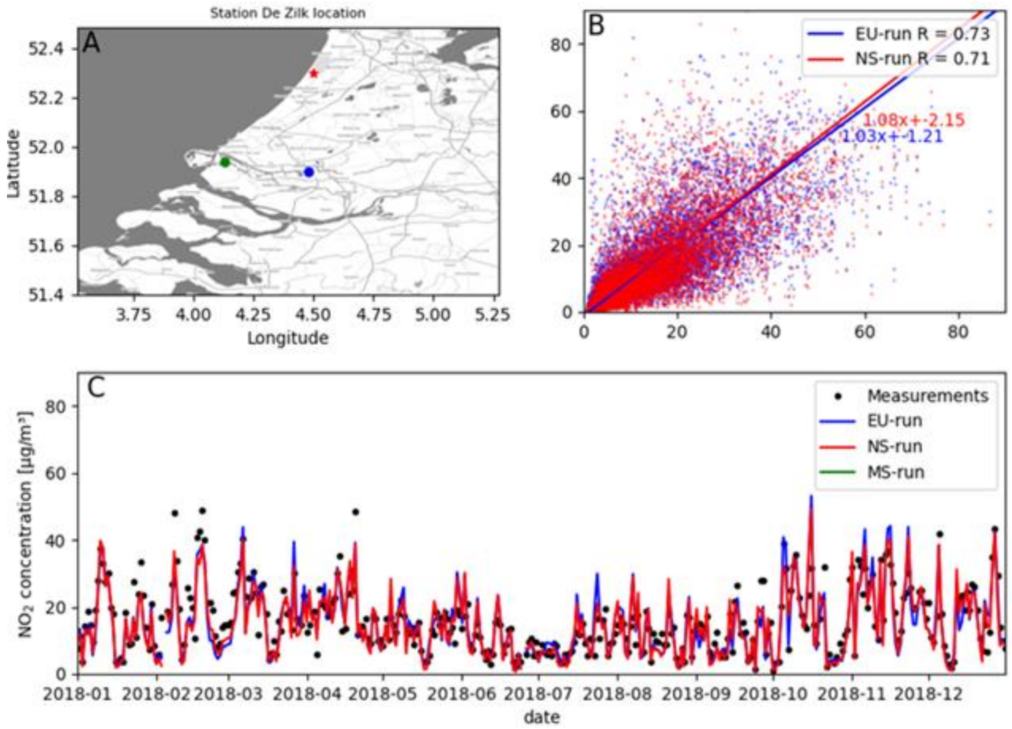


Figure 15 Model vs. observations from the measurement station closest to the Rotterdam port. Note that this measurement station is approximately 50km away from the port and hence not a direct reflection of the air quality in the port. Panel A shows the location of the selected station. Panel B shows the scatter plot of hourly averaged NO_2 concentrations observed by the measurement station versus the model results of the European simulation (blue) and embedded Northern Simulation (red). Panel C shows the underlying daily averaged time profiles. The measurements are displayed as black dots

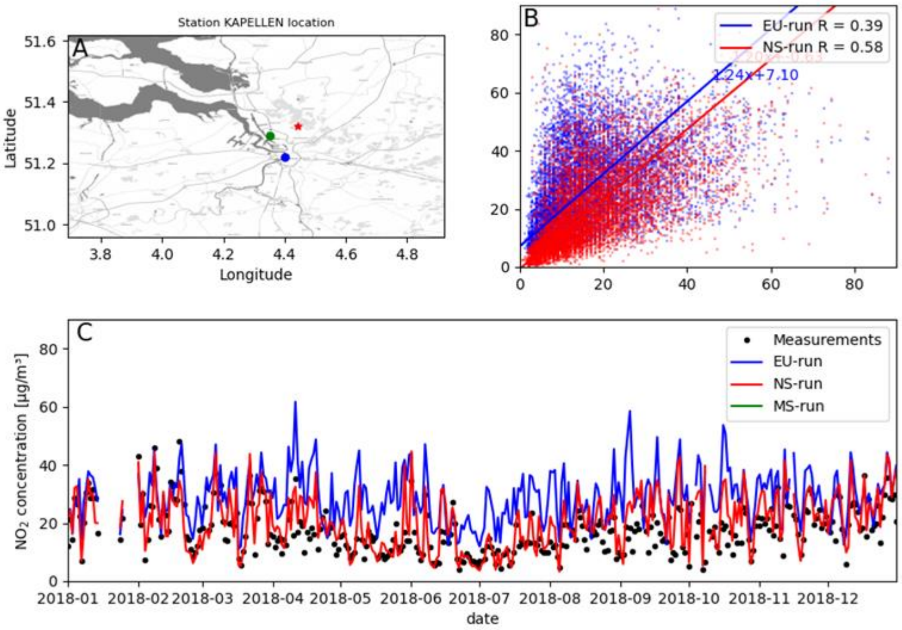


Figure 16 Model results compared to observations closest to the port of Antwerp. Panel A shows the location of the selected measurement station in the European domain. Panel B shows the scatter plot of hourly averaged NO_2 concentrations observed by the measurement station versus the model results of the European simulation (blue) and embedded simulation over the North Sea (red). Panel C shows the underlying daily averaged time profiles. The measurements are displayed as black dots

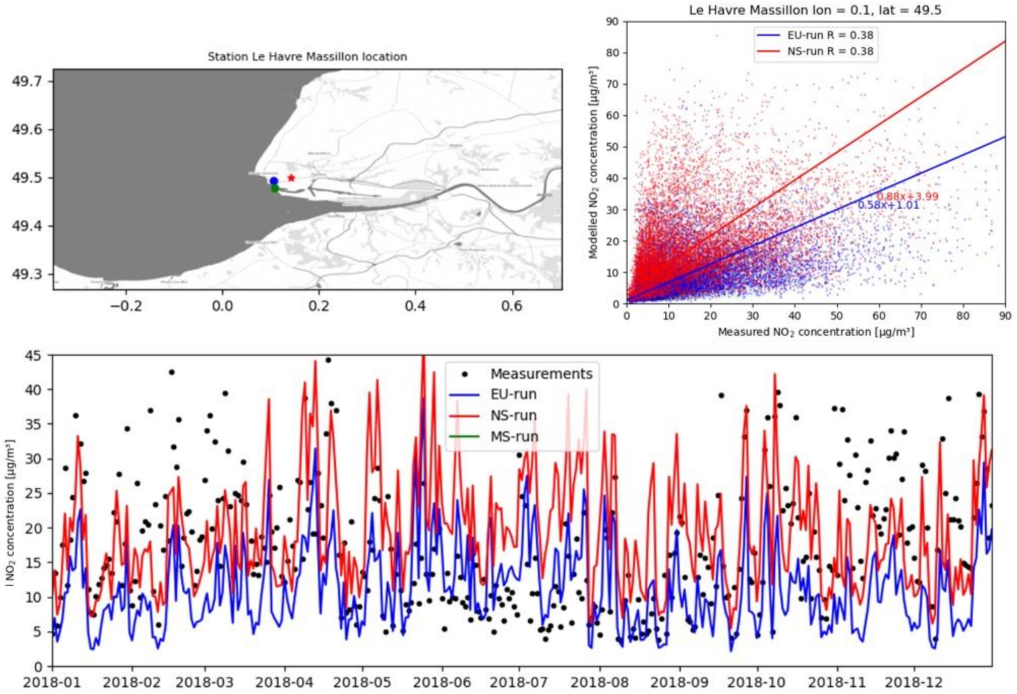


Figure 17 Model results compared to observations closest to the port of Le Havre. Panel A shows the location of the selected measurement station in the European domain. Panel B shows the scatter plot of hourly averaged NO_2 concentrations observed by the measurement station versus the model results of the European simulation (blue) and embedded simulation over the North Sea (red). Panel C shows the underlying time profiles. The measurements are displayed as black dots

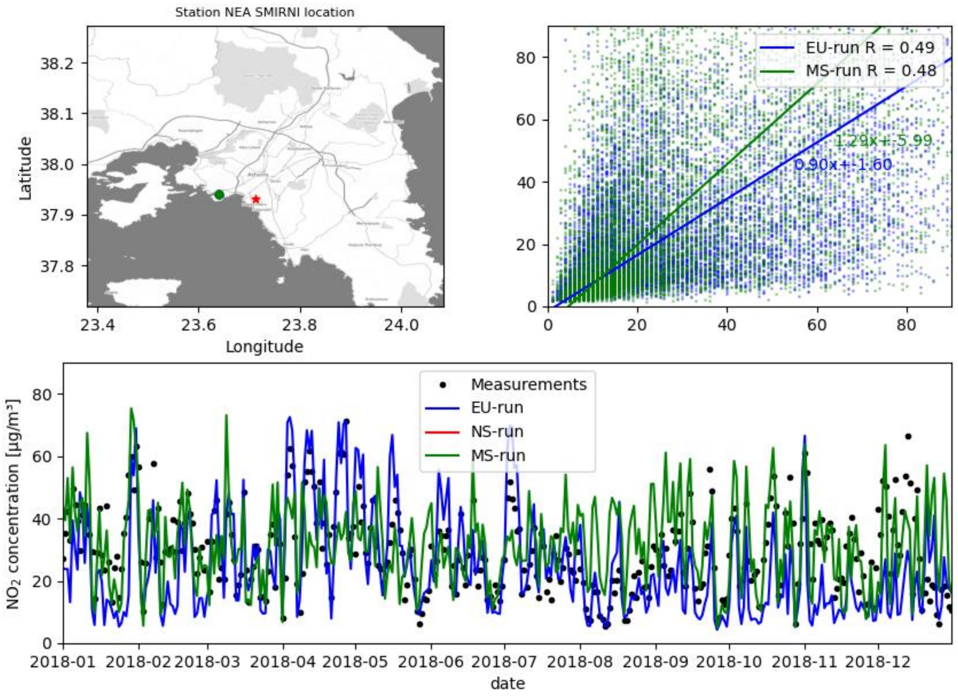


Figure 18 Model results compared to observations closest to the port of Piraeus. Panel A shows the location of the selected measurement station in the European domain. Panel B shows the scatter plot of hourly averaged NO_2 concentrations observed by the measurement station versus the model results of the European simulation (blue) and embedded simulation over the Mediterranean Sea (green). Panel C shows the underlying daily averaged time profiles. The measurements are displayed as black dots

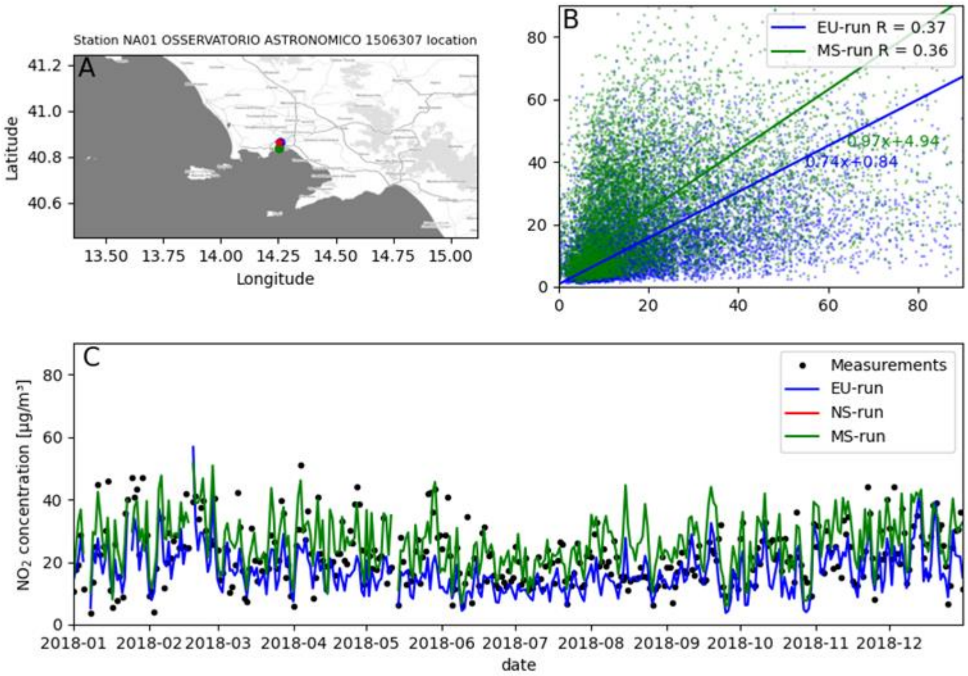


Figure 19 Model results compared to observations closest to the port of Naples. Panel A shows the location of the selected measurement station in the European domain. Panel B shows the scatter plot of hourly averaged NO_2 concentrations observed by the measurement station versus the model results of the European simulation (blue) and embedded simulation over the Mediterranean Sea (green). Panel C shows the underlying daily averaged time profiles. The measurements are displayed as black dots

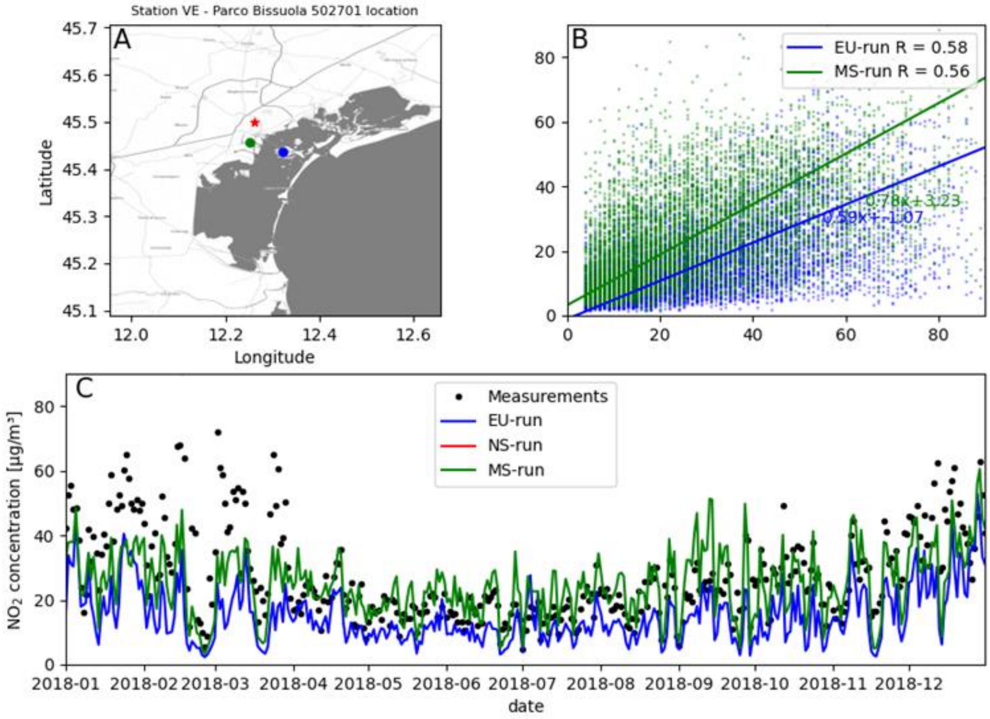


Figure 20 Model results compared to observations closest to the port of Venice. Panel A shows the location of the selected measurement station in the European domain. Panel B shows the scatter plot of hourly averaged NO_2 concentrations observed by the measurement station versus the model results of the European simulation (blue) and embedded simulation over the Mediterranean Sea (green). Panel C shows the underlying time profiles. The measurements are displayed as black dots

4. DISCUSSION

In this section some aspects which should be considered while interpreting the results of the source apportionment modelling simulations, are discussed.

4.1. EMISSION INVENTORIES

The CAMS-REG emission inventory that was used as input to LOTOS-EUROS was prepared using national emission data as reported in the Informative Inventory Reports of all EU Member States (Kuenen et al. 2019). These reports are published annually and scrutinised during annual EU reviews. However, one should bear in mind that these inventories (by agreed definition) do not hold (geographical referenced) emission figures for international shipping in international waters. For example, if a ship travels overseas from one port to another in the same country, the emission can be subscribed to that counties' national emissions. However, when a ship is travelling overseas from one country to another, to which country does the emission belong to? To solve this blind spot in international shipping emissions, the international shipping emissions are calculated by the STEAM model (Jalkanen et al., 2016) and (spatially distributed) incorporated into the CAMS-REG emission inventory. These calculations cover all shipping emissions in the EU (seas), including those which are not calculated in the national inventories. These independent calculated shipping emissions replace the shipping emissions on sea as reported by the countries as the required spatial distributed seagoing shipping emission input to the LOTOS-EUROS model. The spatial disaggregation of the shipping emissions is based on AIS signals and the temporal disaggregation is based on the assumption that international shipping is a continuous activity, meaning a flat time profile is used.

In order to construct the CAMS-REG emission inventory, the spatially distributed emissions from all other sectors in the individual Member States are also used, so the knowledge on the location where emissions are released is included in the dataset. Large point sources as reported to the European Environmental Agency are included in the database at the exact point source location.

The level of detail of the spatially distributed emissions will affect the outcome of the model run. It is expected that when improving the resolution of the emissions, it will increase the accuracy of the calculated air pollutant concentrations, when the model resolution also increases. Also improving the temporal distribution of the emissions through the use of local information and activity data is expected to improve the representation in the model.

4.2. METEOROLOGICAL CONDITIONS

Most of the ports are situated at the peripheries of cities and therefore the shipping emissions take place on a specific edge of the city. Therefore, the air quality in the city itself is, in most of the cases, affected by the prevailing wind direction and the location of the port relative to the city centre. If the wind is directed from the port to the city centre (usually inland wind), higher contribution of the shipping emissions to the pollutant concentrations can be expected in the city centre. For the cities of Rotterdam and Venice this relation has been studied. In **Figure 21** wind roses are displayed of the NO_2 surface level concentration contributed by international shipping in the city centres of Rotterdam (left side) and Venice (right side).

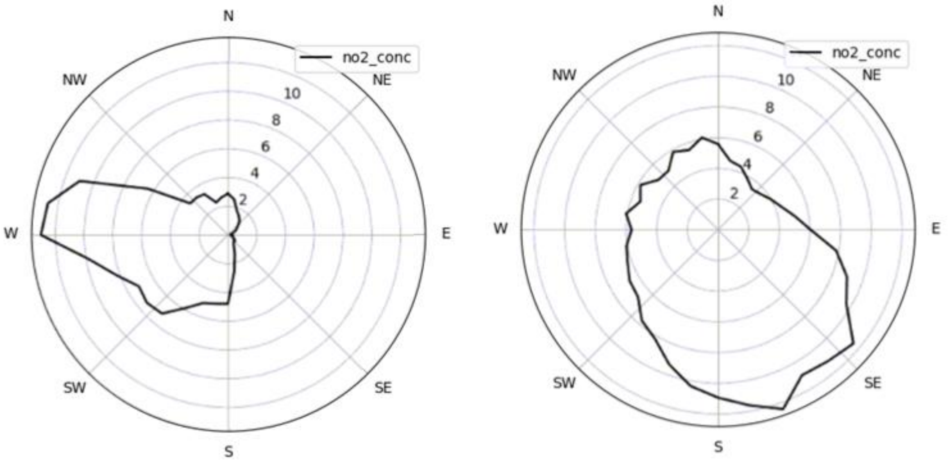


Figure 21 Wind rose displaying the NO_2 surface concentration in Rotterdam (left panel) and Venice (right panel)

In **Figure 21** it can be seen that for Rotterdam high surface level concentration contributed by international shipping (absolute) are often calculated with westerly wind. Since the city centre is situated on the east side of the port, emissions from the port (situated west of the city centre) are blown towards the city under these meteorological conditions. In the left panel of **Figure 22** it can be seen that south-westerly wind was the prevailing direction for 2018, but also westerly wind occurs for ~13% of the year.

In the right wind rose (**Figure 21**) it can be seen that for Venice absolute contribution of international shipping to surface level concentration is high during southeast events. Since the city centre is situated on the northwest side of the port, emissions from the port (southeast) are blown to the city during these events, which happened for 5% of the year in 2018 as can be seen in right panel of **Figure 22**.

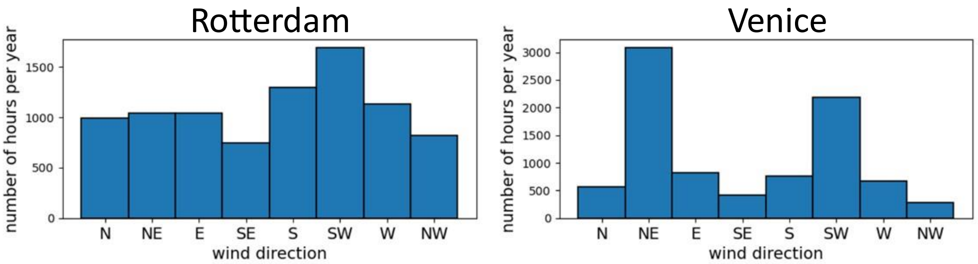


Figure 22 Hours per year when a certain wind direction occurs

These results show that there is a significant correlation between the wind direction and the contribution of international shipping to the air quality at surface level. Presumably other meteorological circumstances also have an influence on the contribution of international shipping to the local air quality in nearby cities. For example, with higher windspeed the concentrations can be expected to be less because the emissions are being spread out and not concentrated in the city centre when the port is located near the city centre. This is generally the case when atmospheric conditions are less stable. For example, in Le Havre the city centre is located close to the port. With high wind speed conditions, the pollutants will be spread and diluted more strongly. Furthermore, it can be expected that with higher temperatures, NO_x reacts with VOC's and the ozone that is formed by the UV in sunlight. Therefore, NO_2 concentrations are possible lower with higher temperature and spatial differences can be detected between North and Southern Europe. In order to have a better understanding of the relation between meteorological conditions and the contribution of shipping on local air quality in cities more extensive research is needed.

With further research effect of emissions, meteorological variables like, wind direction, wind speed, boundary layer height and temperature can be separated and studied. Disaggregation for various levels of pollutant concentrations with respect to the aforementioned parameters will shed light on what conditions are most influential on the air quality in the cities of interest. Other factors like lifetime of the pollutant and location of the city compared to the port, will also be relevant when studying the influence of shipping emissions on the local air quality. The processes that influence each other need a better investigation to get a better understanding in their respective significance.

5. CONCLUSION

The contribution of international and inland shipping to atmospheric pollutant concentrations in Europe were assessed using the chemical transport model LOTOS-EUROS and its source appointment feature that allows tracing of labelled emitted pollutants. For the entire European domain international shipping on average contributed about 18% to the atmospheric yearly mean NO_2 surface concentration in 2018. This is a lower contribution than the contribution to the NO_x emission total, which is 24% (1% contribution from inland and 23% contribution from international shipping). For SO_2, $PM_{2.5}$ and PM_{10} the contribution was smaller at respectively 11%, 5% and 3% for the domain averages. This also holds for the contributions to the emission totals which are respectively 16%, 6% and 3%. Inland shipping has only a minor contribution (<1%) for the domain average annual pollutant concertation for all investigated components. It should be noted that these domain averages contain a large area covered by water, which strongly effect these averages despite not being most relevant for a discussion on European air quality.

Focussing on the local effects by investigating the contributions in areas around big shipping ports, the results show that locally the shipping contribution to air pollution can become more significant. For example, around Rotterdam on average almost 30% of the NO_2 concentration in the Rijnmond area originates from shipping emissions, contributing 6 $\mu g/m^3$ to the total NO_2 concentration (which is ~20 $\mu g/m^3$). Shipping emissions can be the dominant contributor to NO_2 concentrations like for example in Bremen, Le Havre and Genoa where they contribute respectively 59%, 51% and 48%. Similar contributions are found for other cities with large ports. On average over the examined cities, the relative contribution from international shipping is 22% and the absolute contribution is 2.6 $\mu g/m^3$. If we only take sea port locations into account the contribution is higher with an average of 28%.

For the other pollutants the contribution of international shipping to the concentrations in the city centres in all the domains of interest, was on average 18% for SO_2, 8% for $PM_{2.5}$ and 6% for PM_{10}. This clearly shows the increased local effect in the ports when comparing these values with the average contributions to the entire European domain (e.g. 10.8% for SO_2, 5.3% for $PM_{2.5}$ and 2.5% PM_{10}). The absolute contributions are 0.47 $\mu g/m^3$ SO_2, 0.82 $\mu g/m^3$ $PM_{2.5}$ and 1.12 $\mu g/m^3$ PM_{10}.

The wind conditions strongly influence the contribution that shipping emissions have on the NO_2 concentration in cities. Under specific wind conditions the relative contribution from shipping emissions will be higher than the reported annual average contributions. If the wind is directed from the port to the city centre logically high NO_2 concentrations caused by shipping occur as can be seen for Rotterdam and Venice in **Figure 21**. Next to the direction the windspeed influences the concentration. For example, higher windspeeds lead to more transport and more dilution. However, for example for the harbour of Rotterdam, the city centre is around 35 km away from the port and in windless conditions pollution from the port will hardly influence the city centre. There will be some wind direction and speed that optimally transports emissions from the harbour to the port that is location specific and dependent on the distance between port and city and the lifetime of the pollutant of interest. Further study is needed to draw a clear conclusion on this.

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7. APPENDIX

7.1. ULTRAFINE PARTICLES (UFP)

An overview was made throughout this report to describe the effect of shipping in or near cities with a big port and associated nautical activity on the local air quality. This was done by computing the concentration of several air pollutants emitted by ships which are known to cause environmental and/or ecological damage.

However, the investigated pollutants, NO_2, SO_2 and PM are not the only relevant components. It is well know that Ultra Fine Particles (UFPs), i.e. particulate matter with a diameter smaller than 0.1 micron, are also emitted by exhausts from ships (Alanen et al., 2020; Kuittinen et al., 2021). Currently no adequate regulations exist for this size class of atmospheric particulates, which hardly contribute mass to the regulated PM_{10} and $PM_{2.5}$ particle classes. In theory they contribute to both PM_{10} and $PM_{2.5}$ but due to the small size when expressing air pollution in $\mu g/m^3$ they hardly contribute to total mass (a 2.5 micron particle weighs about the same as 16 billion particles of 0.1 micron).

However, these particles are believed to have more aggressive health implications than those classes of larger particles (Howard, 2009). In modelling UFPs not the mass but the particle number is of interest. In this study this type of air pollution has not been taken into account even though more than 50% of UFPs in the Rijnmond area near Rotterdam for example have been shown to originate from shipping emissions (Visschedijk & Denier van der Gon, 2022) as can be seen in **Figure 23.**

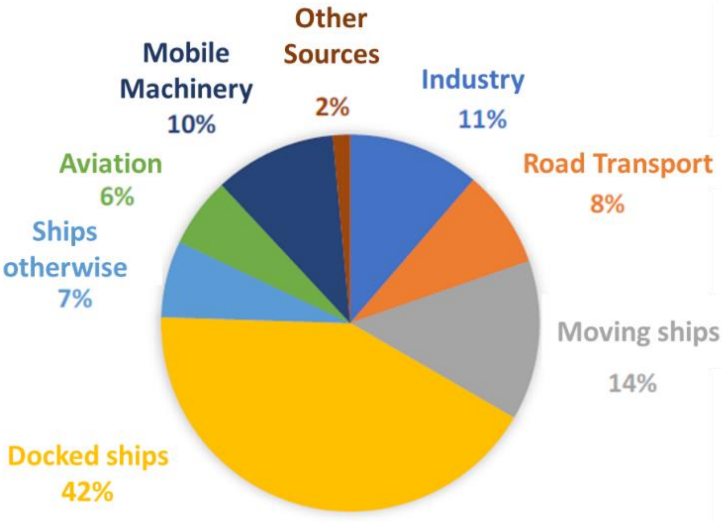


Figure 23 Most important sources of UFP in the Rijnmond area and their relative contributions for 2019. A detailed split of the shipping contribution to the overall UFP concentration is shown. Figure adapted from Visschedijk & Denier van der Gon, 2022

7.2. AVERAGE CONCENTRATIONS AND SOURCE APPORTIONMENT RESULTS

7.2.1. OVERVIEW

Table 7 The relative contribution of international shipping (%) to the average annual concentration of the pollutants of interest in the various domains. Inland shipping ports are marked with *

	NO_2	SO_2	PM_{10}	$PM_{2.5}$
Rotterdam	28	4.2	6.1	8.3
Antwerp	24	4.6	5.8	8.0
Amsterdam	22	4.8	6.3	8.6
Hamburg	23	5.1	5.4	8.6
Bremerhaven	21	19	9.6	15
Marseille	14	30	7.1	9.6
Barcelona	32	26	5.6	8.4
Le Havre	14	5.0	8.6	14
Genoa	19	73	10.7	13
Piraeus	34	42	6.1	13
Lisbon	15	14	4.8	6.2
Naples	25	42	5.2	6.9
Venice	16	34	6.5	7.5
Vienna	18	0.43	1.1	1.3
Liege	18	0.70	3.5	4.2
Duisburg	27	0.16	2.6	3.4
Cologne	26	0.25	2.3	3.0
Nijmegen	17	1.9	5.0	6.4
London	26	1.1	4.2	6.2

7.2.2. NO_2

Table 8 The average concentration of NO_2 [µg/m^3] in the city centre and how much of that concentration is caused by the various sectors

	Total	Energy	Refineries	Industry	Res. comb.	Fuel prod.	Solvent use	Road Transport - exh.	Road Transport - non-exh.	Inland Shipping	International Shipping	Aviation	Mobile machinery	Waste	Livestock	Manure and storage	Wildfire	Saharan Dust	Seasalt	Biogenic	Boundary
Rotterdam	27.8	0.741	0.784	2.15	1.95	0.0493	0.238	7.52	0	8.1	3.69	0.136	1.93	0.0265	0	0.000098	0	0	0	0.426	0.0582
Antwerp	24.1	1.25	0.62	3	2.74	0.0344	0.0354	7.76	0	0.973	5.78	0.145	1.22	0.0215	0	0.000116	0	0	0	0.461	0.0567
Amsterdam	22.3	0.719	0.174	1.6	2.26	0.0691	0.319	7.58	0	3.61	2.96	0.731	1.72	0.0285	0	0.0000748	0	0	0	0.425	0.0603
Hamburg	22.8	2.38	0.13	2.8	2.16	0.0965	0.0179	6.54	0	0.908	5.83	0.217	1.09	0.0303	0	0.000236	0	0	0	0.479	0.06
Bremerhaven	20.9	1.52	0.0641	1.74	0.801	0.122	0.0091	2.66	0	0.267	12.4	0.0404	0.646	0.0101	0	0.00020	0	0	0	0.538	0.0591
Marseille	14.3	0.184	0.263	1.28	2.37	0.00834	0.0352	5.16	0	0.00527	4.12	0.101	0.431	0.0373	0.0000012	0.000203	0	0	0	0.224	0.0643
Barcelona	31.5	0.26	0.045	3.65	5.05	0.00964	0.023	14.3	0	0.000492	6.23	0.414	1.03	0.0338	0.000000688	0.00026	0	0	0	0.417	0.0728
Le Havre	13.7	0.365	1.23	1.09	0.755	0.0334	0.00955	2.26	0	0.0344	6.98	0.0267	0.441	0.0268	0	0.000104	0	0	0	0.385	0.0537
Genoa	18.9	0.128	0.198	0.779	2.41	0.0092	0.00506	5.4	0	0.00243	9.16	0.0779	0.417	0.0356	0.00000103	0.00148	0	0	0	0.262	0.0675
Piraeus	33.7	2.36	1.79	3.79	1.71	0.000724	0.00834	11.3	0	0.00141	11.6	0.0421	0.82	0.00475	0.00000169	0.000854	0	0	0	0.197	0.0727
Lisbon	14.5	0.0892	0.204	3.77	1.03	0.0025	0.00976	4.11	0	0.000116	2.2	2.32	0.403	0.0129	0.000000582	0.000136	0	0	0	0.271	0.0564
Naples	25.3	0.0943	0.0575	0.691	7.07	0.0104	0.0159	10.2	0	0.000656	4.8	0.968	0.577	0.0808	0.00000509	0.000556	0	0	0	0.637	0.0514
Venice	15.7	0.525	0.369	1.58	2.14	0.0413	0.00325	4.61	0	0.00569	4.45	0.425	0.7	0.0759	0.00000295	0.000607	0	0	0	0.668	0.0685
Vienna	17.7	2.28	0.384	3.38	2.58	0.0503	0.00751	5.34	0	0.281	0.0577	0.375	2.26	0.0115	0	0.000832	0	0	0	0.667	0.0785
Liege	18.4	1.3	0.0535	3.13	2.32	0.0154	0.0224	8.86	0	0.499	0.512	0.124	0.975	0.0105	0	0.000128	0	0	0	0.528	0.0577
Duisburg	27	3.35	0.266	8.2	2.28	0.0292	0.0254	7.79	0	2.36	0.54	0.28	1.32	0.0366	0	0.000139	0	0	0	0.482	0.0629
Cologne	25.6	3.72	0.582	4.62	2.66	0.0218	0.0247	9.23	0	2.19	0.408	0.22	1.24	0.0434	0	0.000168	0	0	0	0.562	0.0658
Nijmegen	17.5	0.915	0.118	1.53	1.81	0.0431	0.151	7.3	0	2.31	1.13	0.0818	1.4	0.0183	0	0.000144	0	0	0	0.591	0.0605
London	26	0.912	0.0585	1.66	5.71	0.0446	0.0454	11.8	0	0.0418	1.42	0.498	3.33	0.106	0	0.000112	0	0	0	0.347	0.0603

7.2.3. SO_2

Table 9 The average concentration of SO_2 [µg/m^3] in the city center and how much of that concentration is caused by the various sectors

	Total	Energy	Refineries	Industry	Res. comb.	Fuel prod.	Solvent use	Road Transport - exh.	Road Transport - non-exh.	Inland Shipping	International Shipping	Aviation	Mobile machinery	Waste	Livestock	Manure and storage	Wildfire	Saharan Dust	Seasalt	Biogenic	Boundary
Rotterdam	3.52	0.302	1.39	1.34	0.235	0.0417	0.00585	0.0206	0	0.00555	0.148	0.00887	0.00523	0.00641	0	0.0000221	0	0	0	0	0.0143
Antwerp	6.83	0.354	1.71	2.43	1.63	0.314	0.00323	0.0157	0	0.00037	0.315	0.00996	0.0188	0.00242	0	0.0000243	0	0	0	0	0.0167
Amsterdam	1.84	0.325	0.295	0.817	0.192	0.0197	0.0068	0.0179	0	0.0019	0.0892	0.0561	0.00376	0.00712	0	0.0000177	0	0	0	0	0.0133
Hamburg	6.2	1.1	0.672	3.54	0.46	0.0444	0.00636	0.0137	0	0.000535	0.314	0.013	0.00877	0.00521	0	0.0000658	0	0	0	0	0.0191
Bremerhaven	3.32	0.637	0.292	1.52	0.198	0.0111	0.00134	0.00476	0	0.0000703	0.636	0.0025	0.0028	0.00162	0	0.0000484	0	0	0	0	0.0178
Marseille	3.76	0.081	0.806	1.13	0.508	0.0538	0.00022	0.011	0	0	1.13	0.00784	0.000514	0.00503	0	0.0000112	0	0	0	0	0.0217
Barcelona	8.63	0.0752	0.124	3.33	2.72	0.0115	0.00252	0.033	0	0	2.25	0.033	0.00998	0.0262	0	0.000000187	0	0	0	0	0.015
Le Havre	5.85	0.16	3.86	1.12	0.214	0.177	0.000167	0.0049	0	0.00000855	0.291	0.00263	0.00181	0.00424	0	0.00000915	0	0	0	0	0.0165
Genoa	3.74	0.109	0.111	0.491	0.228	0.0361	0.00123	0.0077	0	8.69E-08	2.72	0.00624	0.00328	0.000954	0	0.000123	0	0	0	0	0.0247
Piraeus	9.35	0.494	3.34	0.485	1.03	0.00104	0.0001	0.0153	0	0.00000529	3.91	0.00278	0.00741	0.000222	0	0.0000766	0	0	0	0	0.0666
Lisbon	5.93	1.02	0.191	3.62	0.128	0.00129	0.000413	0.00794	0	0	0.841	0.0842	0.0044	0.000973	0	0.0000048	0	0	0	0	0.023
Naples	3.85	0.124	0.0489	1.13	0.794	0.00252	0.00629	0.0167	0	0	1.61	0.088	0.0115	0.000706	0	0.0000192	0	0	0	0	0.0204
Venice	3.68	0.506	0.194	1.28	0.286	0.0985	0.000769	0.00742	0	0.00000718	1.25	0.0282	0.00308	0.00228	0	0.000112	0	0	0	0	0.0317
Vienna	3.07	0.936	0.32	1.13	0.565	0.01	0.00195	0.011	0	0.000217	0.013	0.0236	0.0143	0.00316	0	0.000511	0	0	0	0	0.038
Liege	2.95	0.43	0.104	1.09	1.24	0.0108	0.00249	0.0164	0	0.000134	0.0207	0.00753	0.0151	0.00168	0	0.0000264	0	0	0	0	0.0184
Duisburg	13.7	1.54	0.81	10.8	0.459	0.0181	0.0059	0.017	0	0.0014	0.0221	0.0203	0.0107	0.005	0	0.0000279	0	0	0	0	0.0185
Cologne	6.37	1.52	0.728	3.45	0.551	0.0167	0.00781	0.0195	0	0.00129	0.016	0.0152	0.0103	0.00639	0	0.000035	0	0	0	0	0.0198
Nijmegen	1.81	0.397	0.197	0.915	0.203	0.0198	0.003	0.0161	0	0.000957	0.034	0.00461	0.00352	0.00323	0	0.0000236	0	0	0	0	0.0148
London	5.75	0.111	0.122	0.707	4.32	0.00892	0.00472	0.0766	0	0.00000766	0.0628	0.0713	0.211	0.046	0	0.0000109	0	0	0	0	0.0118

7.2.4. PM$_{10}$

Table 10 The average concentration of PM$_{10}$ [µg/m^3] in the city centre and how much of that concentration is caused by the various sectors

	Total	Energy	Refineries	Industry	Res. comb.	Fuel prod.	Solvent use	Road Transport - exh.	Road Transport - non-exh.	Inland Shipping	International Shipping	Aviation	Mobile machinery	Waste	Livestock	Manure and storage	Wildfire	Saharan Dust	Seasalt	Biogenic	Boundary
Rotterdam	21.7	0.676	0.255	3.1	1.75	0.101	0.841	1.6	1.91	0.648	1.32	0.0529	0.49	0.272	0.568	0.846	0	0.0404	4.5	0.204	2.51
Antwerp	23.4	0.662	0.238	3.85	3.17	0.0921	0.287	1.61	2.72	0.176	1.36	0.0529	0.568	0.432	0.962	1.02	0	0.049	3.48	0.203	2.49
Amsterdam	20.4	0.693	0.17	2.54	1.69	0.111	0.949	1.54	1.37	0.309	1.28	0.0646	0.457	0.281	0.55	0.731	0	0.039	4.88	0.21	2.48
Hamburg	23.2	0.903	0.17	6.41	1.9	0.154	0.622	1.3	1.61	0.118	1.25	0.0376	0.689	0.427	0.751	0.781	0	0.0394	3.58	0.198	2.24
Bremerhaven	19.6	0.833	0.145	3.49	1.57	0.141	0.149	1.26	0.427	0.101	1.88	0.0397	0.423	0.152	1.04	0.763	0	0.0336	4.66	0.223	2.32
Marseille	16.4	0.362	0.163	1.9	2.34	0.0209	0.0726	1.11	1.5	0.0127	1.17	0.0383	0.23	0.739	0.348	0.496	0	0.364	2.71	0.144	2.69
Barcelona	38	0.679	0.203	4	6.8	0.0304	0.831	1.7	11.4	0.00725	2.11	0.0734	0.333	0.665	2.09	0.577	0	0.331	2.63	0.241	3.23
Le Havre	18.5	0.389	0.262	2.01	1.58	0.0571	0.0418	1.07	0.454	0.0524	1.59	0.0354	0.289	0.236	0.437	0.762	0	0.0466	6.08	0.209	2.91
Genoa	19.5	0.509	0.215	1.36	4.27	0.112	0.198	1.58	1.55	0.00956	2.08	0.041	0.266	0.188	0.857	0.643	0	0.376	2.26	0.212	2.78
Piraeus	35.9	1.12	0.414	6.07	1.92	0.0987	0.632	1.09	7.2	0.0058	2.18	0.0122	0.175	0.135	0.381	0.511	0	2.92	3.45	0.123	7.46
Lisbon	32.3	0.346	0.157	10.4	1.22	0.0621	0.412	0.682	3.16	0.00247	1.54	1.32	0.105	0.33	0.283	0.286	0	0.182	6.21	0.108	5.53
Naples	34.5	0.545	0.088	2.22	8.67	0.199	0.846	1.78	6.53	0.00664	1.81	0.0588	0.277	0.344	0.713	0.681	0	1.2	3.76	0.226	4.59
Venice	25.6	0.949	0.205	3.02	6.49	0.104	0.151	2.89	1.2	0.0159	1.66	0.105	0.534	0.368	1.89	1.29	0	0.269	1.64	0.434	2.36
Vienna	21.9	1.64	0.181	5.22	4.58	0.0681	0.292	1.5	1.58	0.0525	0.249	0.0736	0.589	0.639	0.614	1.13	0	0.17	0.847	0.258	2.2
Liege	18.7	0.688	0.127	3.03	2.98	0.0669	0.223	1.64	1.34	0.123	0.662	0.0492	0.476	0.335	0.858	0.858	0	0.0618	2.62	0.199	2.38
Duisburg	25.6	0.905	0.195	8.49	2.54	0.305	0.631	1.56	1.57	0.229	0.657	0.0507	0.788	0.45	0.806	0.886	0	0.0544	2.86	0.19	2.39
Cologne	23.5	0.927	0.187	6.75	2.61	0.149	0.842	1.63	1.64	0.218	0.55	0.0495	0.762	0.56	0.689	0.913	0	0.056	2.48	0.187	2.3
Nijmegen	18.8	0.748	0.17	2.15	2.13	0.126	0.435	1.7	1.28	0.254	0.937	0.0506	0.469	0.186	1.22	0.928	0	0.0507	3.34	0.231	2.36
London	24.2	0.458	0.119	3.48	2.28	0.0755	0.931	1.37	3.84	0.0351	1.01	0.0592	0.539	0.885	0.239	0.565	0	0.0365	4.85	0.154	3.24

7.2.5. PM$_{2.5}$

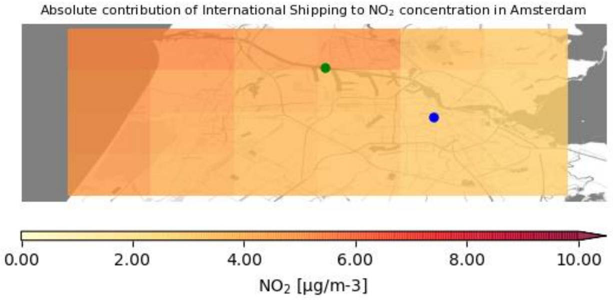
Table 11 The average concentration of PM$_{2.5}$ [µg/m^3] in the city centre and how much of that concentration is caused by the various sectors

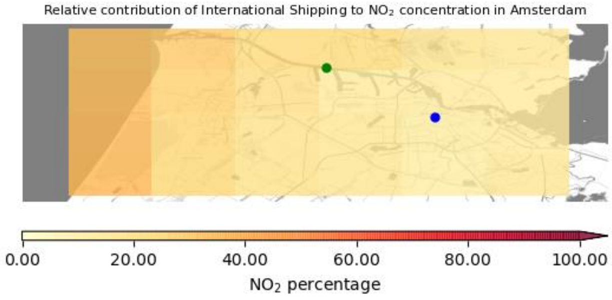
	Total	Energy	Refineries	Industry	Res. comb.	Fuel prod.	Solvent use	Road Transport - exh.	Road Transport - non-exh.	Inland Shipping	International Shipping	Aviation	Mobile machinery	Waste	Livestock	Manure and storage	Wildfire	Saharan Dust	Seasalt	Biogenic	Boundary
Rotterdam	11.9	0.593	0.235	1.92	1.68	0.0513	0.831	1.39	0.371	0.637	0.987	0.0432	0.423	0.259	0.465	0.524	0	0.00642	0.663	11.9	0.593
Antwerp	13.5	0.583	0.224	2.26	3.07	0.0542	0.275	1.41	0.662	0.162	1.08	0.0441	0.443	0.429	0.763	0.596	0	0.00764	0.556	13.5	0.583
Amsterdam	11	0.606	0.157	1.61	1.61	0.0583	0.937	1.33	0.278	0.296	0.944	0.0522	0.389	0.266	0.452	0.478	0	0.00534	0.691	11	0.606
Hamburg	11.8	0.795	0.16	2.37	1.81	0.073	0.495	1.11	0.44	0.107	1.02	0.0301	0.498	0.417	0.664	0.413	0	0.00558	0.54	11.8	0.795
Bremerhaven	10.4	0.735	0.135	1.56	1.5	0.0761	0.126	1.06	0.164	0.0897	1.59	0.0315	0.348	0.146	0.895	0.441	0	0.00464	0.659	10.4	0.735
Marseille	9.06	0.302	0.145	1.21	2.25	0.0164	0.0612	0.798	0.378	0.00747	0.871	0.025	0.156	0.736	0.328	0.336	0	0.0369	0.458	9.06	0.302
Barcelona	20.3	0.568	0.171	2.62	6.62	0.019	0.774	1.44	2.14	0.00449	1.71	0.0586	0.275	0.663	1.28	0.276	0	0.0406	0.452	20.3	0.568
Le Havre	8.75	0.323	0.25	1.23	1.52	0.0337	0.0373	0.852	0.144	0.0429	1.19	0.0264	0.23	0.234	0.399	0.481	0	0.00604	0.862	8.75	0.323
Genoa	12.7	0.443	0.201	1.1	4.13	0.107	0.164	1.25	0.407	0.00547	1.68	0.0289	0.206	0.184	0.826	0.419	0	0.0546	0.383	12.7	0.443
Piraeus	12.7	0.864	0.353	2.19	1.84	0.0223	0.527	0.85	1.19	0.00211	1.72	0.00554	0.119	0.126	0.357	0.332	0	0.17	0.519	12.7	0.864
Lisbon	14.6	0.284	0.103	6.63	1.17	0.0587	0.364	0.501	0.503	0.00105	0.9	1.31	0.0689	0.33	0.233	0.15	0	0.0171	0.853	14.6	0.284
Naples	19.3	0.453	0.0744	1.7	8.45	0.191	0.697	1.42	1.41	0.0028	1.33	0.0438	0.21	0.341	0.573	0.381	0	0.0845	0.58	19.3	0.453
Venice	20.1	0.861	0.195	2.56	6.35	0.0946	0.133	2.61	0.429	0.0122	1.51	0.0968	0.477	0.355	1.77	0.763	0	0.0514	0.307	20.1	0.861
Vienna	13.7	1.45	0.171	1.93	4.45	0.0346	0.262	1.32	0.372	0.0472	0.181	0.0688	0.482	0.545	0.574	0.468	0	0.0341	0.187	13.7	1.45
Liege	11.4	0.612	0.119	1.78	2.89	0.0348	0.21	1.44	0.483	0.109	0.482	0.0406	0.372	0.332	0.748	0.447	0	0.00999	0.436	11.4	0.612
Duisburg	14	0.814	0.185	3.79	2.44	0.0798	0.519	1.35	0.512	0.216	0.48	0.0426	0.567	0.441	0.685	0.517	0	0.0084	0.459	14	0.814
Cologne	13.1	0.836	0.177	2.75	2.5	0.0518	0.682	1.43	0.579	0.204	0.396	0.0417	0.547	0.548	0.598	0.5	0	0.00875	0.411	13.1	0.836
Nijmegen	11.1	0.675	0.162	1.49	2.05	0.0607	0.425	1.51	0.314	0.239	0.711	0.0427	0.406	0.178	0.847	0.546	0	0.0076	0.537	11.1	0.675
London	11.7	0.384	0.106	1.76	2.18	0.0413	0.771	1.17	1.1	0.0292	0.726	0.0496	0.475	0.831	0.197	0.336	0	0.00464	0.72	11.7	0.384

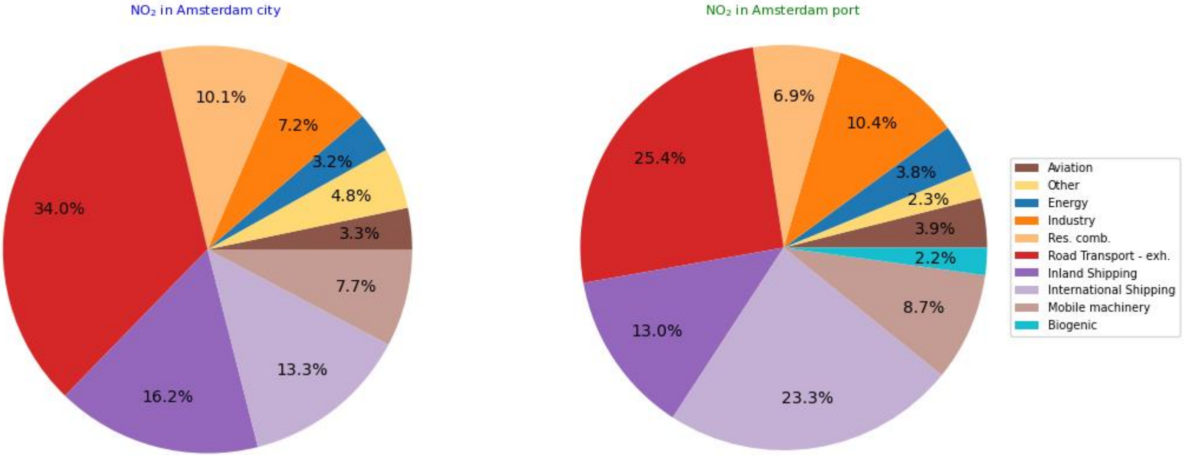
7.3. COMPUTED RESULTS FOR ALL POLLUTANTS AND FOR ALL PORT/CITIES ASSESSED IN THIS STUDY

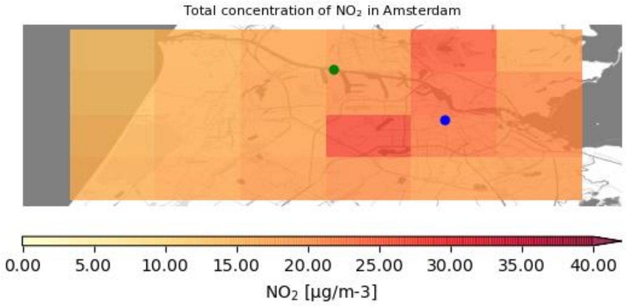
7.3.1. NO_2

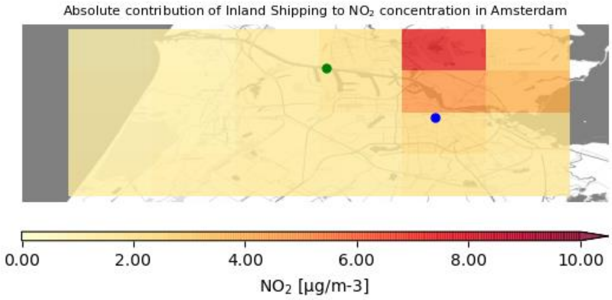
7.3.1.1. Amsterdam



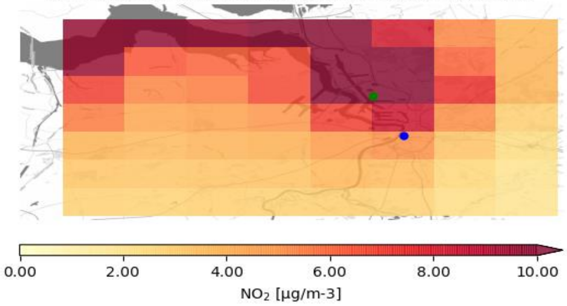


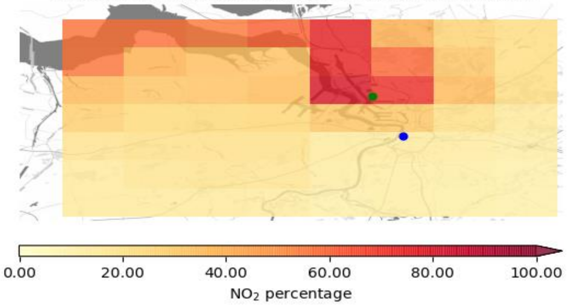


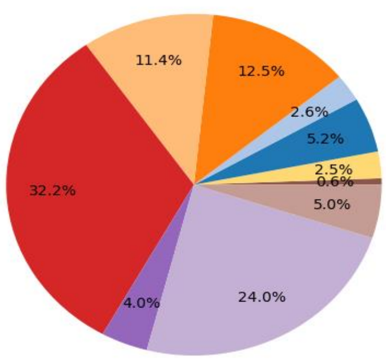


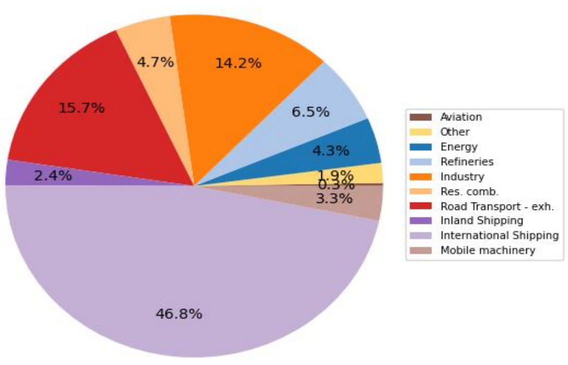


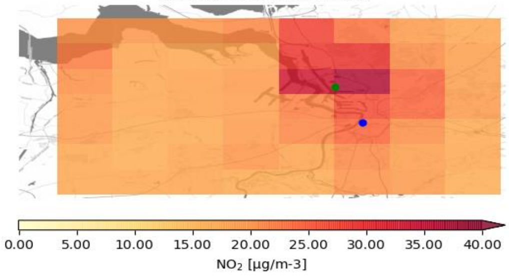
7.3.1.2. Antwerp

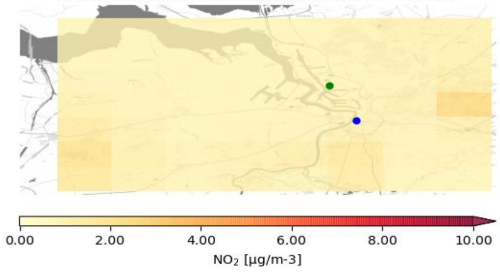

Absolute contribution of International Shipping to NO₂ concentration in Antwerp


Relative contribution of International Shipping to NO₂ concentration in Antwerp

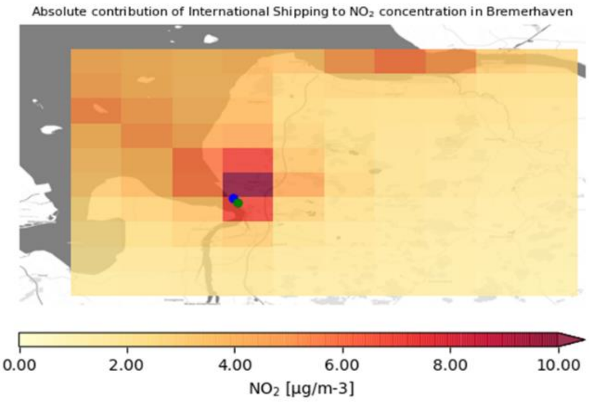

NO₂ in Antwerp city

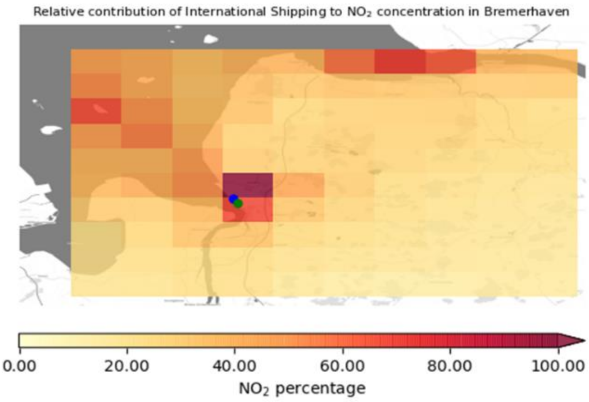

NO₂ in Antwerp port

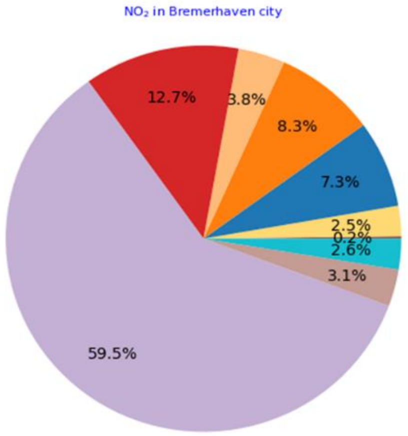

Total concentration of NO₂ in Antwerp

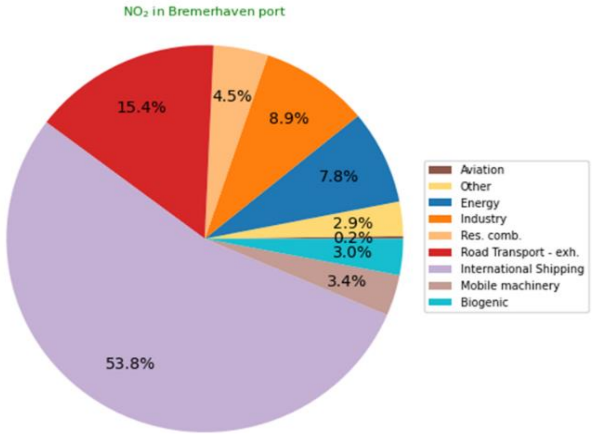

Absolute contribution of Inland Shipping to NO₂ concentration in Antwerp

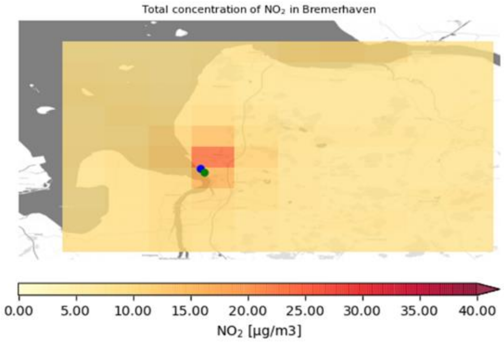
7.3.1.3. Bremerhaven

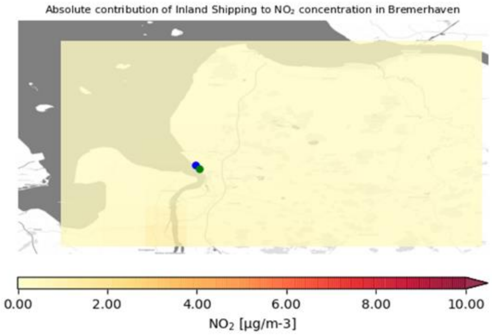




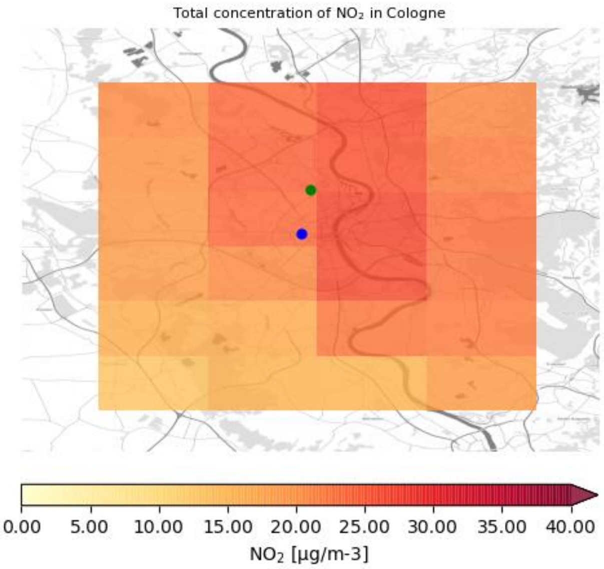


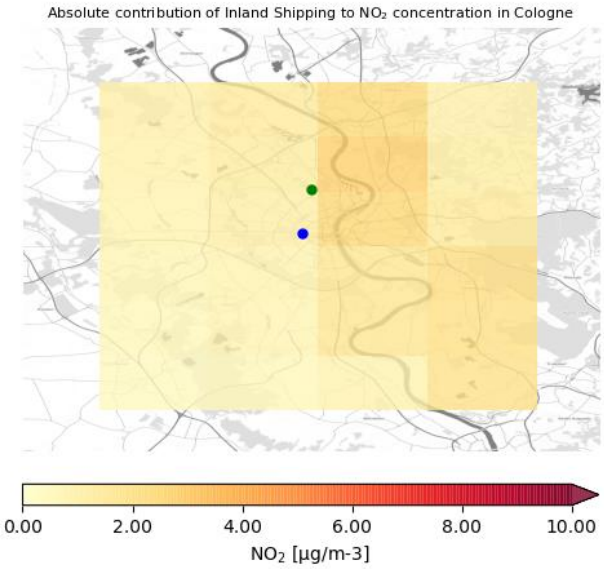




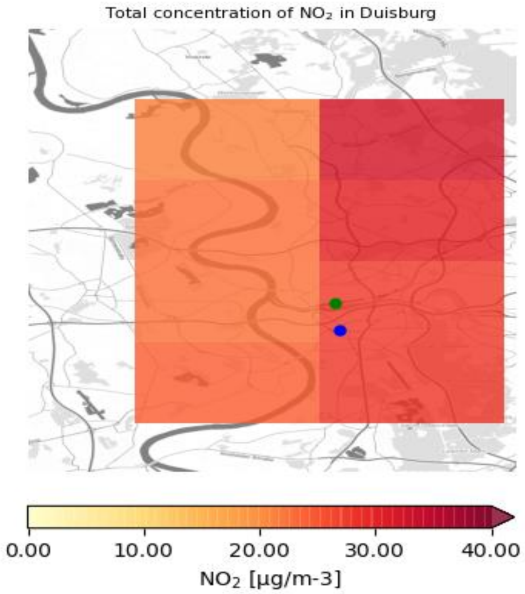


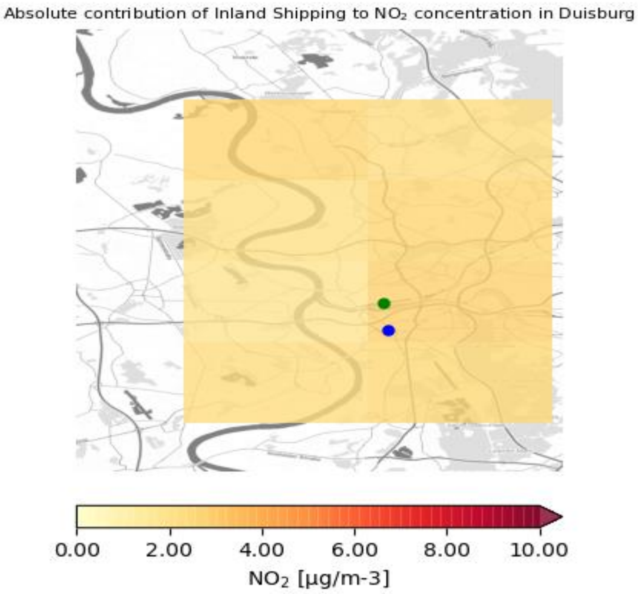
7.3.1.4. Cologne


Total concentration of NO_2 in Cologne


Absolute contribution of Inland Shipping to NO_2 concentration in Cologne

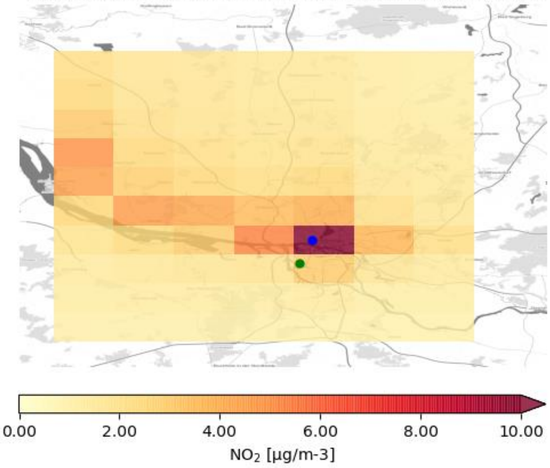
7.3.1.5. Duisburg


Total concentration of NO_2 in Duisburg

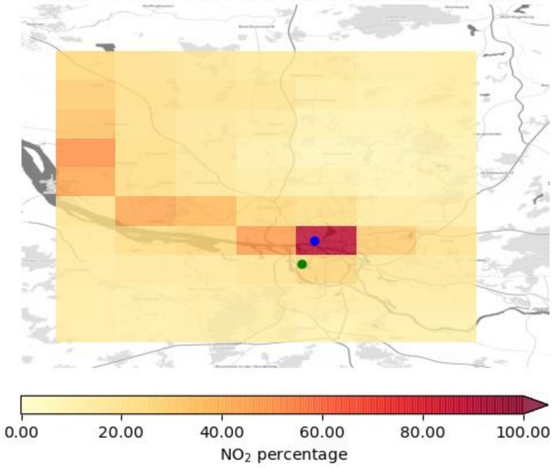

Absolute contribution of Inland Shipping to NO_2 concentration in Duisburg

7.3.1.6. Hamburg

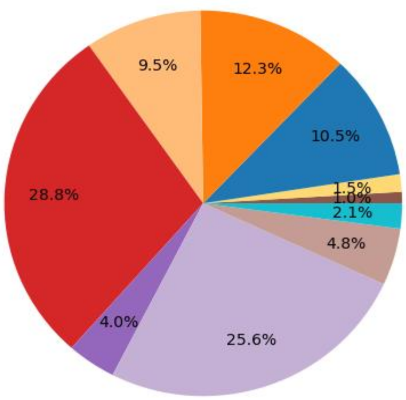
Absolute contribution of International Shipping to NO_2 concentration in Hamburg



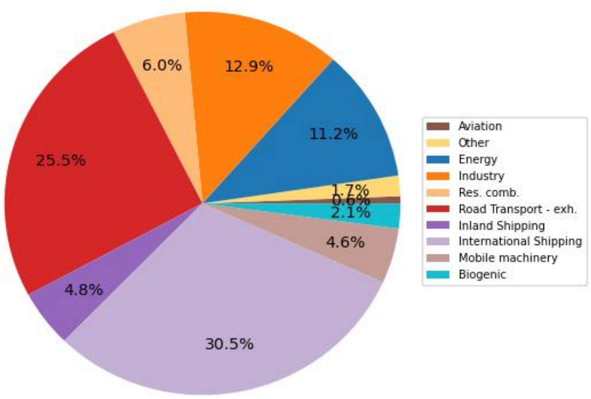
Relative contribution of International Shipping to NO_2 concentration in Hamburg



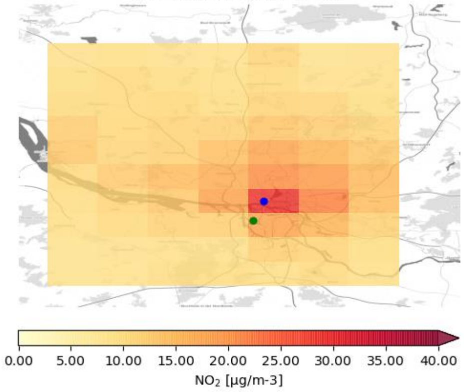
NO_2 in Hamburg city



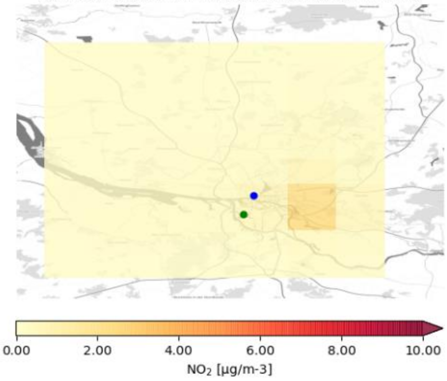
NO_2 in Hamburg port



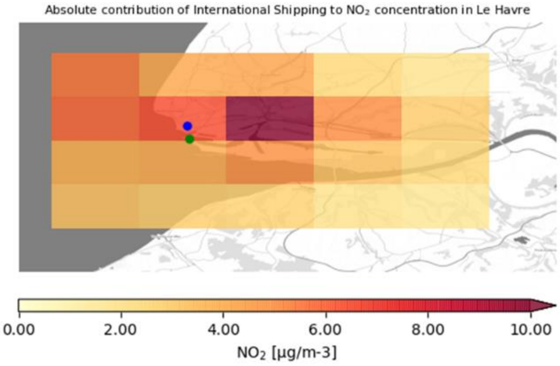
Total concentration of NO_2 in Hamburg

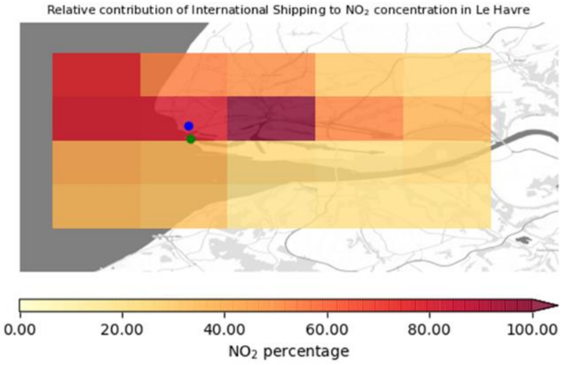


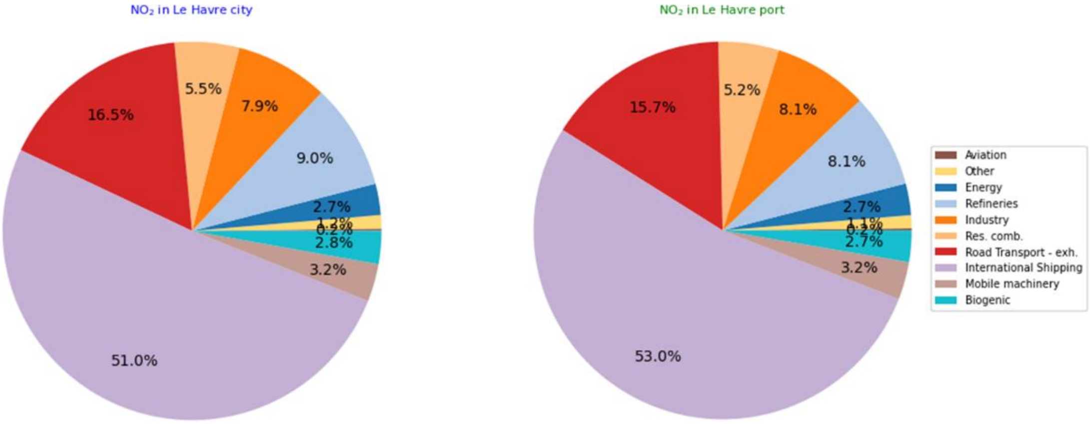
Absolute contribution of Inland Shipping to NO_2 concentration in Hamburg

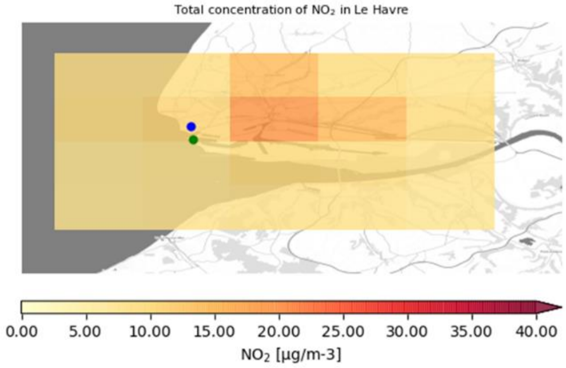


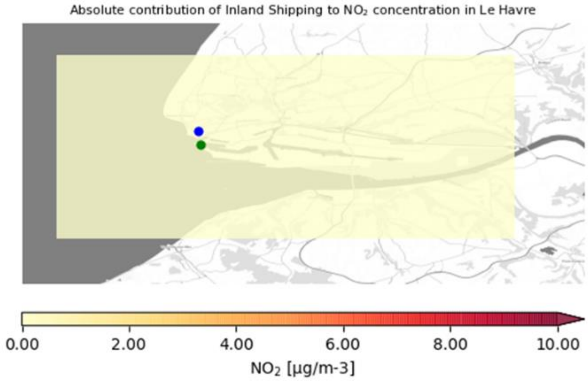
7.3.1.7. Le Havre



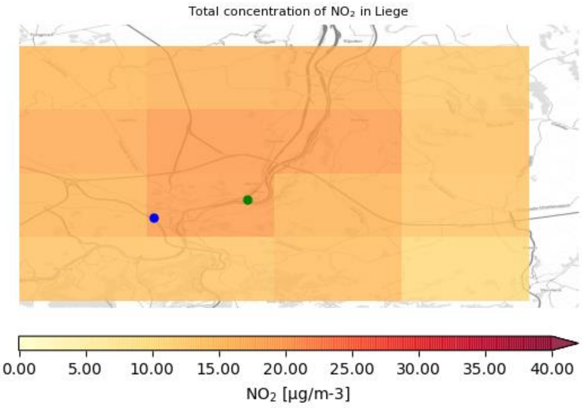


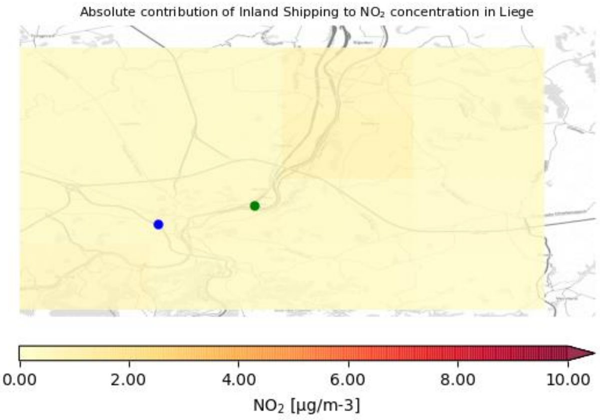




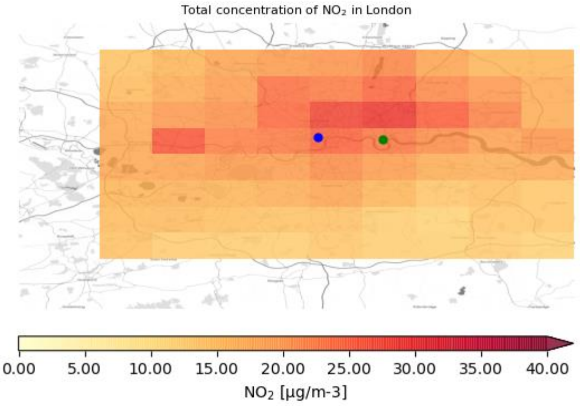


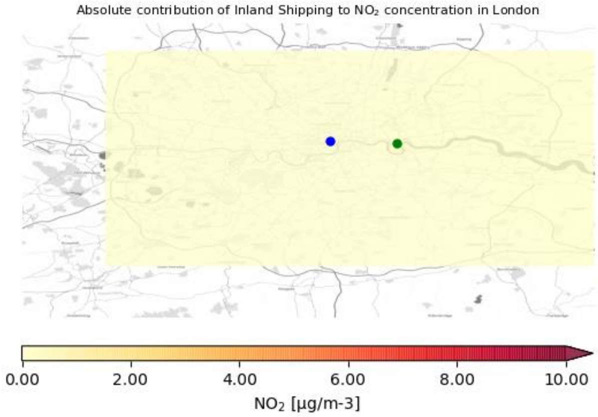
7.3.1.8. Liege


Total concentration of NO₂ in Liege

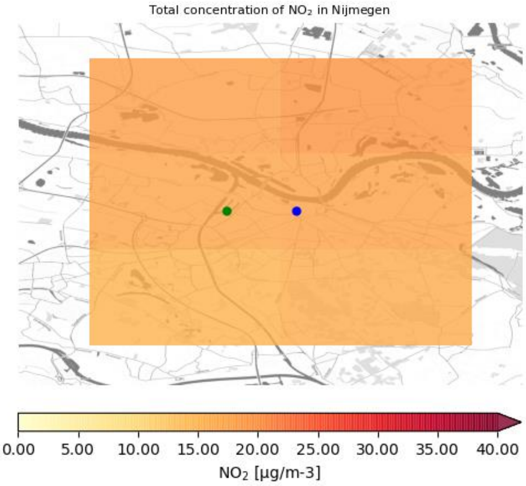

Absolute contribution of Inland Shipping to NO₂ concentration in Liege

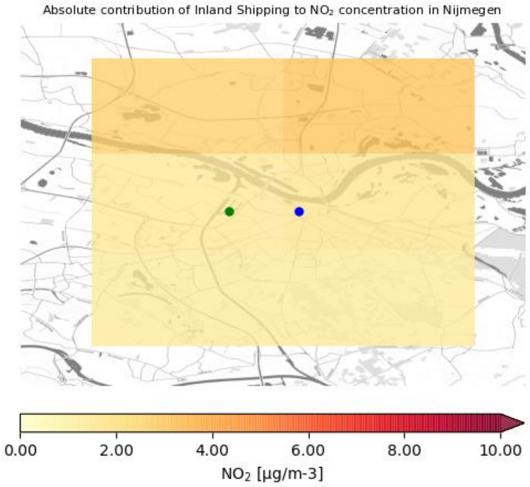
7.3.1.9. London


Total concentration of NO₂ in London


Absolute contribution of Inland Shipping to NO₂ concentration in London

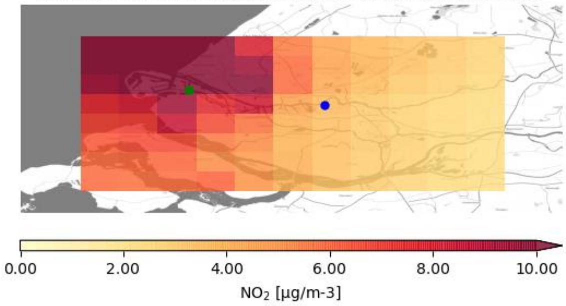
7.3.1.10. Nijmegen


Total concentration of NO₂ in Nijmegen

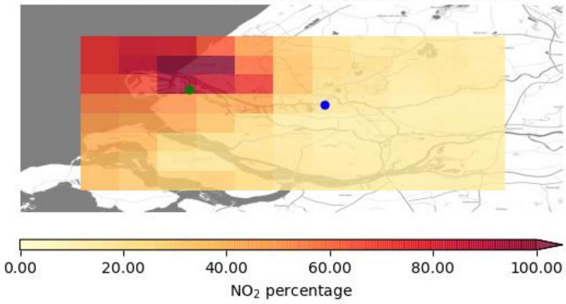

Absolute contribution of Inland Shipping to NO₂ concentration in Nijmegen

7.3.1.11. Rotterdam

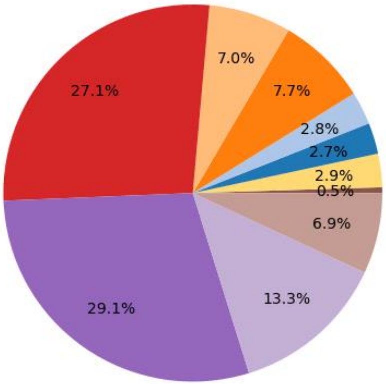
Absolute contribution of International Shipping to NO_2 concentration in Rotterdam



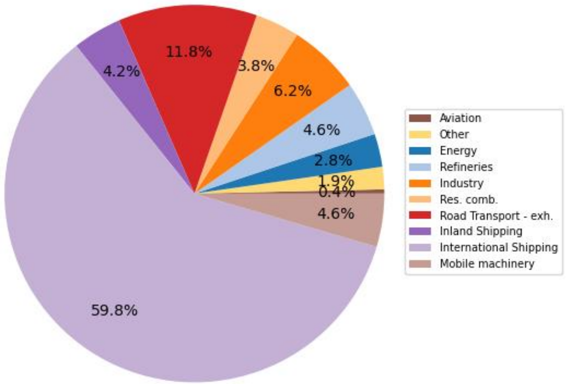
Relative contribution of International Shipping to NO_2 concentration in Rotterdam



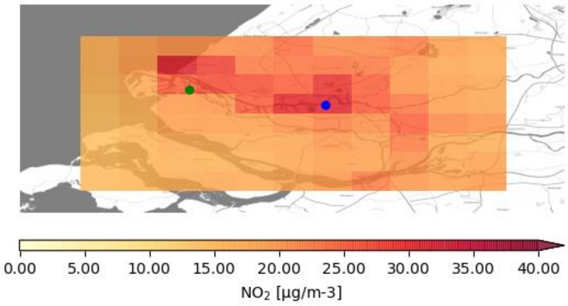
NO_2 in Rotterdam city



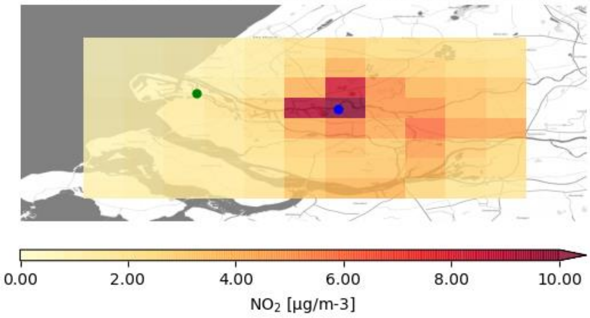
NO_2 in Rotterdam port



Total concentration of NO_2 in Rotterdam

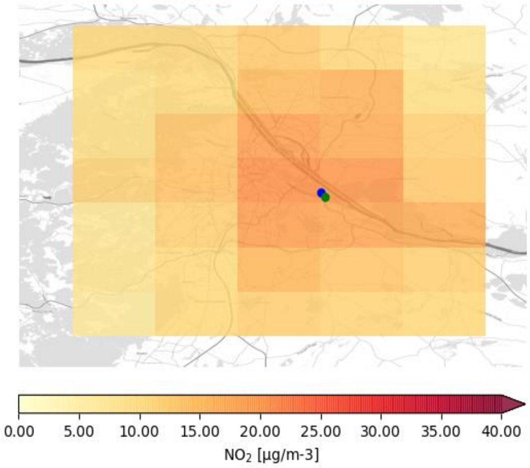


Absolute contribution of Inland Shipping to NO_2 concentration in Rotterdam

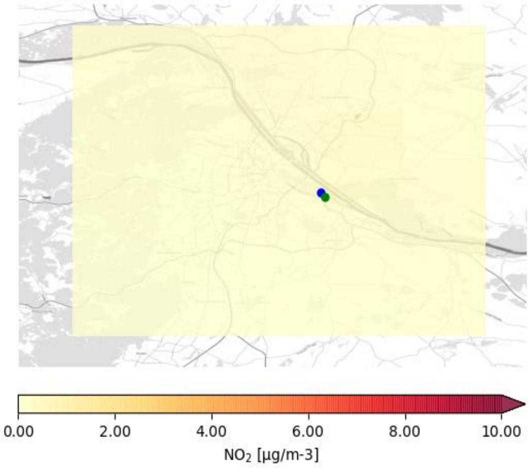


7.3.1.12. Vienna

Total concentration of NO_2 in Vienna

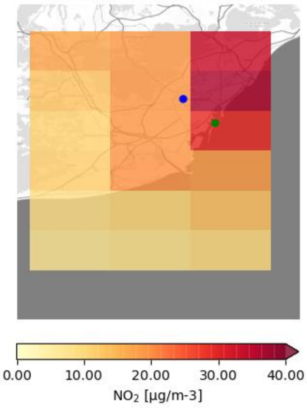


Absolute contribution of Inland Shipping to NO_2 concentration in Vienna

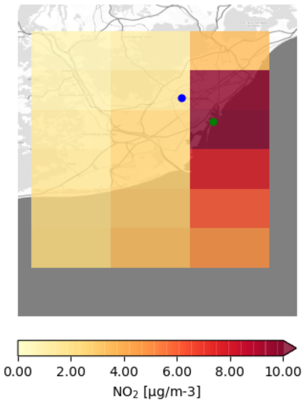


7.3.1.13. Barcelona

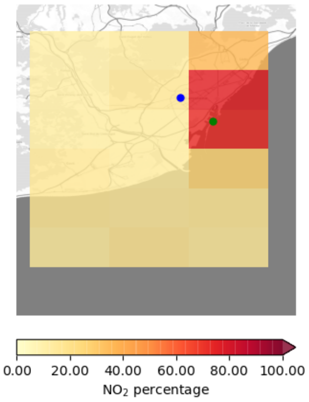
Total concentration of NO_2 in Barcelona



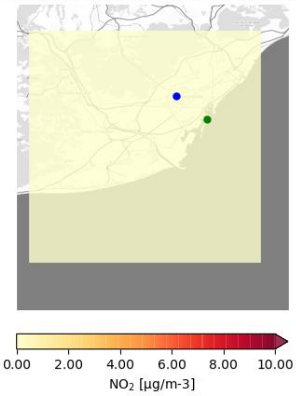
Absolute contribution of International Shipping to NO_2 concentration in Barcelona



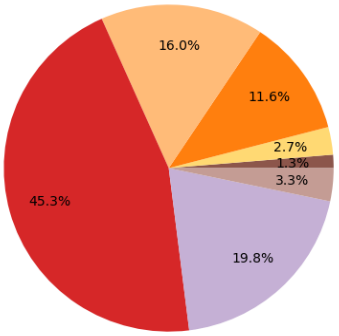
Relative contribution of International Shipping to NO_2 concentration in Barcelona



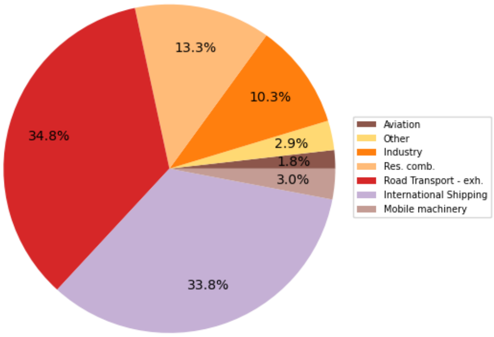
Absolute contribution of Inland Shipping to NO_2 concentration in Barcelona



NO_2 in Barcelona city

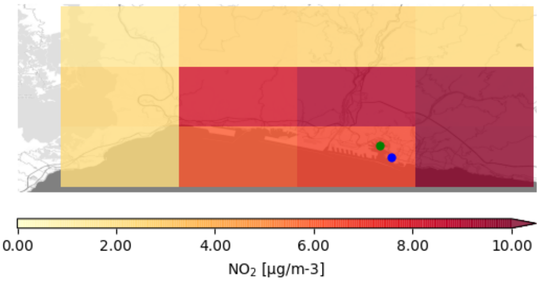


NO_2 in Barcelona port

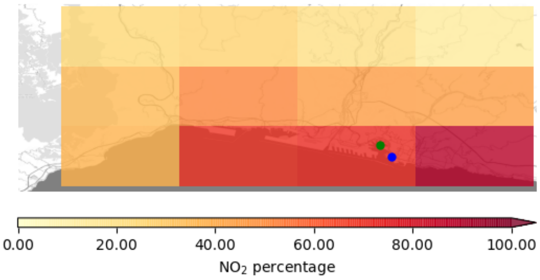


7.3.1.14. Genoa

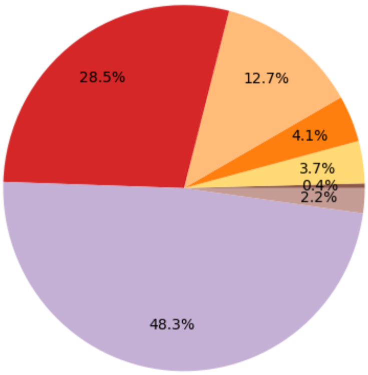
Absolute contribution of International Shipping to NO_2 concentration in Genoa



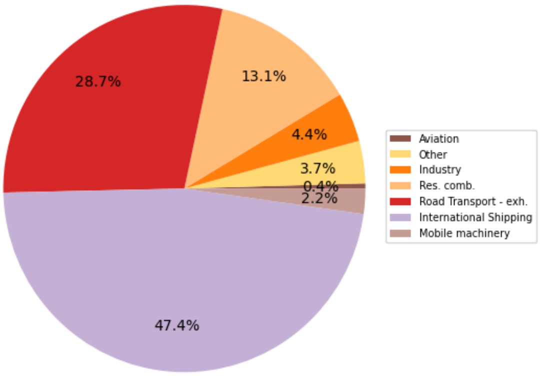
Relative contribution of International Shipping to NO_2 concentration in Genoa



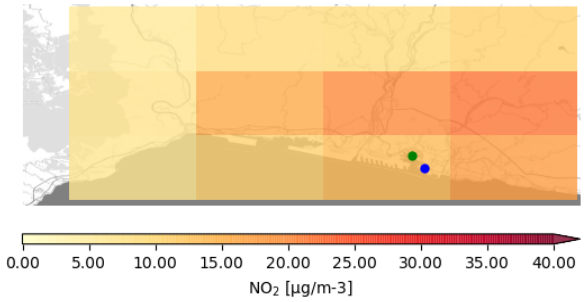
NO_2 in Genoa city



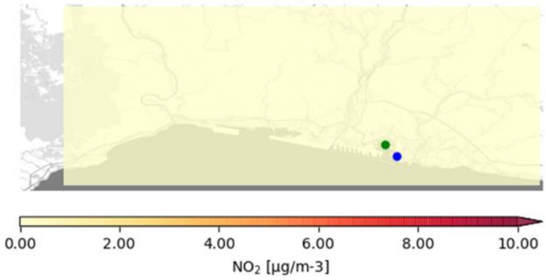
NO_2 in Genoa port



Total concentration of NO_2 in Genoa

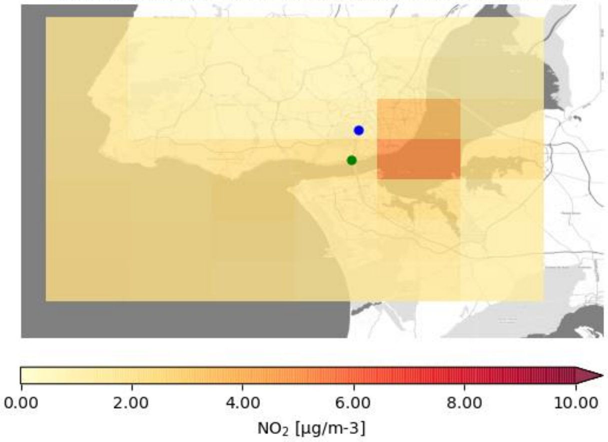


Absolute contribution of Inland Shipping to NO_2 concentration in Genoa

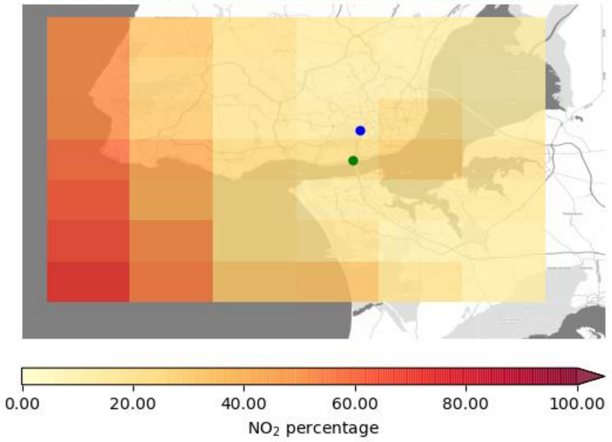


7.3.1.15. Lisbon

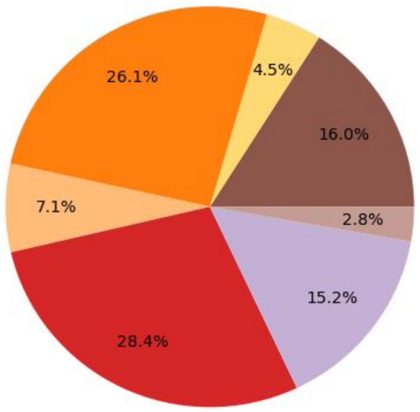
Absolute contribution of International Shipping to NO_2 concentration in Lisbon



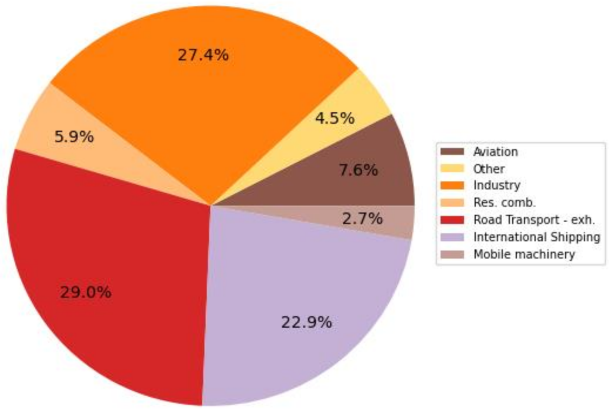
Relative contribution of International Shipping to NO_2 concentration in Lisbon



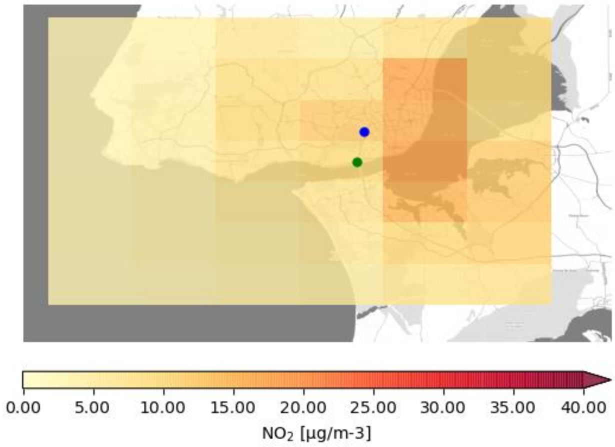
NO_2 in Lisbon city



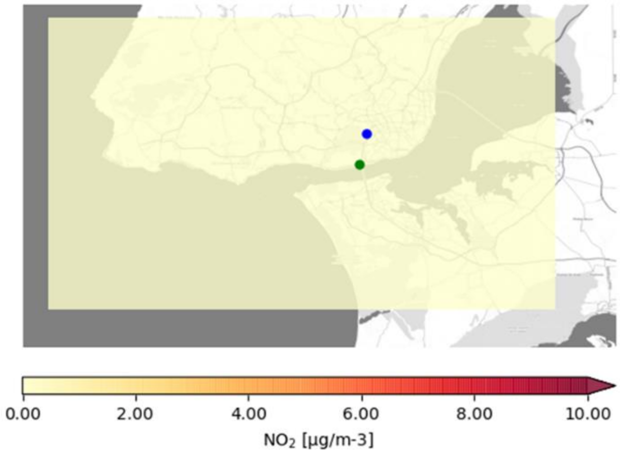
NO_2 in Lisbon port



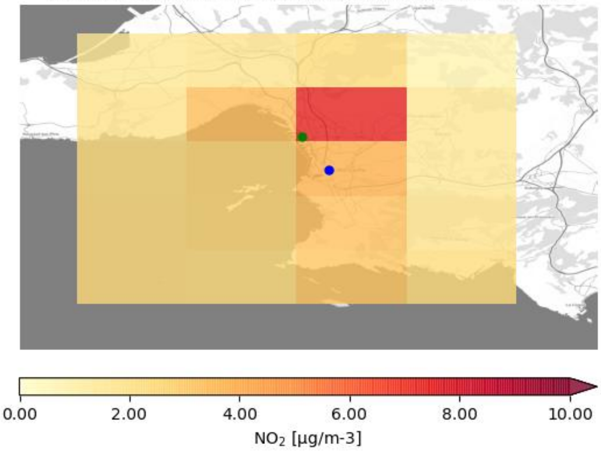
Total concentration of NO_2 in Lisbon

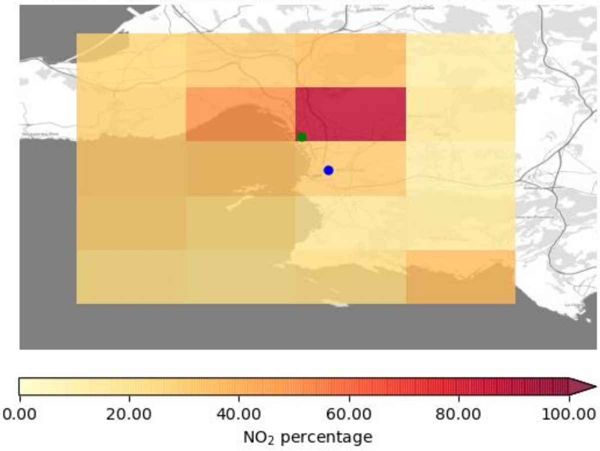


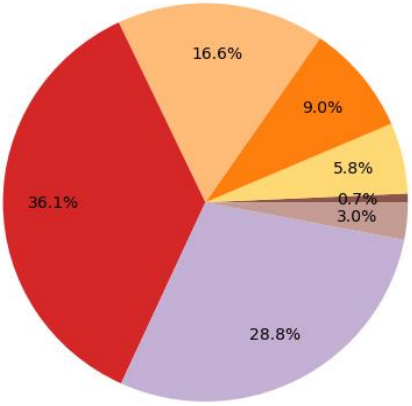
Absolute contribution of Inland Shipping to NO_2 concentration in Lisbon

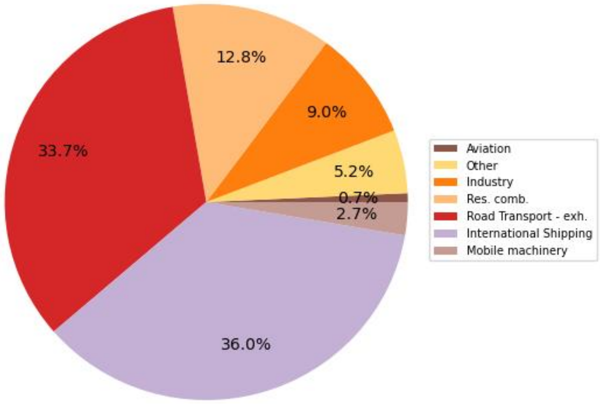


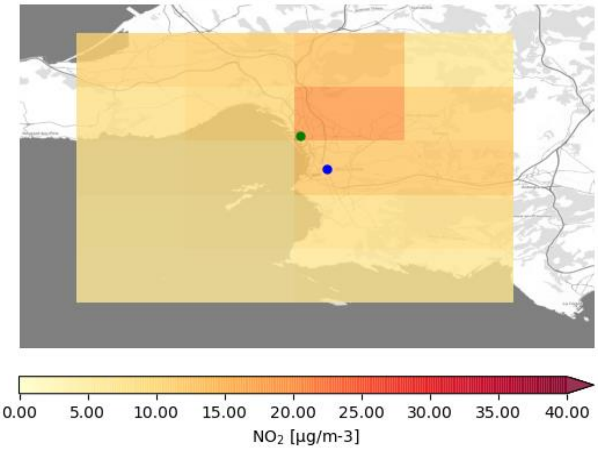
7.3.1.16. Marseille

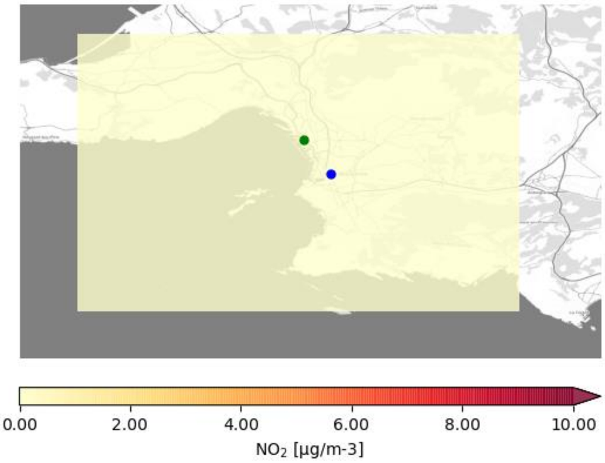

Absolute contribution of International Shipping to NO_2 concentration in Marseille


Relative contribution of International Shipping to NO_2 concentration in Marseille

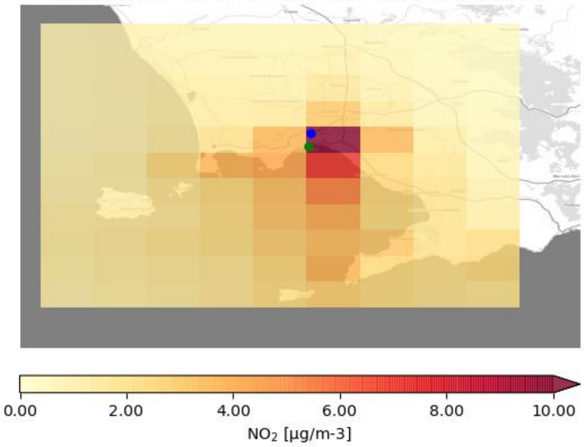

NO_2 in Marseille city

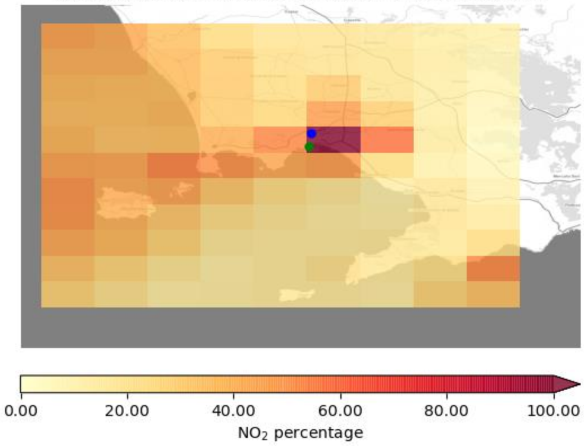

NO_2 in Marseille port

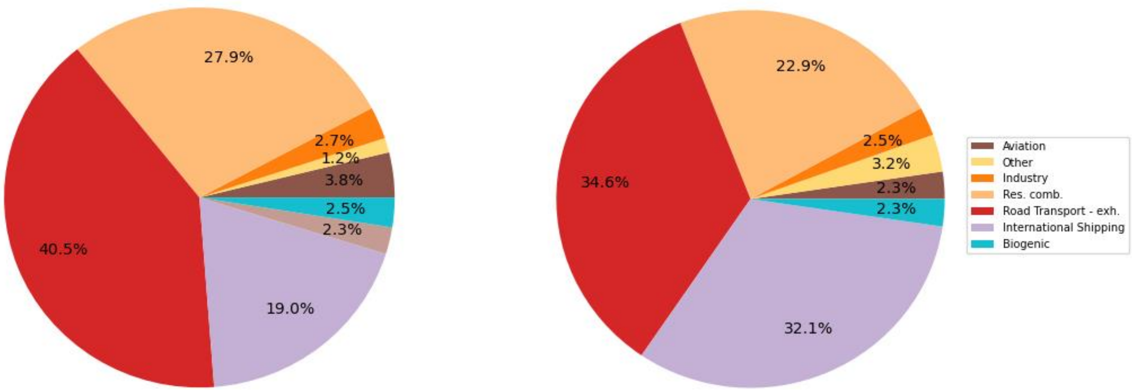

Total concentration of NO_2 in Marseille


Absolute contribution of Inland Shipping to NO_2 concentration in Marseille

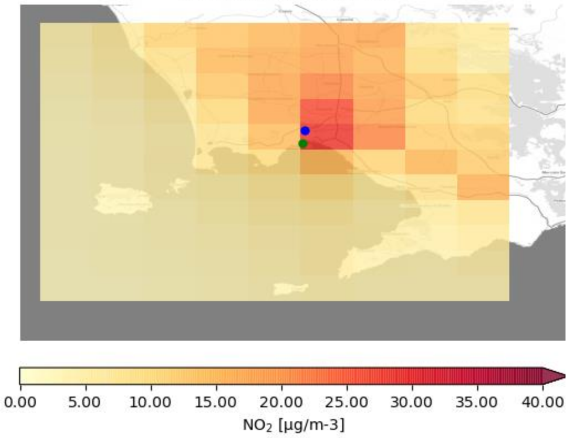
7.3.1.17. Naples

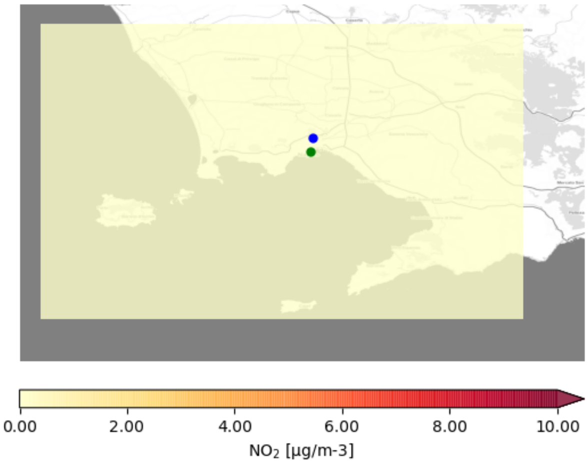

Absolute contribution of International Shipping to NO₂ concentration in Naples


Relative contribution of International Shipping to NO₂ concentration in Naples

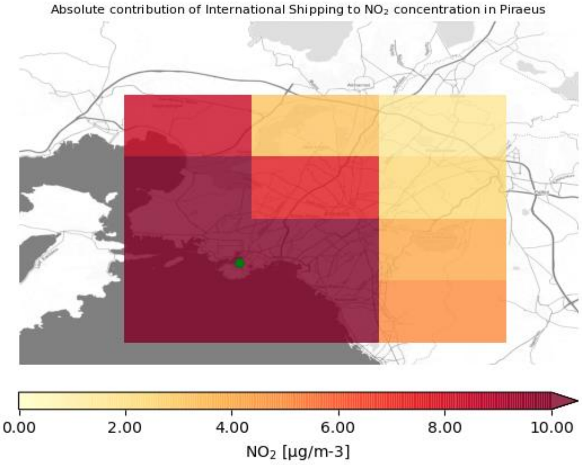

NO₂ in Naples city

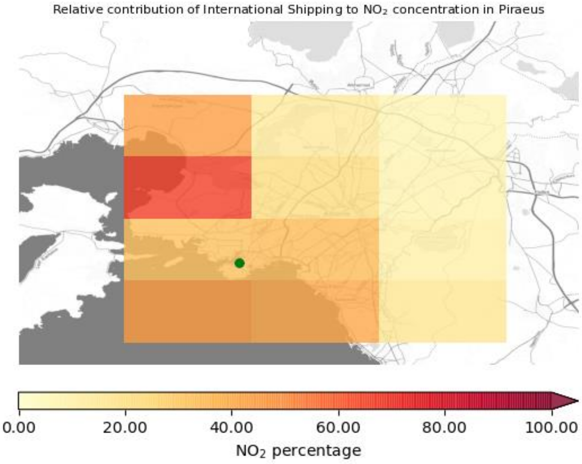
NO₂ in Naples port

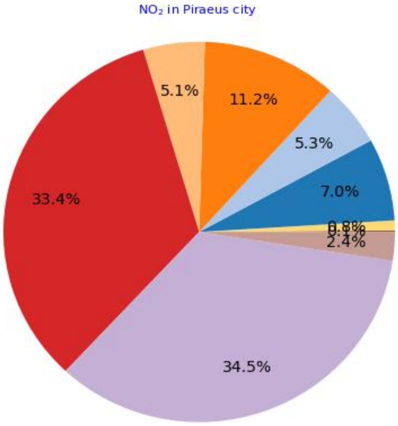

Total concentration of NO₂ in Naples

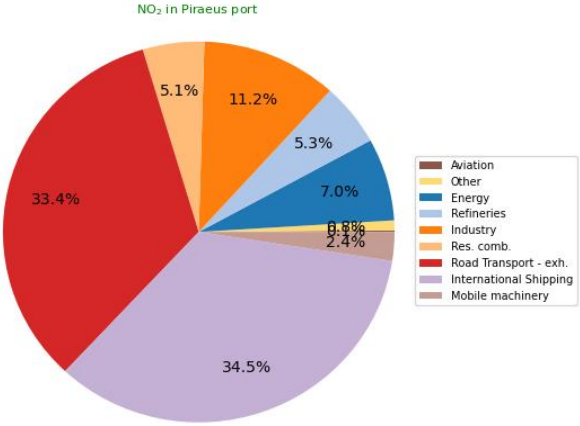

Absolute contribution of Inland Shipping to NO₂ concentration in Naples

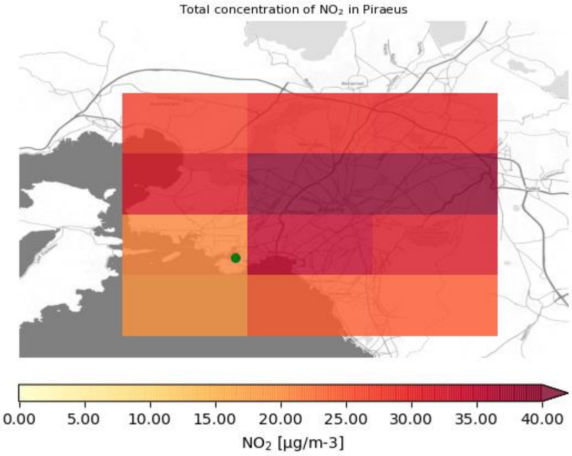
7.3.1.18. Piraeus

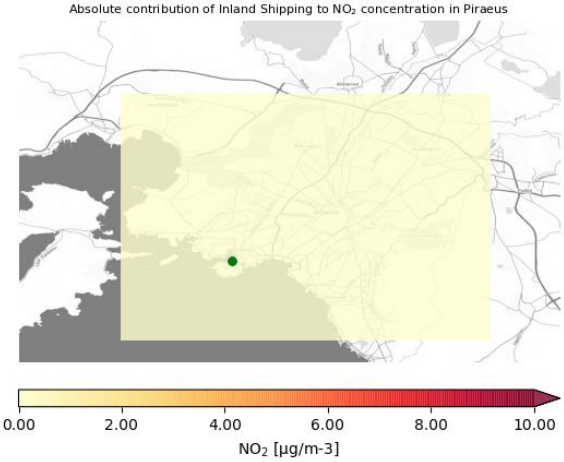

Absolute contribution of International Shipping to NO_2 concentration in Piraeus


Relative contribution of International Shipping to NO_2 concentration in Piraeus


NO_2 in Piraeus city

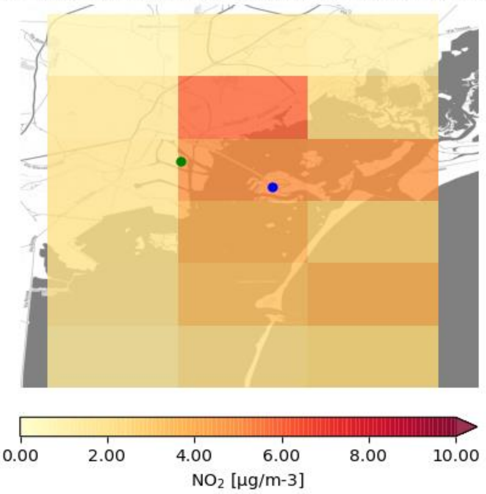

NO_2 in Piraeus port


Total concentration of NO_2 in Piraeus

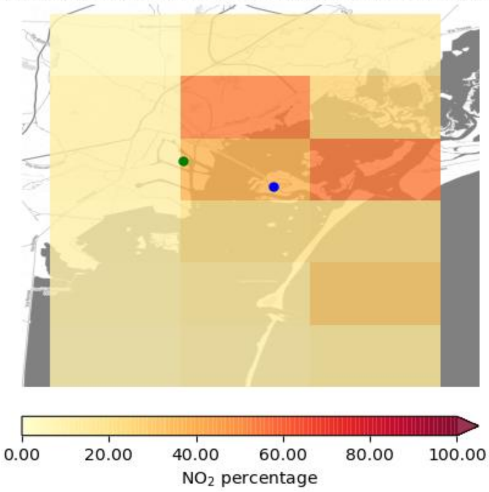

Absolute contribution of Inland Shipping to NO_2 concentration in Piraeus

7.3.1.19. Venice

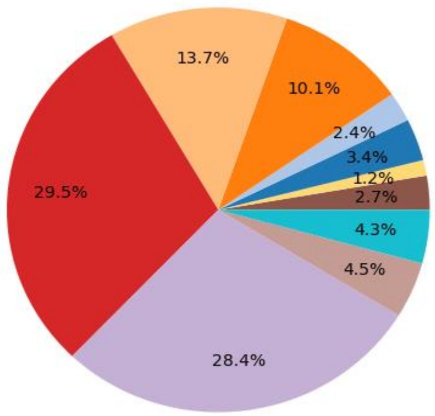
Absolute contribution of International Shipping to NO_2 concentration in Venice



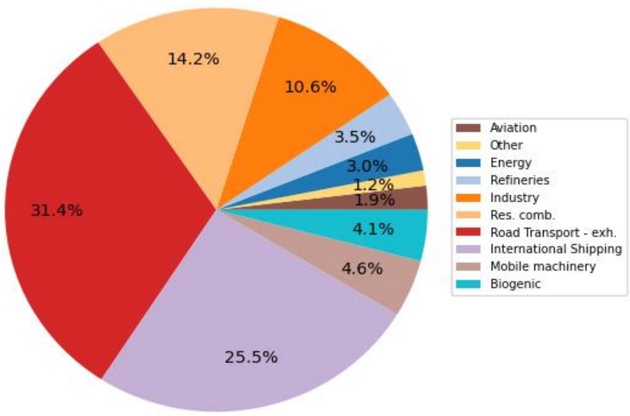
Relative contribution of International Shipping to NO_2 concentration in Venice



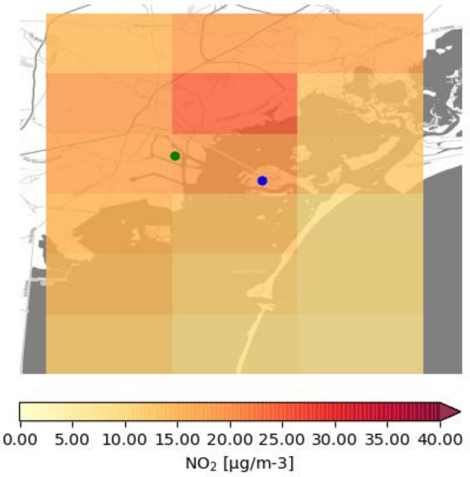
NO_2 in Venice city



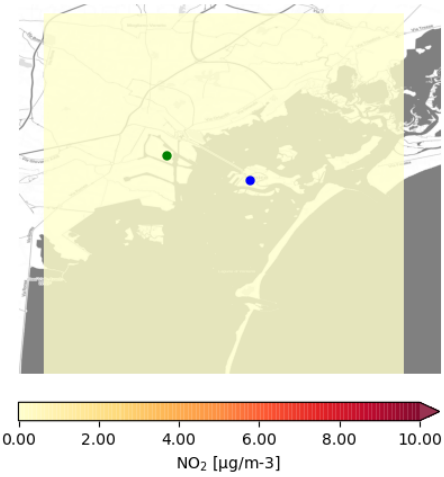
NO_2 in Venice port



Total concentration of NO_2 in Venice



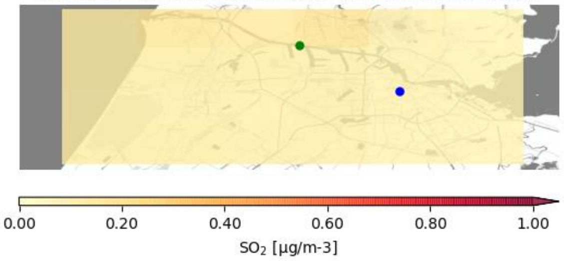
Absolute contribution of Inland Shipping to NO_2 concentration in Venice



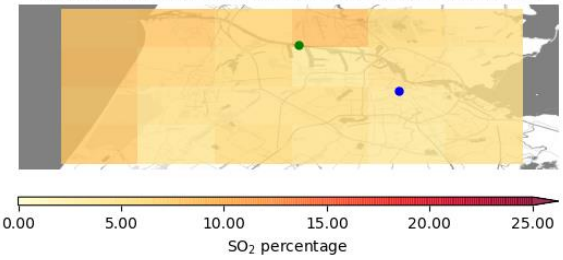
7.3.2. SO_2

7.3.2.1. Amsterdam

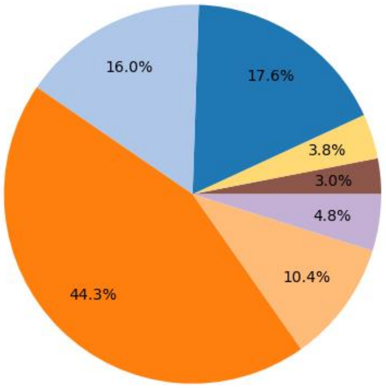
Absolute contribution of International Shipping to SO_2 concentration in Amsterdam



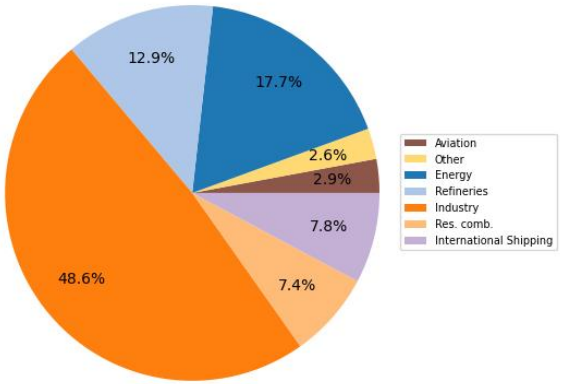
Relative contribution of International Shipping to SO_2 concentration in Amsterdam



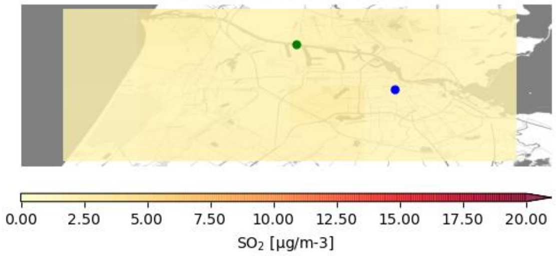
SO_2 in Amsterdam city



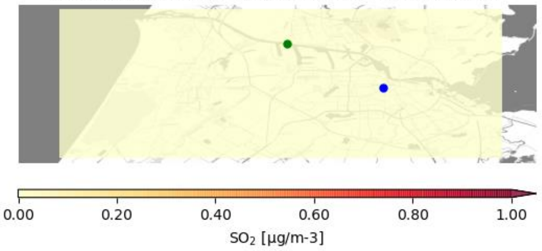
SO_2 in Amsterdam port



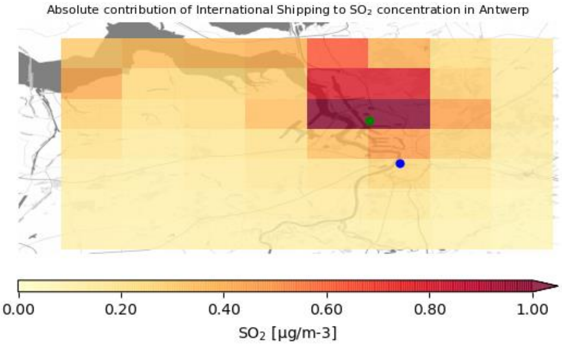
Total concentration of SO_2 in Amsterdam

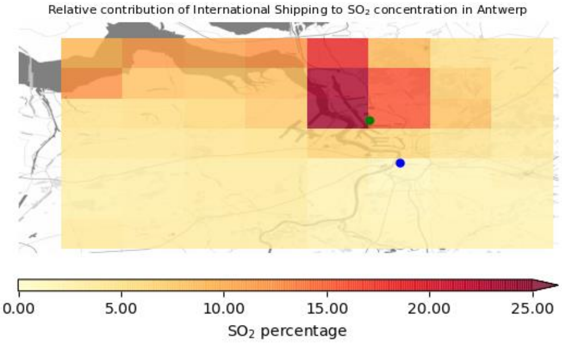


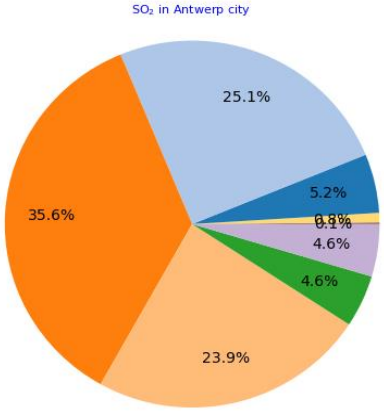
Absolute contribution of Inland Shipping to SO_2 concentration in Amsterdam

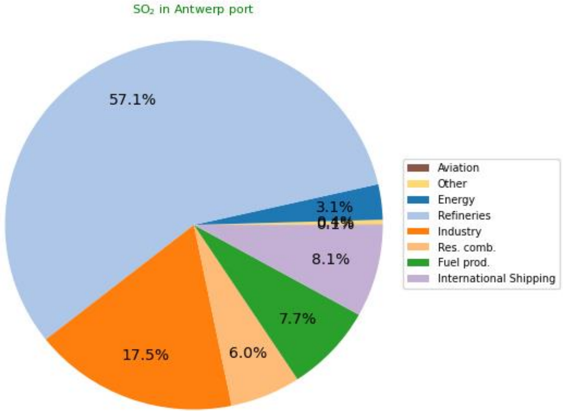


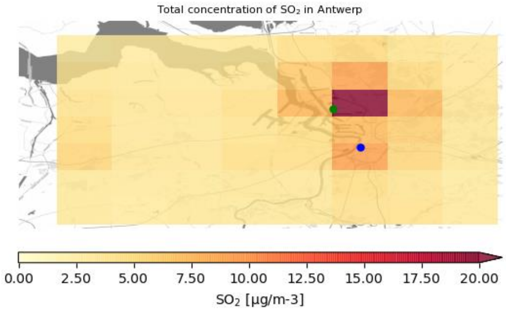
7.3.2.2. Antwerp

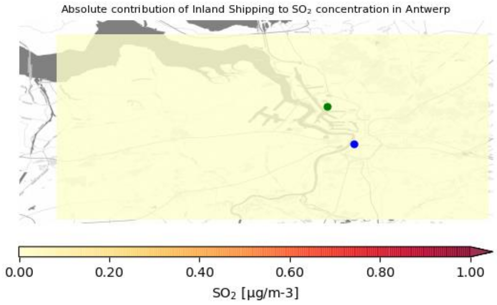

Absolute contribution of International Shipping to SO_2 concentration in Antwerp


Relative contribution of International Shipping to SO_2 concentration in Antwerp

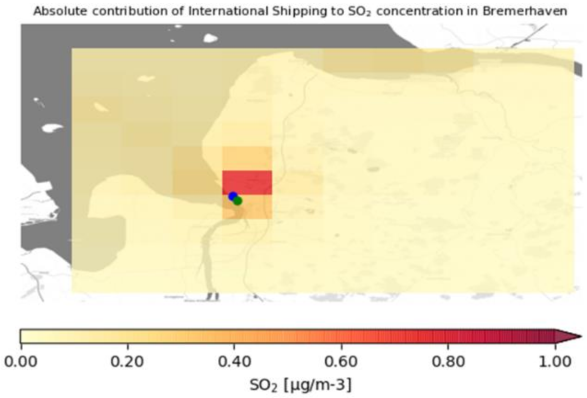

SO_2 in Antwerp city

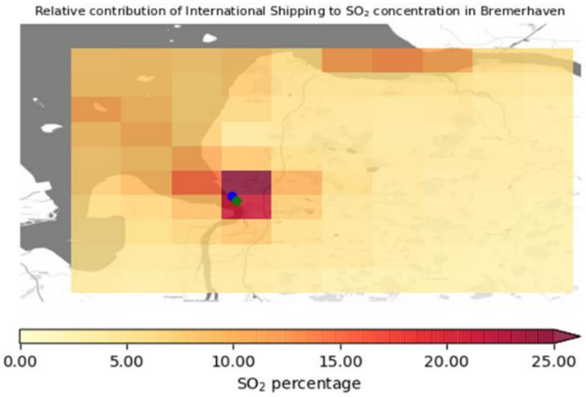

SO_2 in Antwerp port

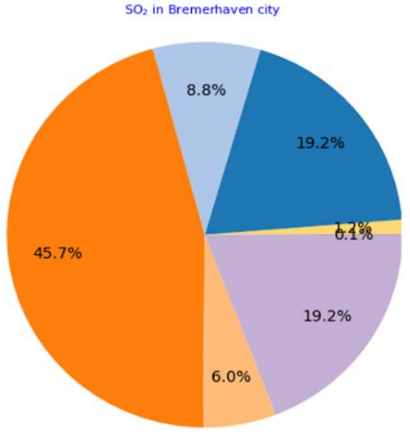

Total concentration of SO_2 in Antwerp

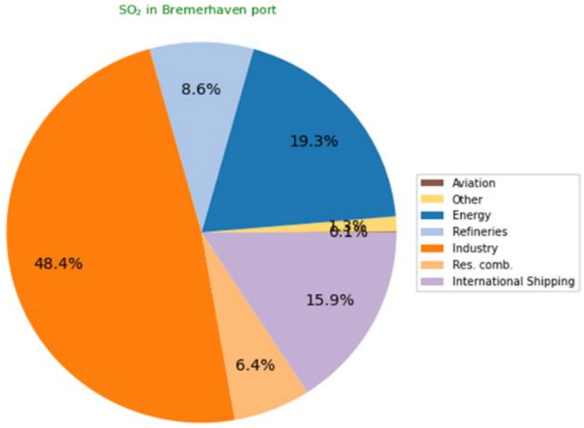

Absolute contribution of Inland Shipping to SO_2 concentration in Antwerp

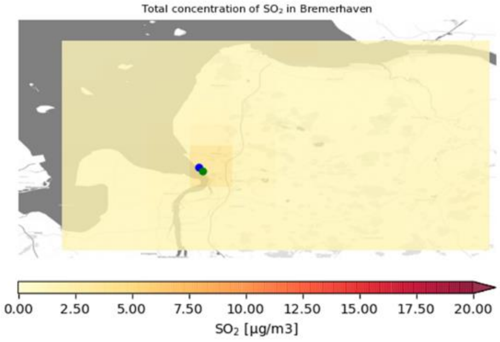
7.3.2.3. Bremerhaven

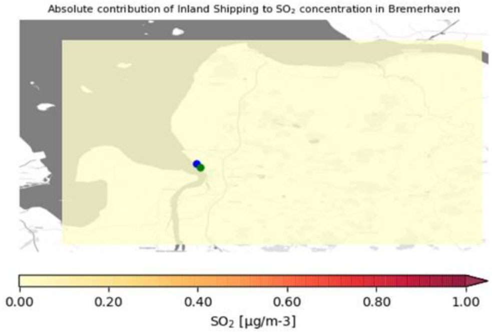

Absolute contribution of International Shipping to SO_2 concentration in Bremerhaven


Relative contribution of International Shipping to SO_2 concentration in Bremerhaven

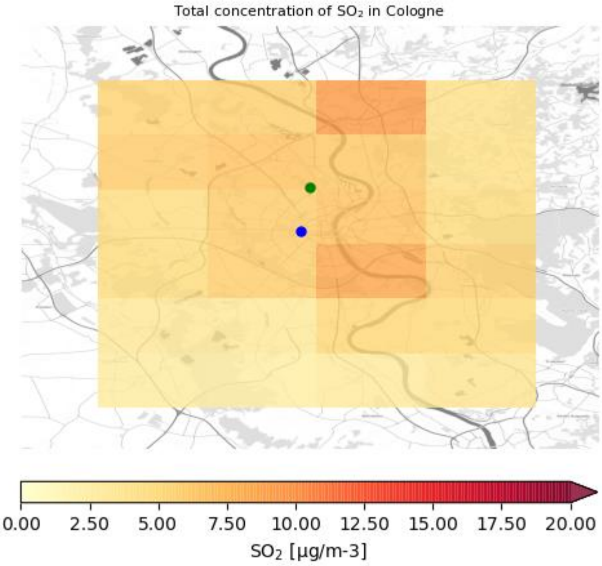

SO_2 in Bremerhaven city

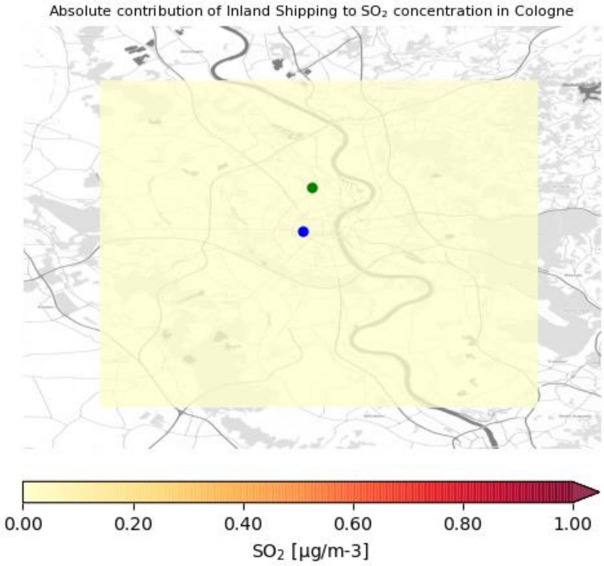

SO_2 in Bremerhaven port


Total concentration of SO_2 in Bremerhaven

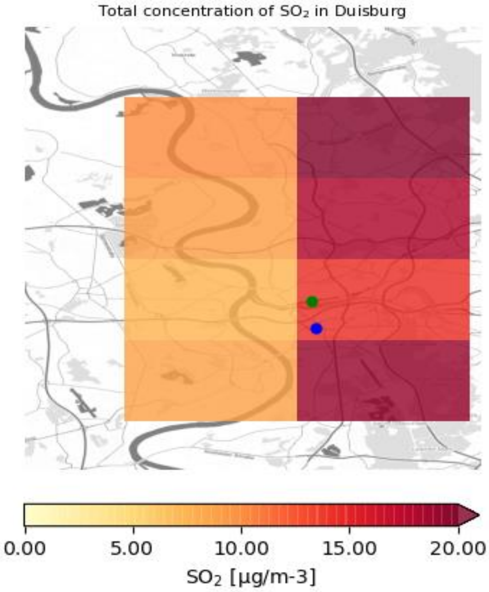

Absolute contribution of Inland Shipping to SO_2 concentration in Bremerhaven

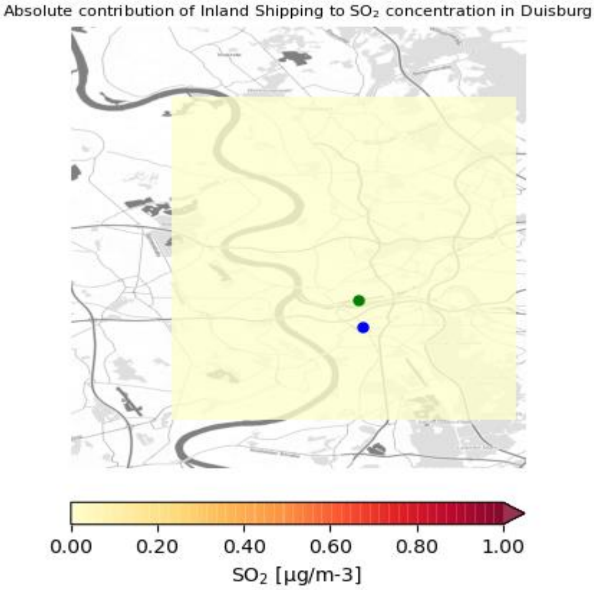
7.3.2.4. Cologne


Total concentration of SO_2 in Cologne


Absolute contribution of Inland Shipping to SO_2 concentration in Cologne

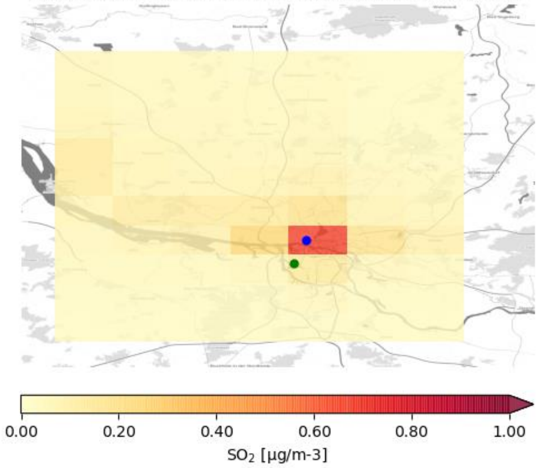
7.3.2.5. Duisburg


Total concentration of SO_2 in Duisburg

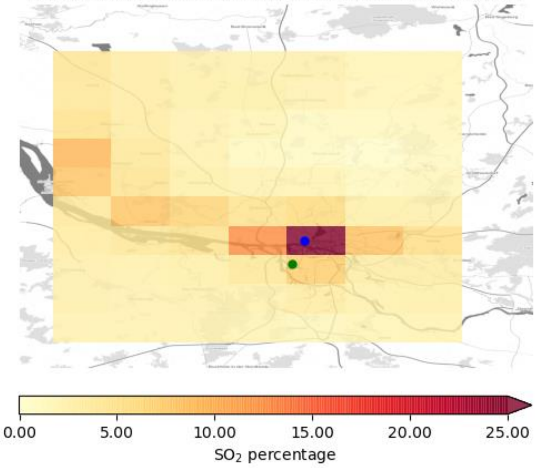

Absolute contribution of Inland Shipping to SO_2 concentration in Duisburg

7.3.2.6. Hamburg

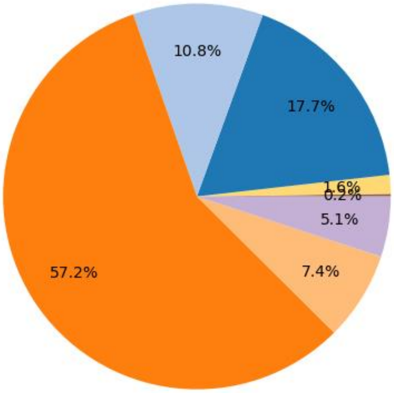
Absolute contribution of International Shipping to SO₂ concentration in Hamburg



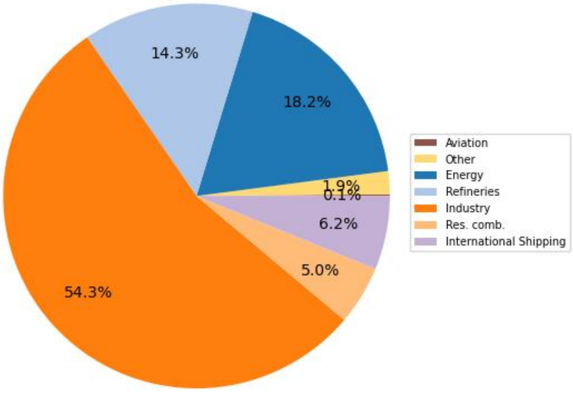
Relative contribution of International Shipping to SO₂ concentration in Hamburg



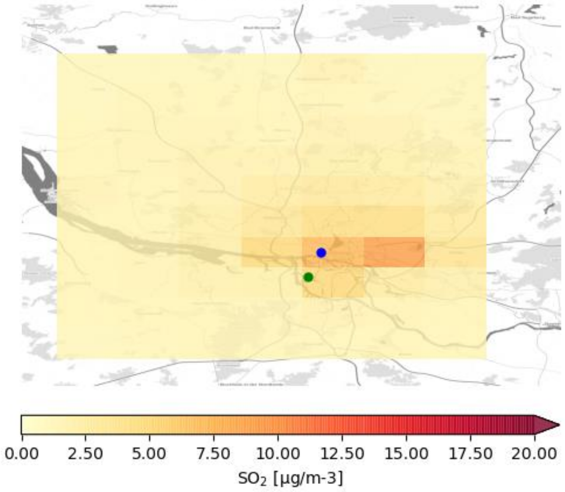
SO₂ in Hamburg city



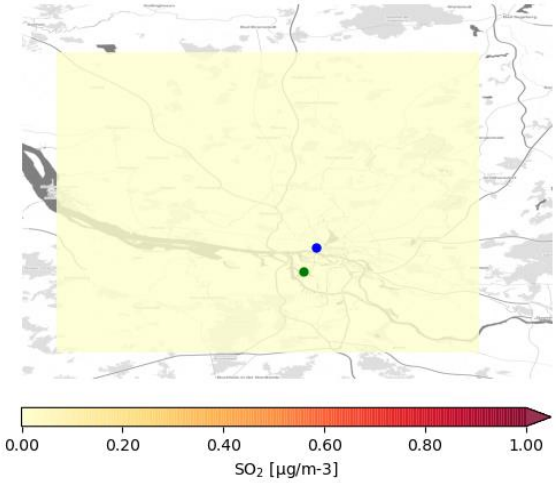
SO₂ in Hamburg port



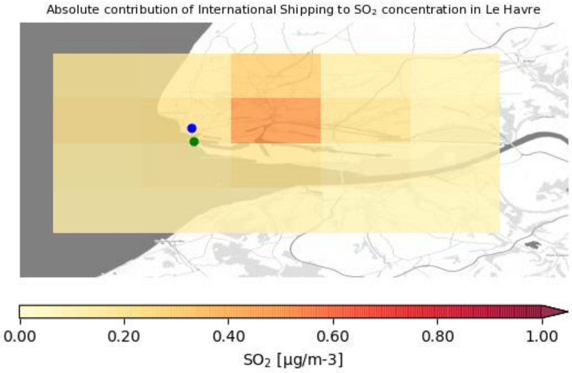
Total concentration of SO₂ in Hamburg

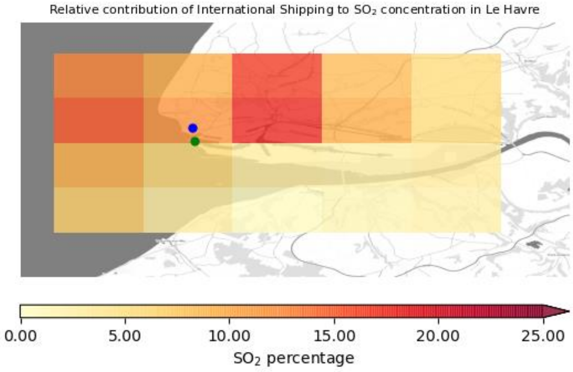


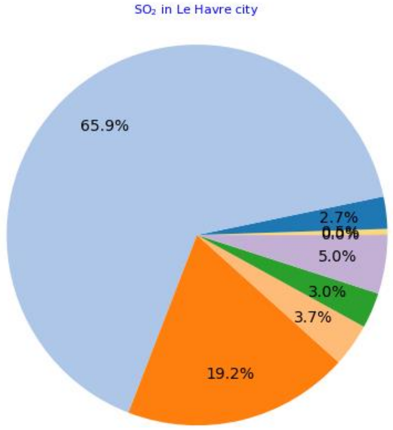
Absolute contribution of Inland Shipping to SO₂ concentration in Hamburg

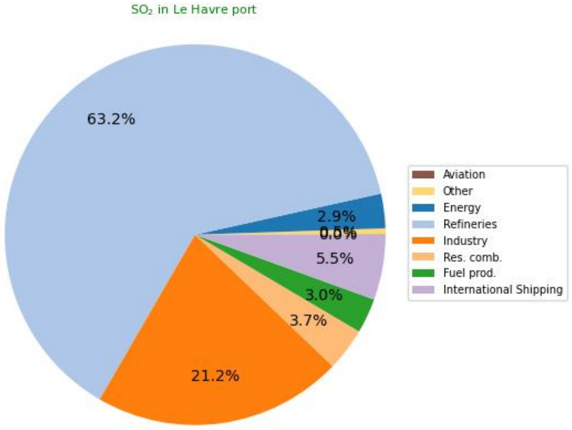


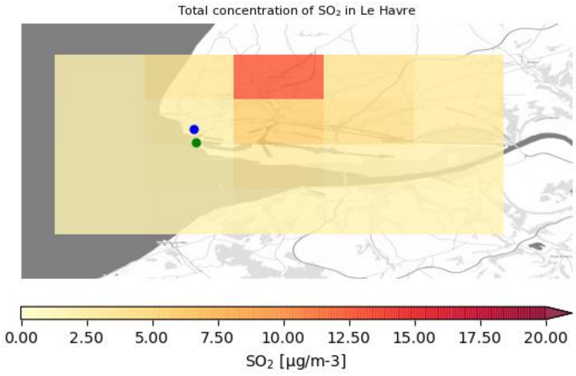
7.3.2.7. Le Havre

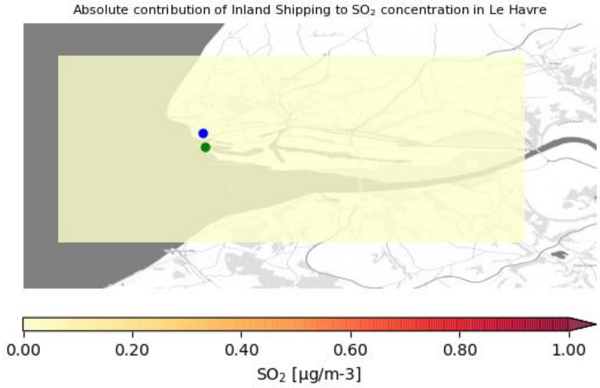

Absolute contribution of International Shipping to SO_2 concentration in Le Havre


Relative contribution of International Shipping to SO_2 concentration in Le Havre

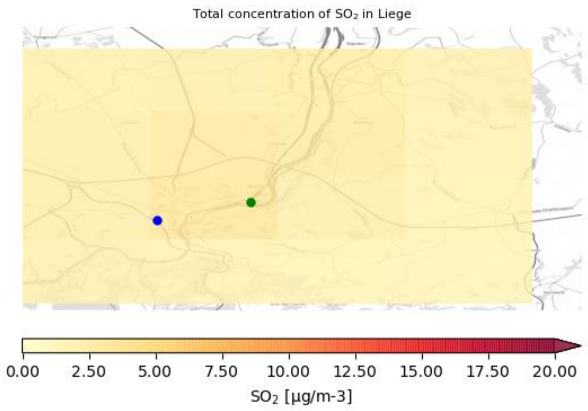

SO_2 in Le Havre city

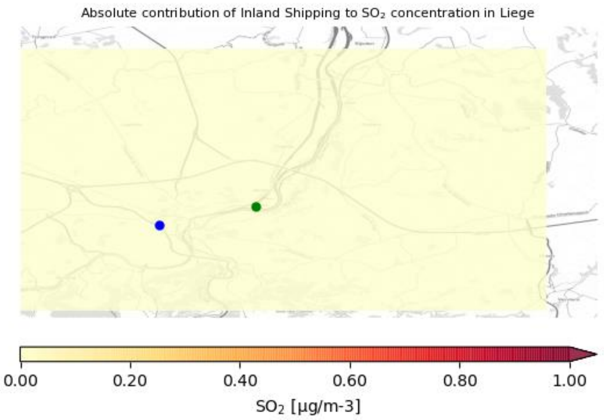

SO_2 in Le Havre port


Total concentration of SO_2 in Le Havre

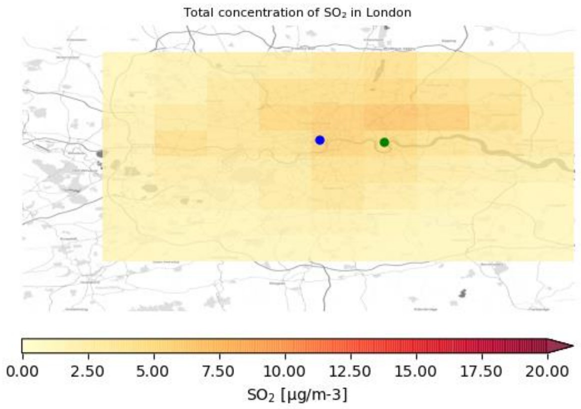

Absolute contribution of Inland Shipping to SO_2 concentration in Le Havre

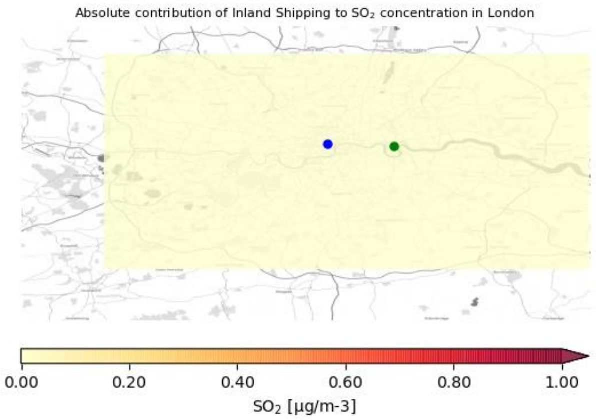
7.3.2.8. Liege



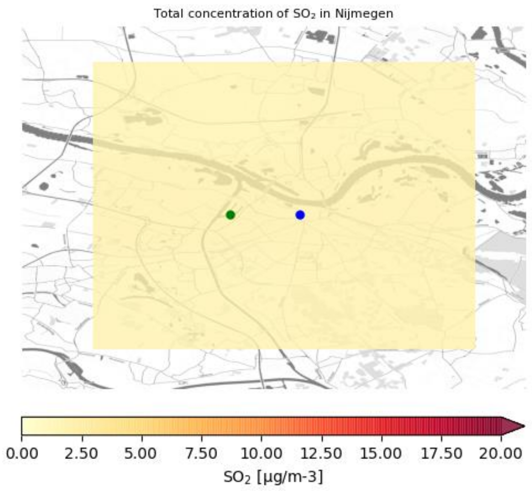


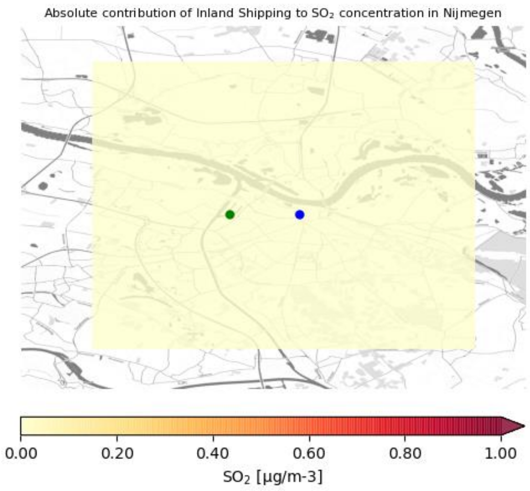
7.3.2.9. London



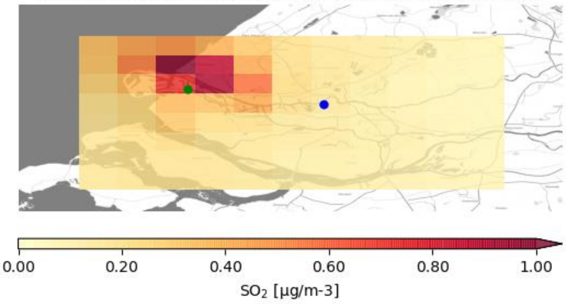


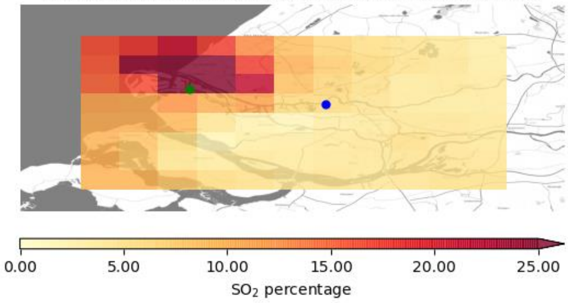
7.3.2.10. Nijmegen

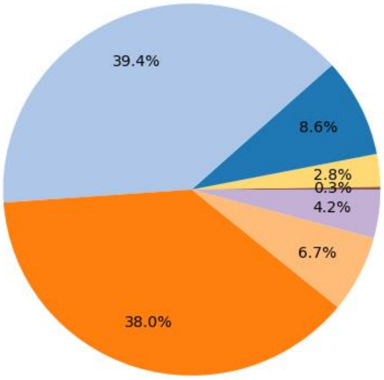


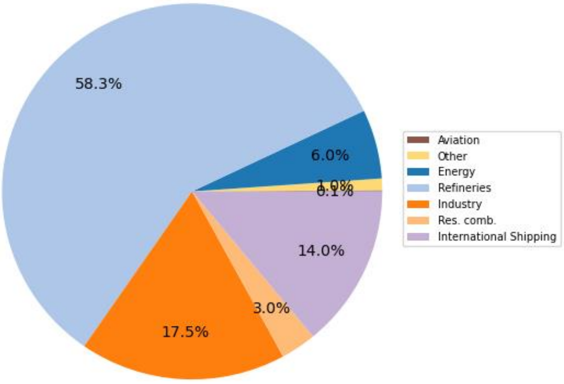


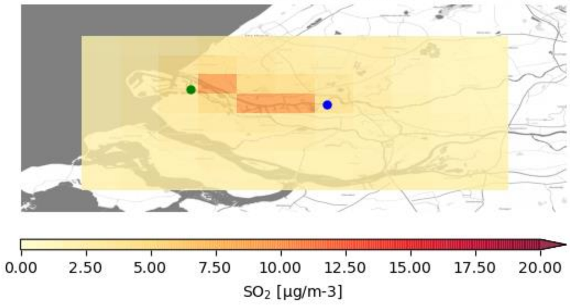
7.3.2.11. Rotterdam

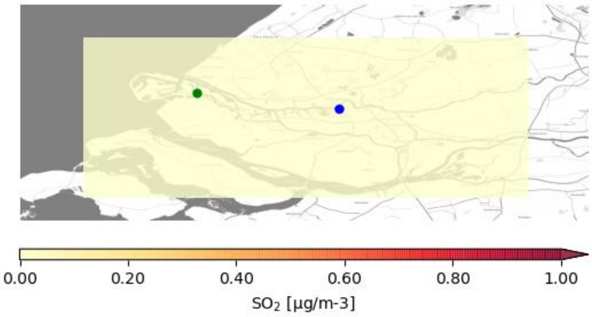

Absolute contribution of International Shipping to SO_2 concentration in Rotterdam


Relative contribution of International Shipping to SO_2 concentration in Rotterdam


SO_2 in Rotterdam city

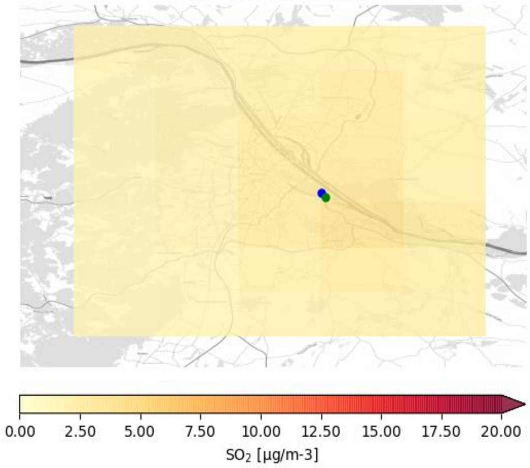

SO_2 in Rotterdam port


Total concentration of SO_2 in Rotterdam

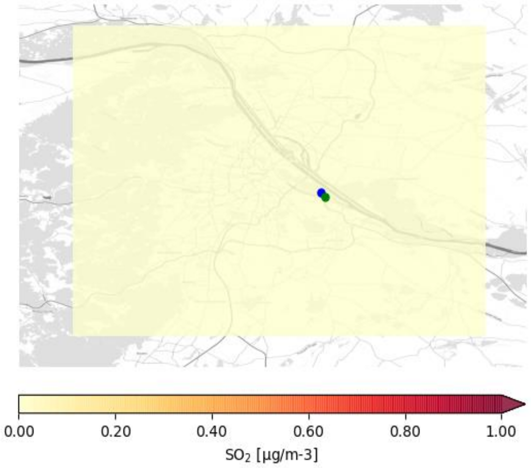

Absolute contribution of Inland Shipping to SO_2 concentration in Rotterdam

7.3.2.12. Vienna

Total concentration of SO_2 in Vienna

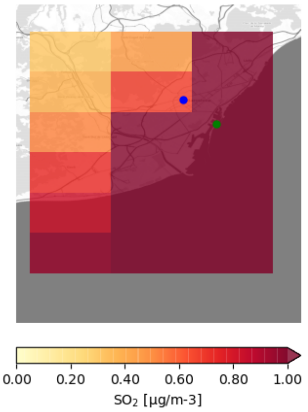


Absolute contribution of Inland Shipping to SO_2 concentration in Vienna

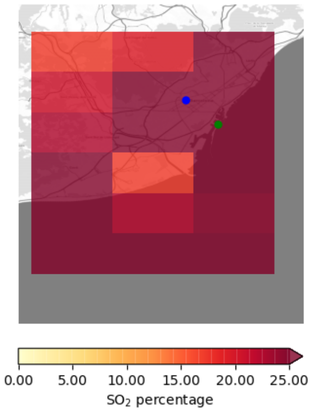


7.3.2.13. Barcelona

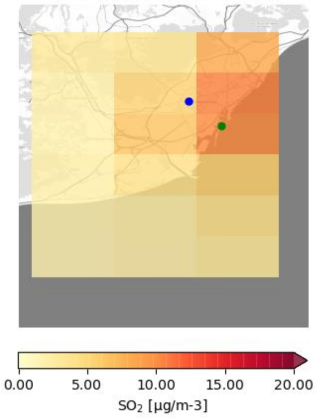
Absolute contribution of International Shipping to SO_2 concentration in Barcelona



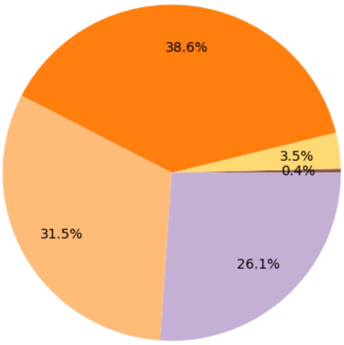
Relative contribution of International Shipping to SO_2 concentration in Barcelona



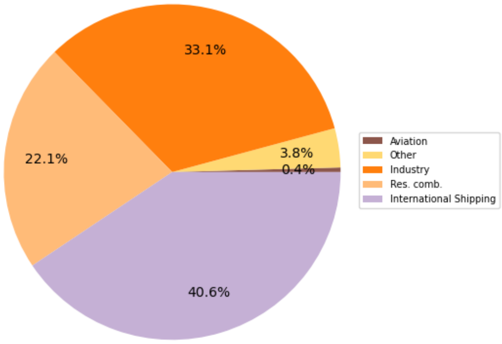
Total concentration of SO_2 in Barcelona



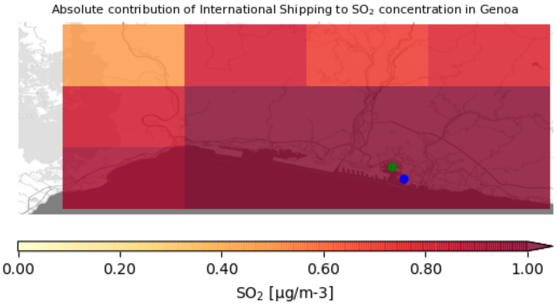
SO_2 in Barcelona city

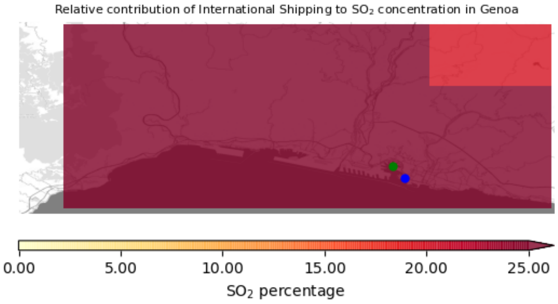


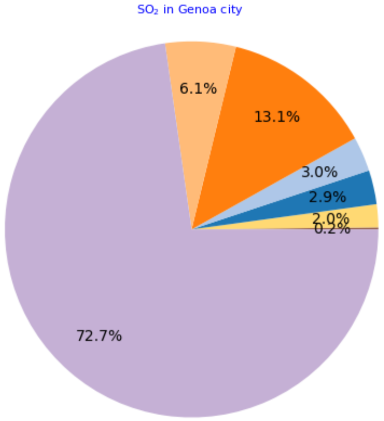
SO_2 in Barcelona port

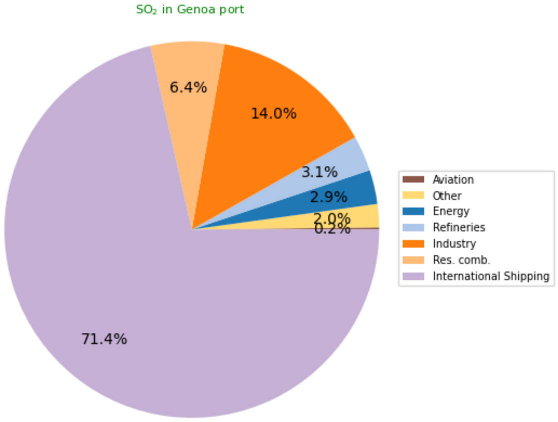


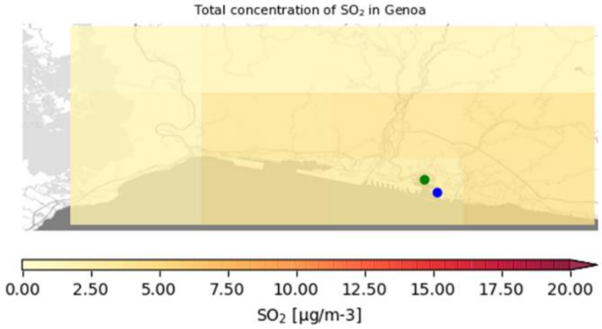
7.3.2.14. Genoa


Absolute contribution of International Shipping to SO_2 concentration in Genoa

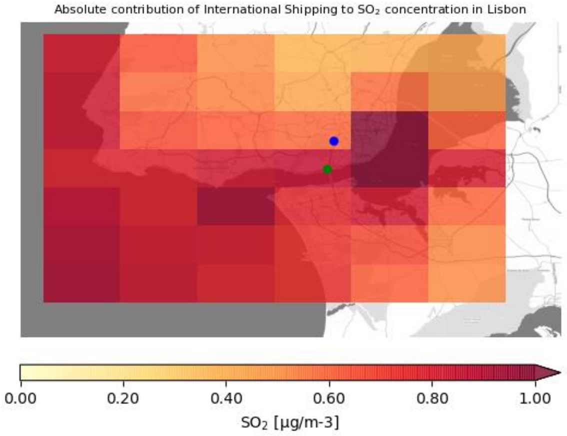

Relative contribution of International Shipping to SO_2 concentration in Genoa

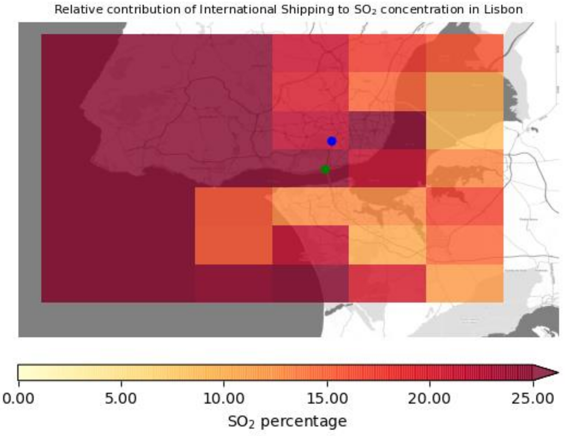

SO_2 in Genoa city

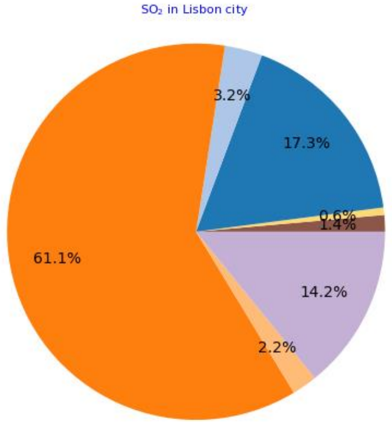

SO_2 in Genoa port

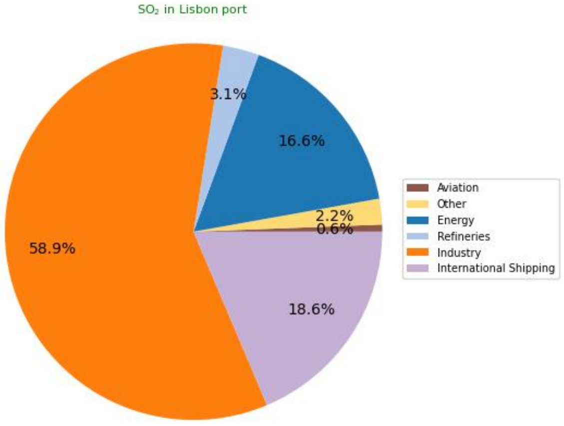

Total concentration of SO_2 in Genoa

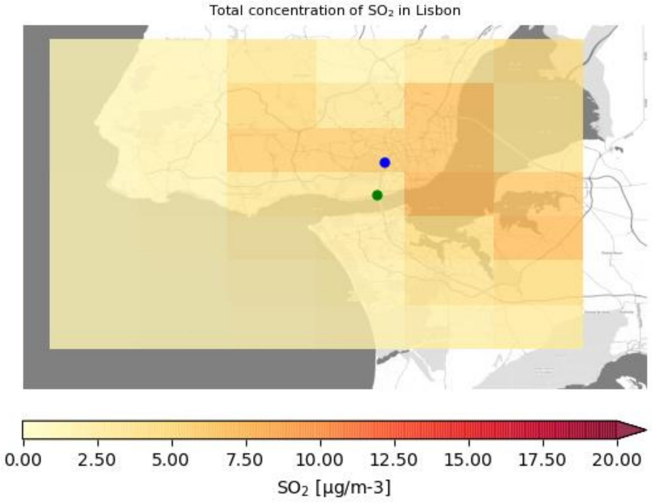
7.3.2.15. Lisbon


Absolute contribution of International Shipping to SO_2 concentration in Lisbon

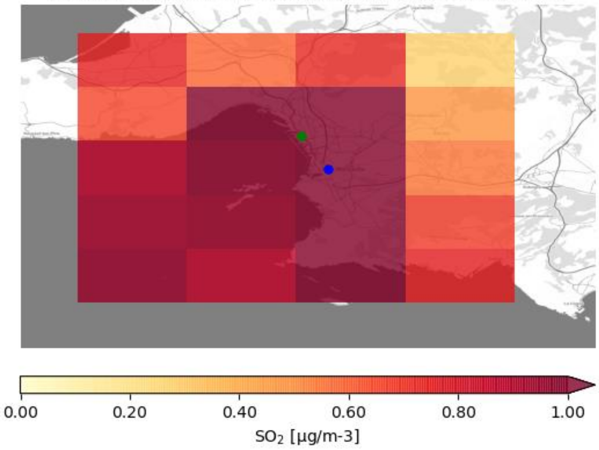

Relative contribution of International Shipping to SO_2 concentration in Lisbon

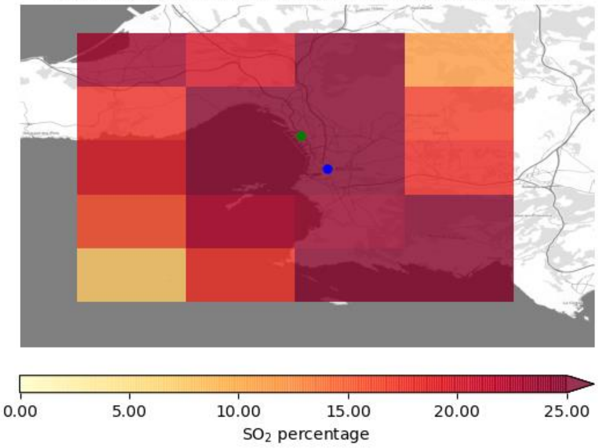

SO_2 in Lisbon city

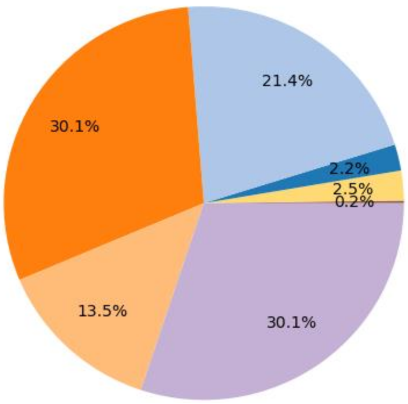

SO_2 in Lisbon port

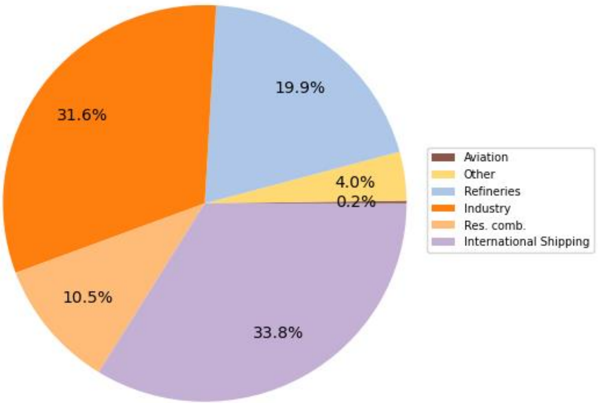

Total concentration of SO_2 in Lisbon

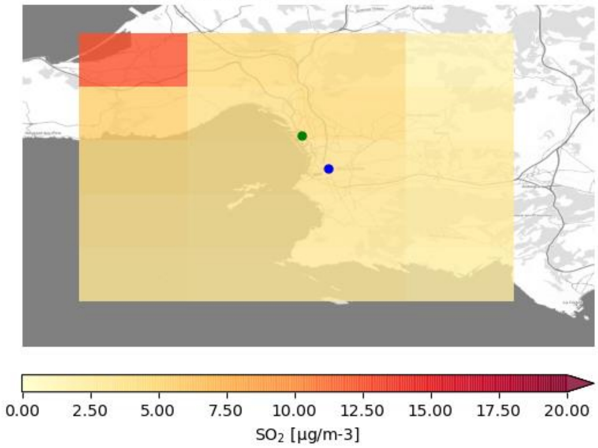
7.3.2.16. Marseille


Absolute contribution of International Shipping to SO_2 concentration in Marseille

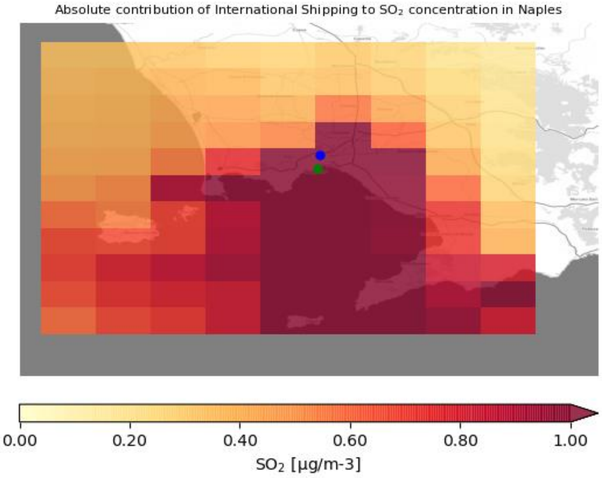

Relative contribution of International Shipping to SO_2 concentration in Marseille

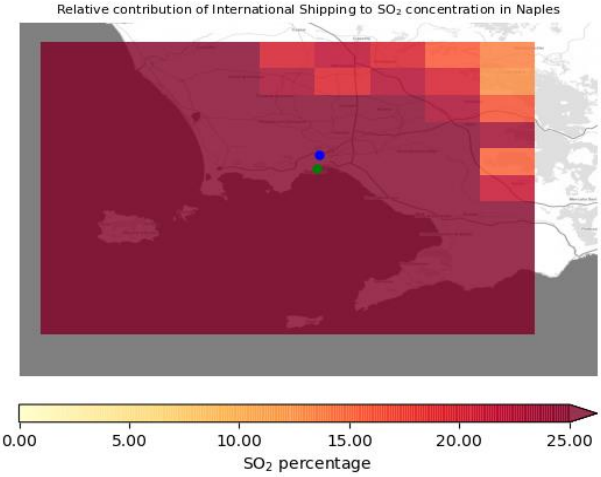

SO_2 in Marseille city

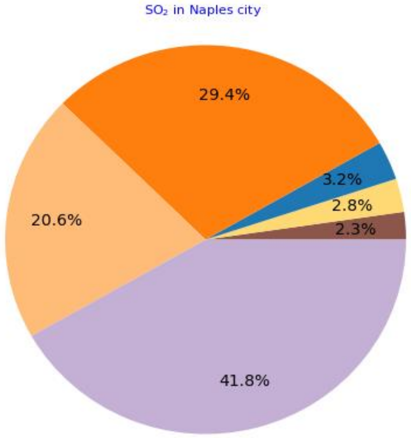

SO_2 in Marseille port

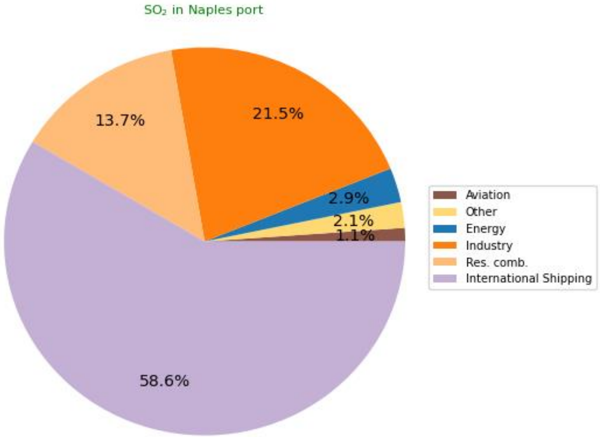

Total concentration of SO_2 in Marseille

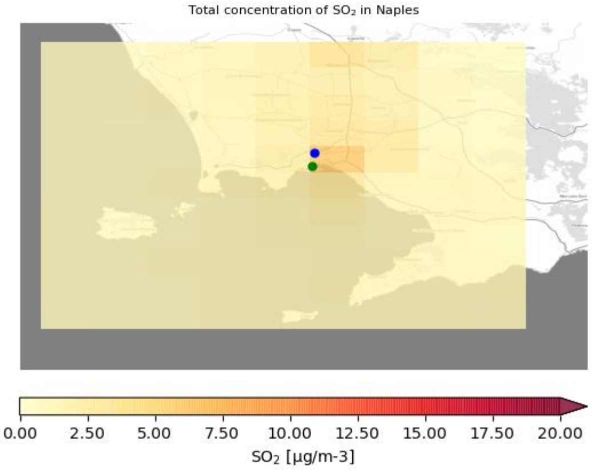
7.3.2.17. Naples


Absolute contribution of International Shipping to SO_2 concentration in Naples

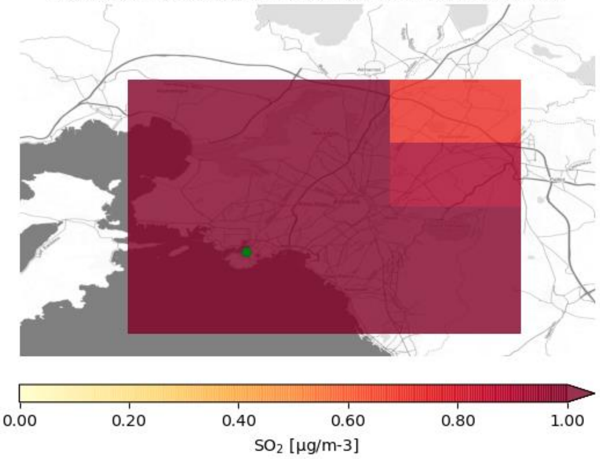

Relative contribution of International Shipping to SO_2 concentration in Naples


SO_2 in Naples city

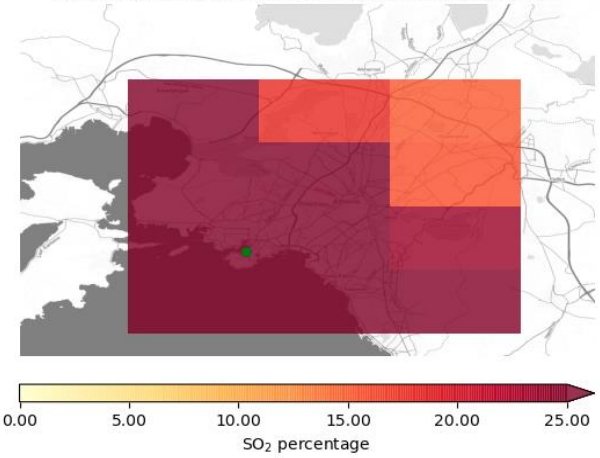

SO_2 in Naples port


Total concentration of SO_2 in Naples

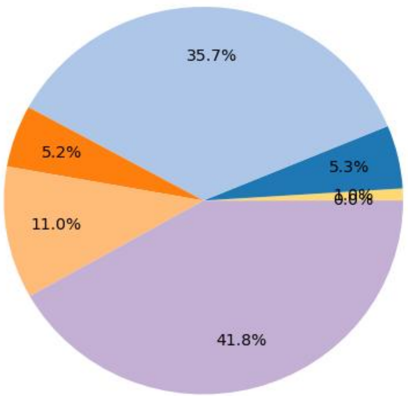
7.3.2.18. Piraeus



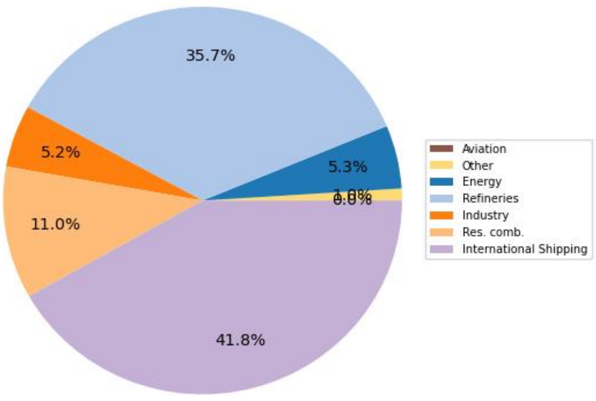
Absolute contribution of International Shipping to SO₂ concentration in Piraeus



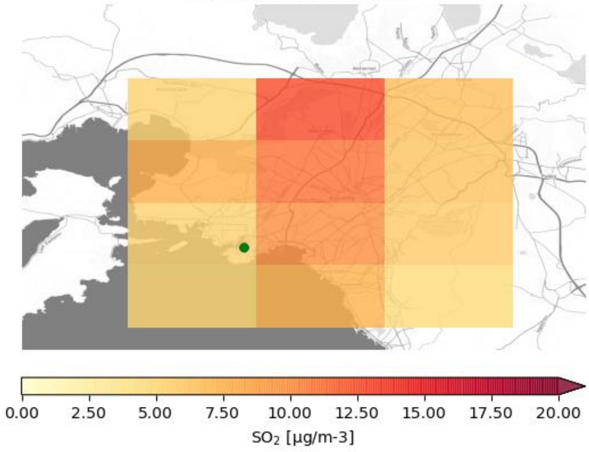
Relative contribution of International Shipping to SO₂ concentration in Piraeus



SO₂ in Piraeus city



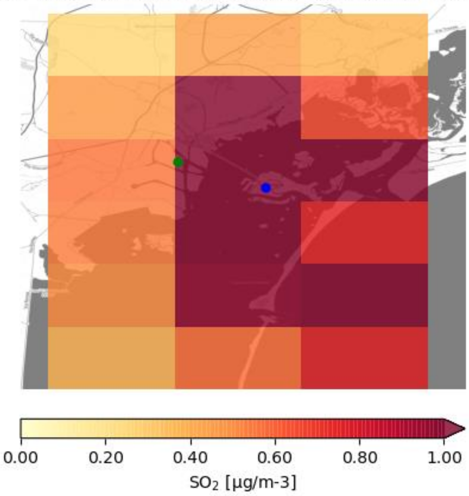
SO₂ in Piraeus port



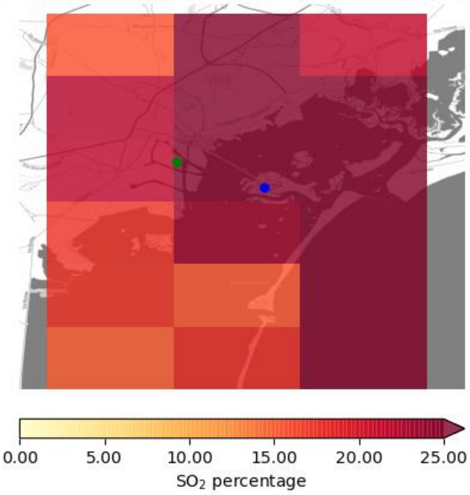
Total concentration of SO₂ in Piraeus

7.3.2.19. Venice

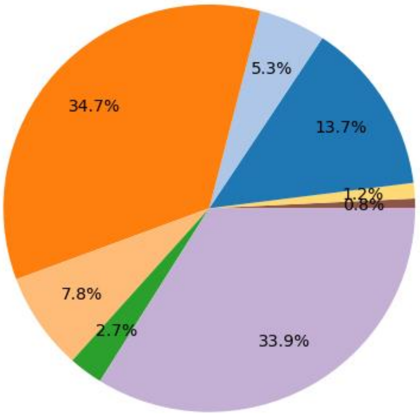
Absolute contribution of International Shipping to SO_2 concentration in Venice



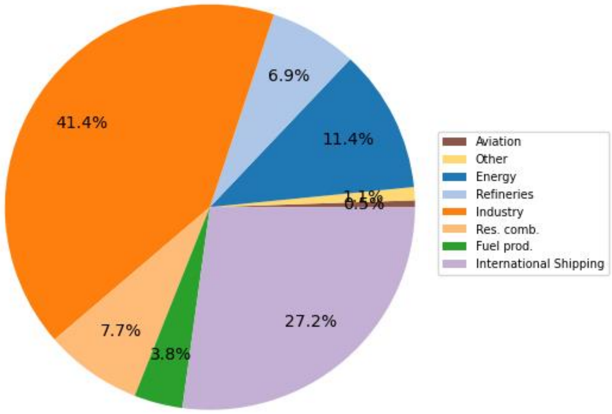
Relative contribution of International Shipping to SO_2 concentration in Venice



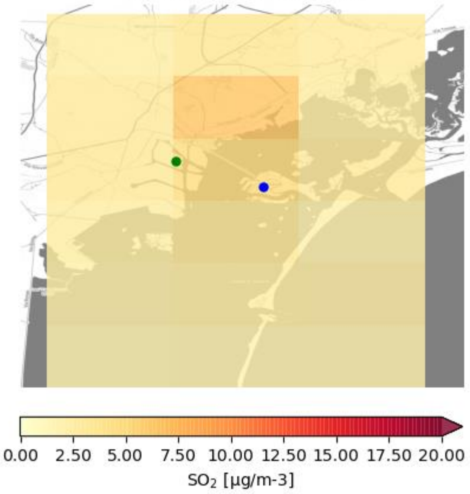
SO_2 in Venice city



SO_2 in Venice port



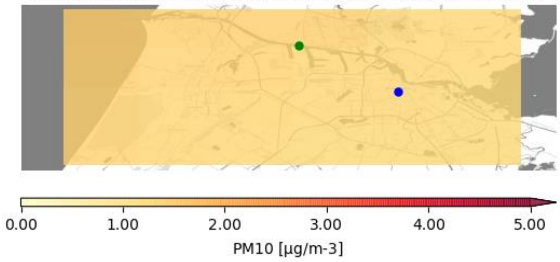
Total concentration of SO_2 in Venice



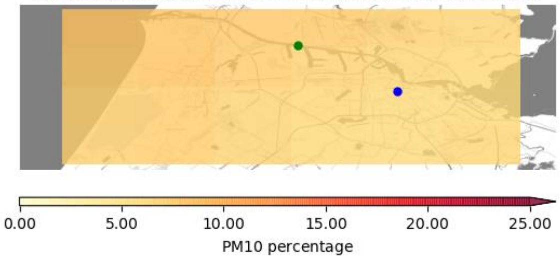
7.3.3. PM$_{10}$

7.3.3.1. Amsterdam

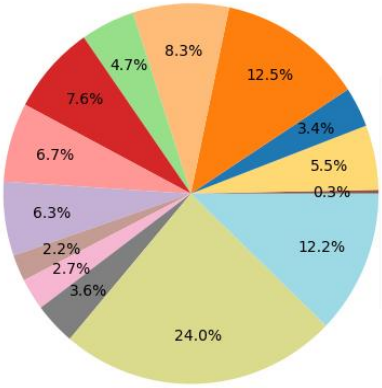
Absolute contribution of International Shipping to PM10 concentration in Amsterdam



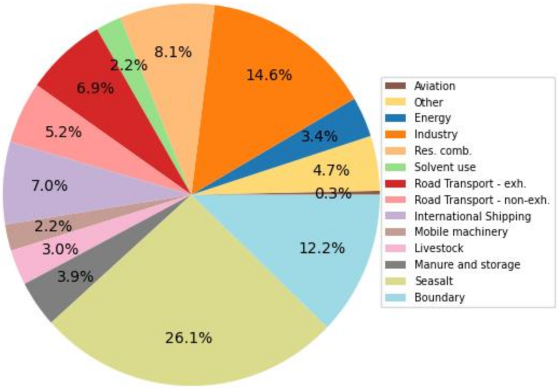
Relative contribution of International Shipping to PM10 concentration in Amsterdam



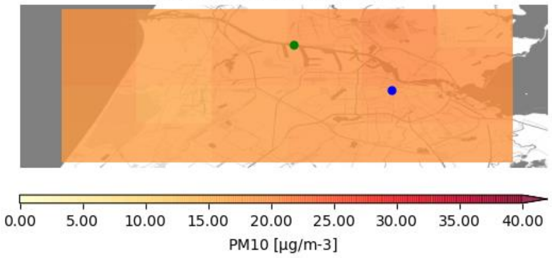
PM10 in Amsterdam city



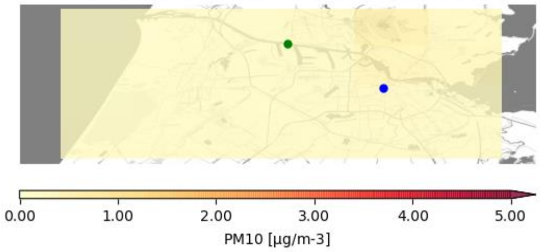
PM10 in Amsterdam port



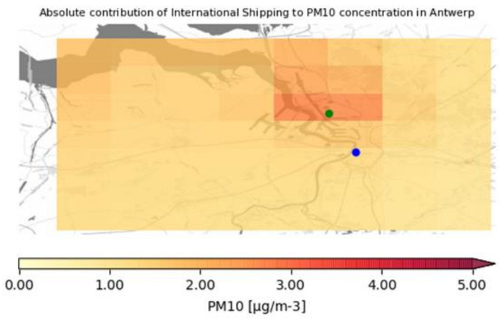
Total concentration of PM10 in Amsterdam

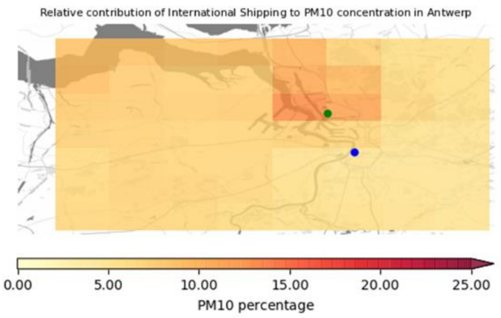


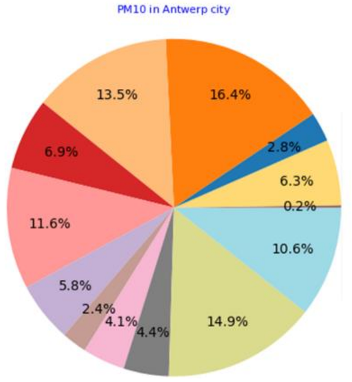
Absolute contribution of Inland Shipping to PM10 concentration in Amsterdam

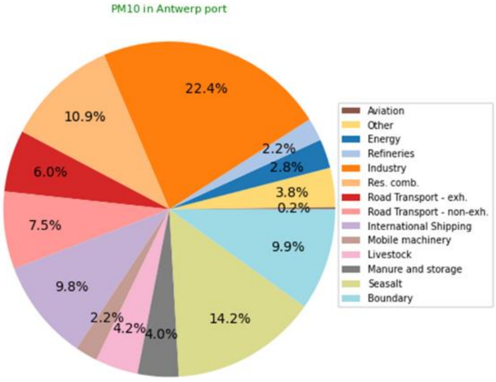


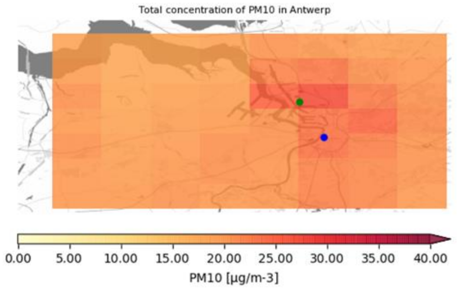
7.3.3.2. Antwerp

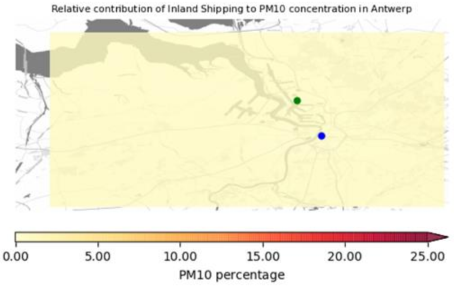

Absolute contribution of International Shipping to PM10 concentration in Antwerp


Relative contribution of International Shipping to PM10 concentration in Antwerp

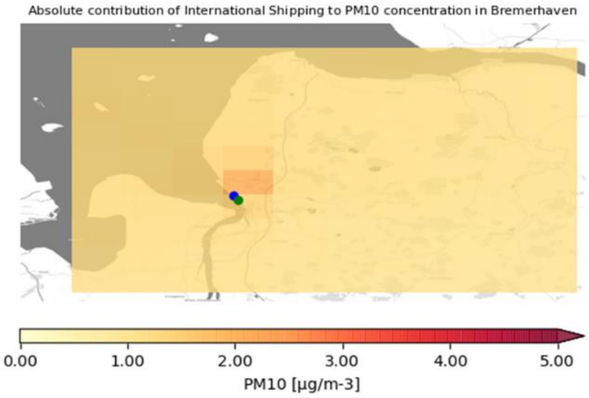

PM10 in Antwerp city

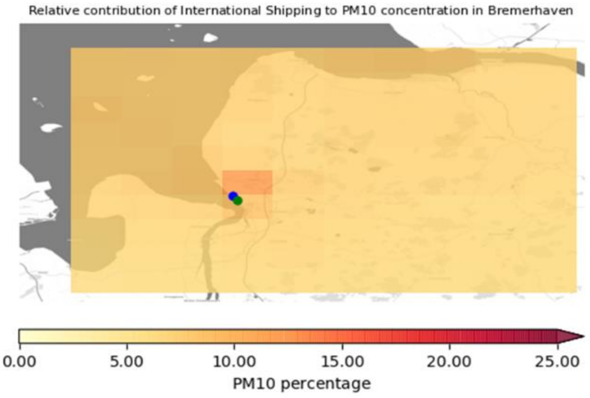

PM10 in Antwerp port

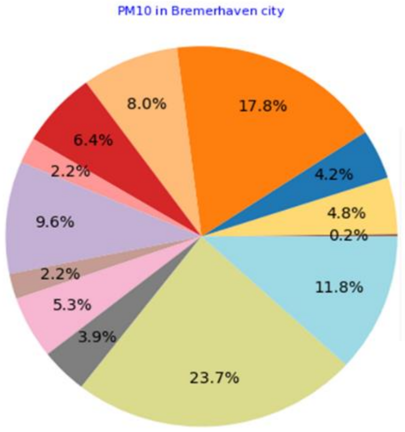

Total concentration of PM10 in Antwerp

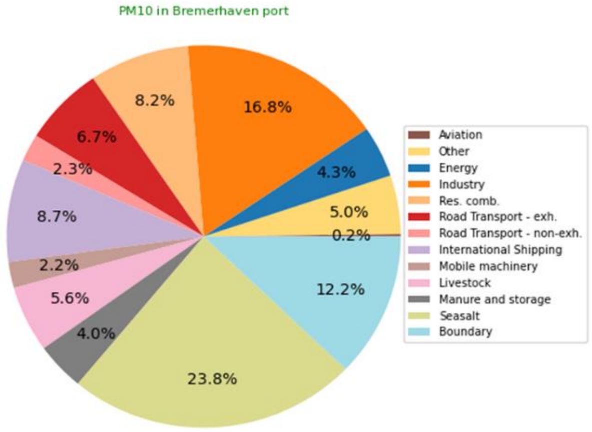

Relative contribution of Inland Shipping to PM10 concentration in Antwerp

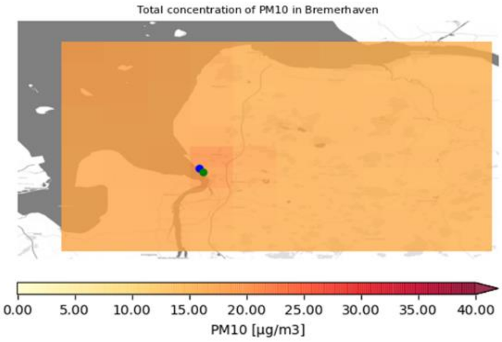
7.3.3.3. Bremerhaven

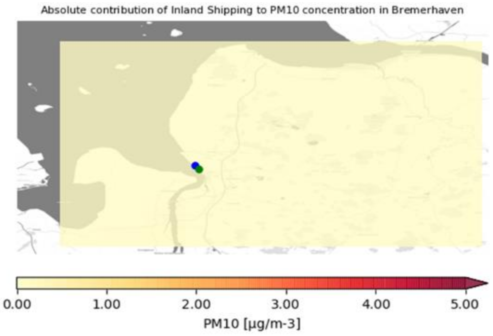

Absolute contribution of International Shipping to PM10 concentration in Bremerhaven


Relative contribution of International Shipping to PM10 concentration in Bremerhaven

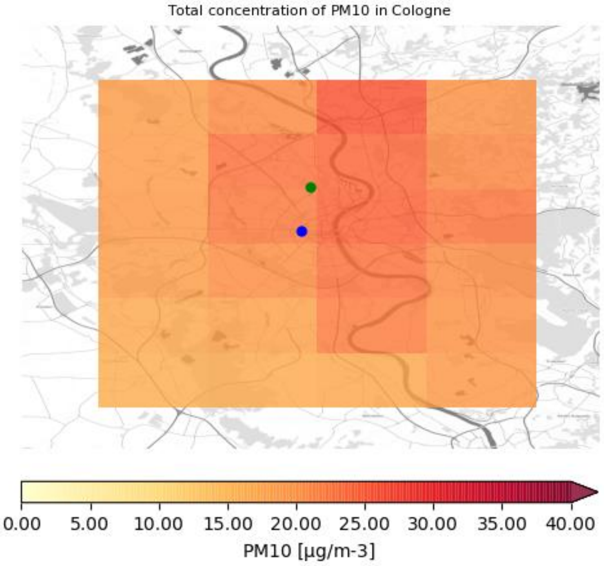

PM10 in Bremerhaven city

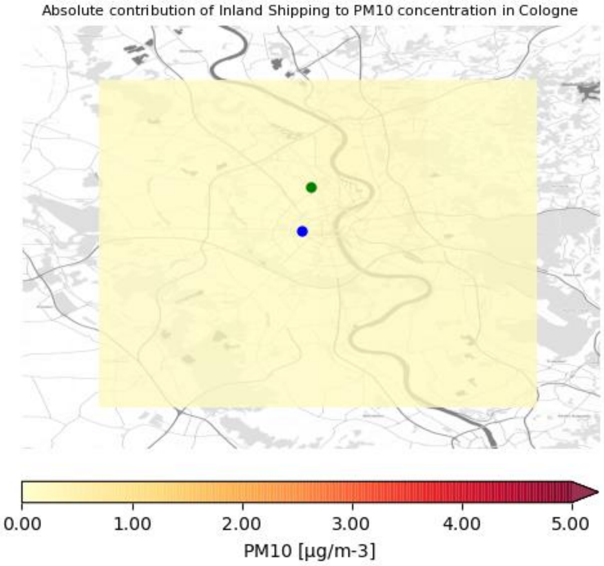

PM10 in Bremerhaven port


Total concentration of PM10 in Bremerhaven

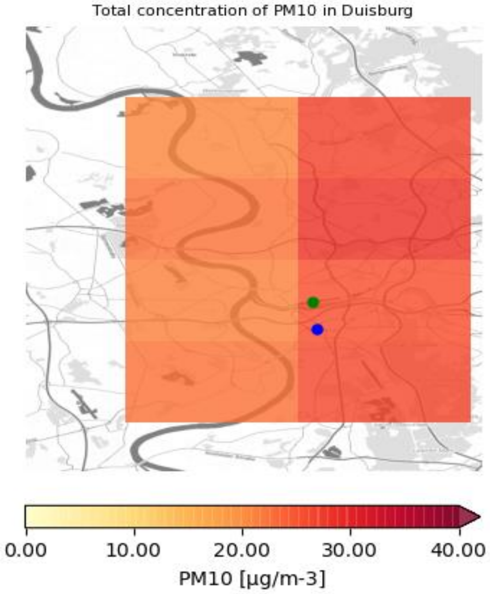

Absolute contribution of Inland Shipping to PM10 concentration in Bremerhaven

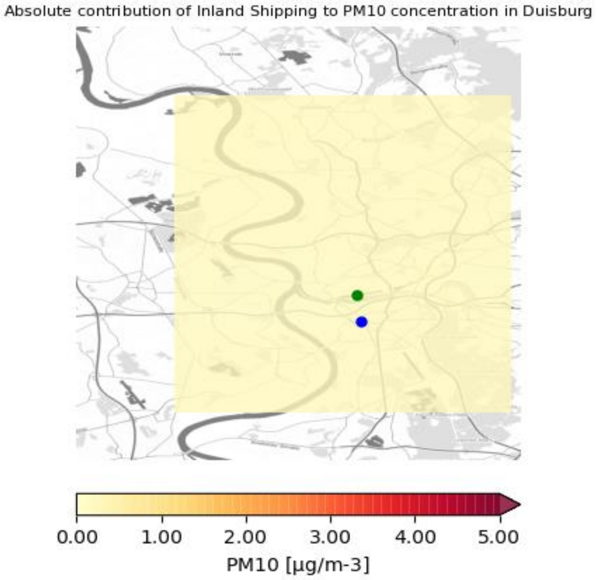
7.3.3.4. Cologne



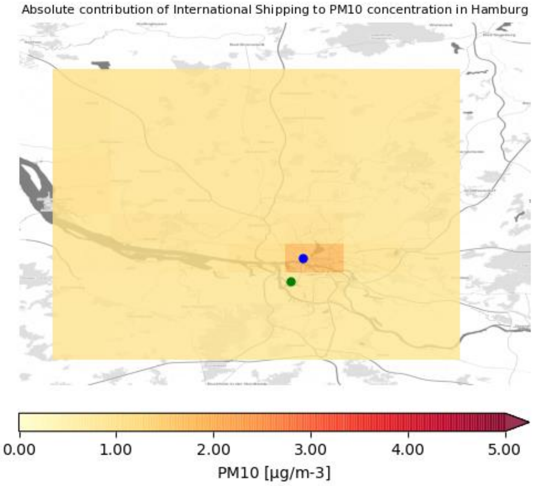


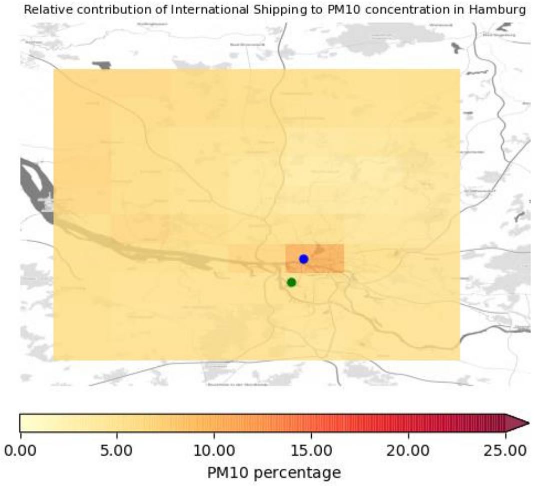
7.3.3.5. Duisburg

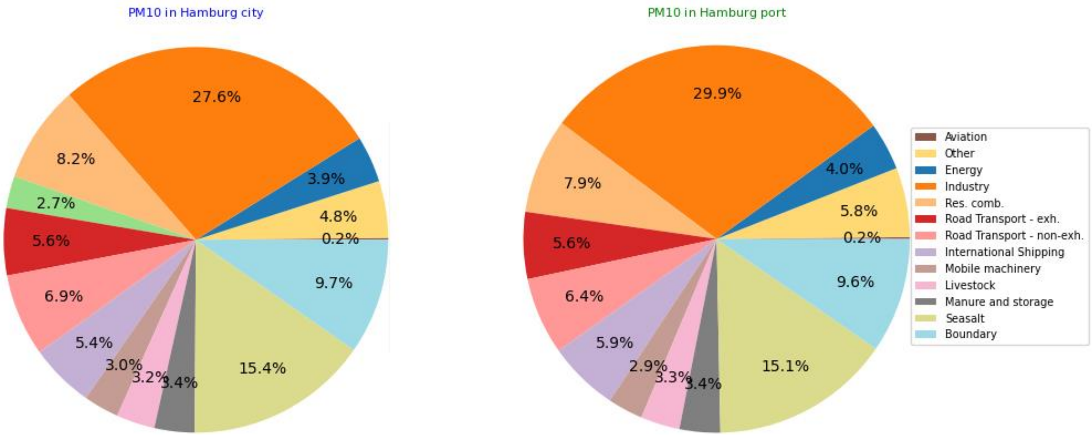




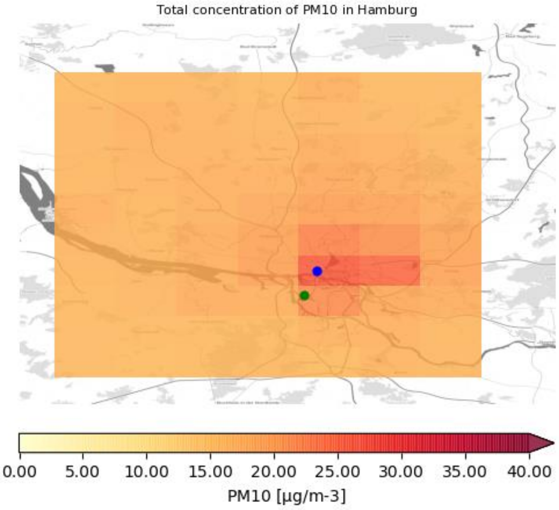
7.3.3.6. Hamburg

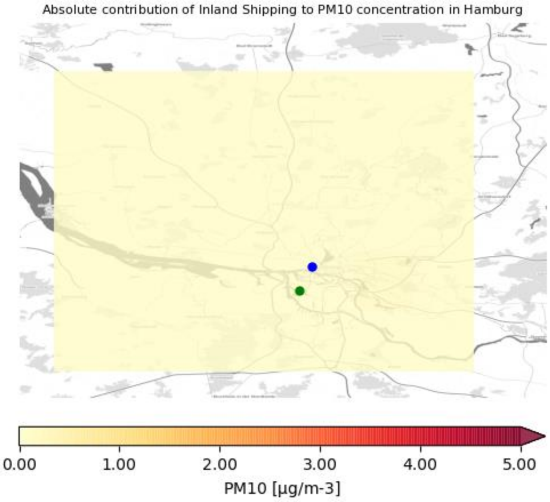

Absolute contribution of International Shipping to PM10 concentration in Hamburg


Relative contribution of International Shipping to PM10 concentration in Hamburg

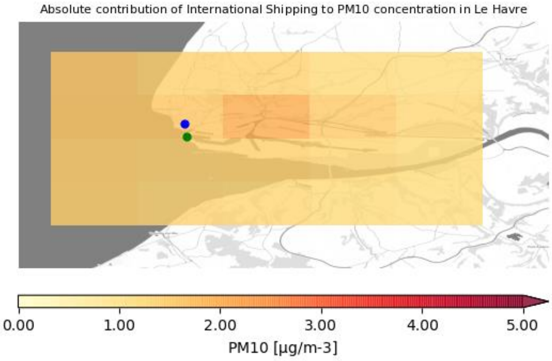

PM10 in Hamburg city

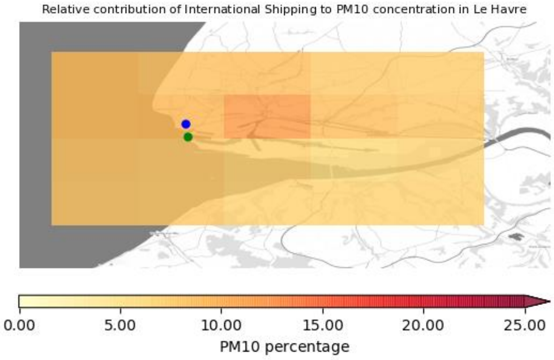
PM10 in Hamburg port

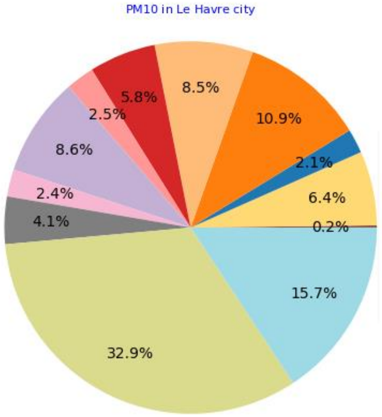

Total concentration of PM10 in Hamburg

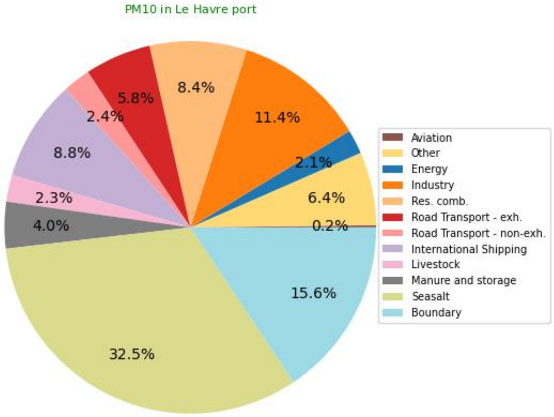

Absolute contribution of Inland Shipping to PM10 concentration in Hamburg

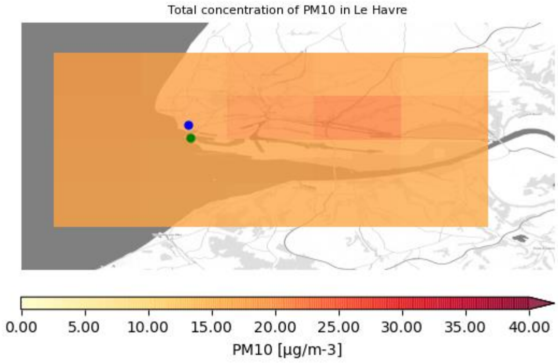
7.3.3.7. Le Havre

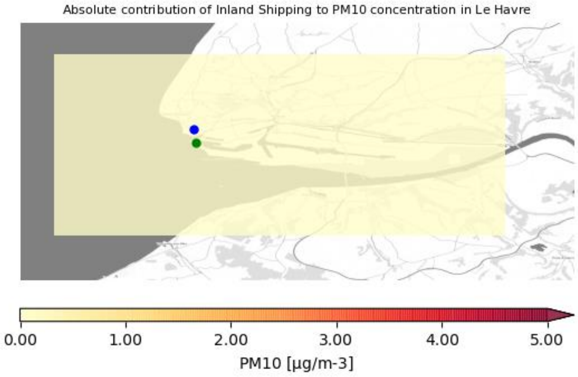

Absolute contribution of International Shipping to PM10 concentration in Le Havre


Relative contribution of International Shipping to PM10 concentration in Le Havre

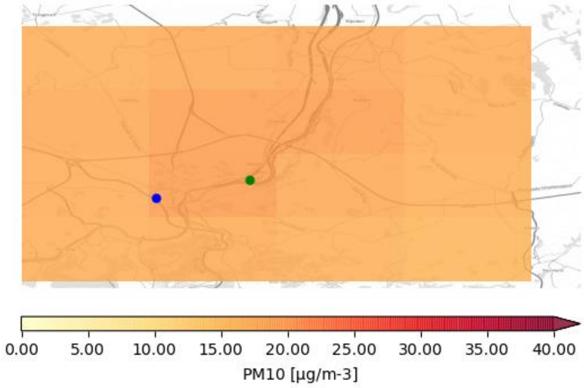

PM10 in Le Havre city

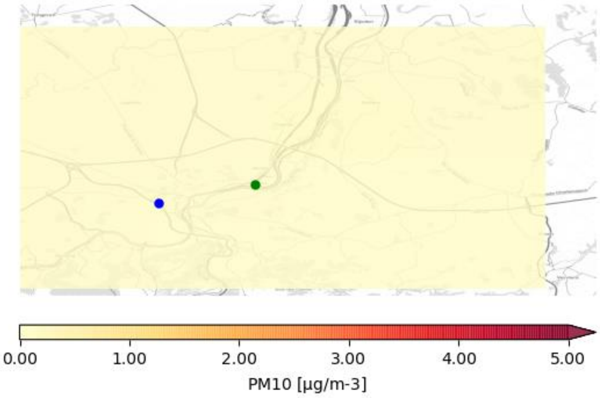

PM10 in Le Havre port


Total concentration of PM10 in Le Havre

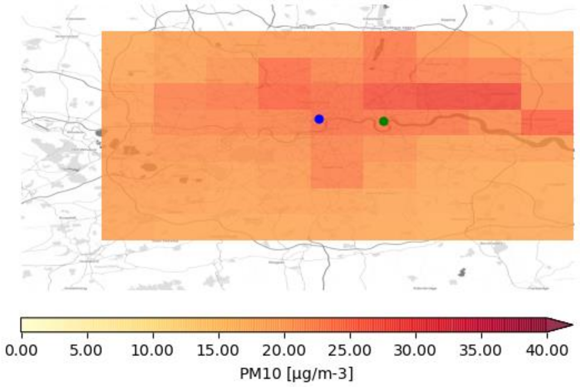

Absolute contribution of Inland Shipping to PM10 concentration in Le Havre

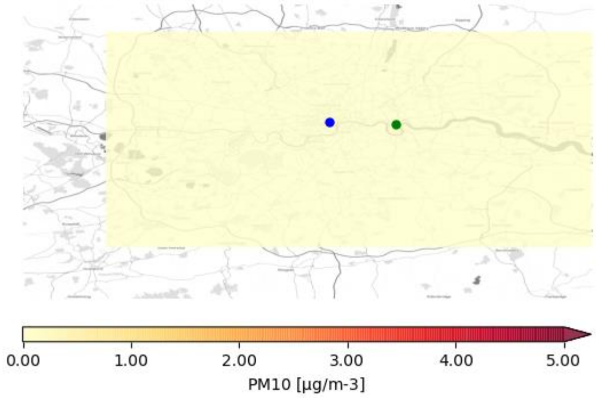
7.3.3.8. Liege


Total concentration of PM10 in Liege

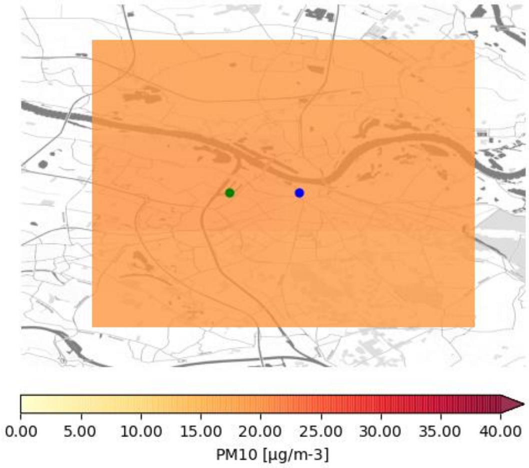

Absolute contribution of Inland Shipping to PM10 concentration in Liege

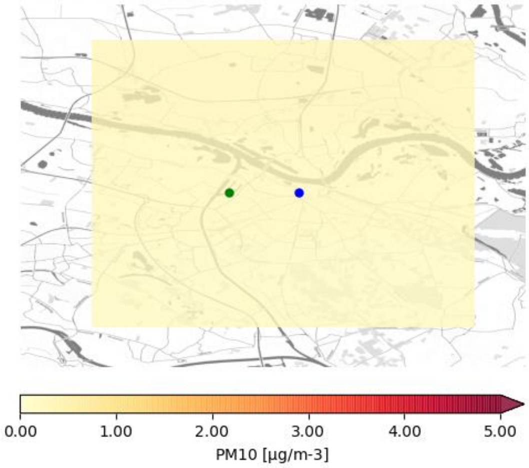
7.3.3.9. London


Total concentration of PM10 in London

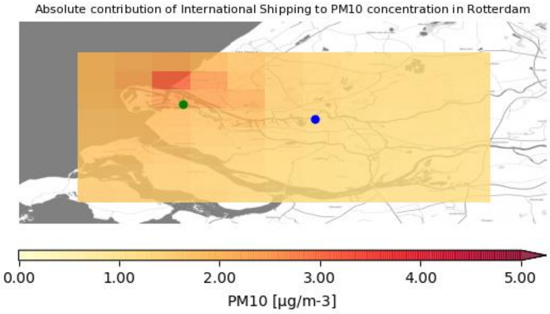

Absolute contribution of Inland Shipping to PM10 concentration in London

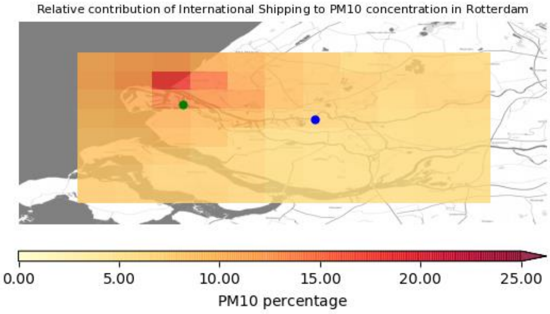
7.3.3.10. Nijmegen

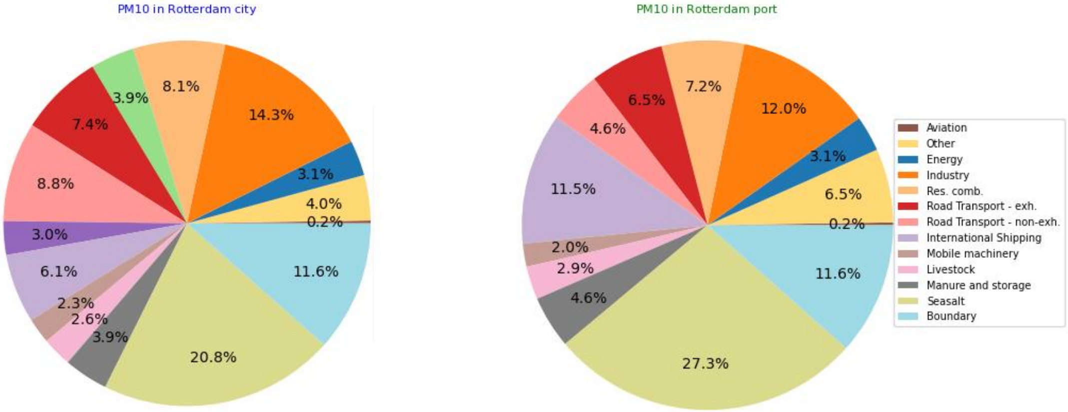

Total concentration of PM10 in Nijmegen


Absolute contribution of Inland Shipping to PM10 concentration in Nijmegen

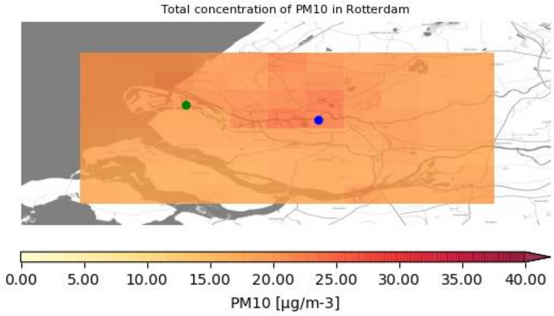
7.3.3.11. Rotterdam

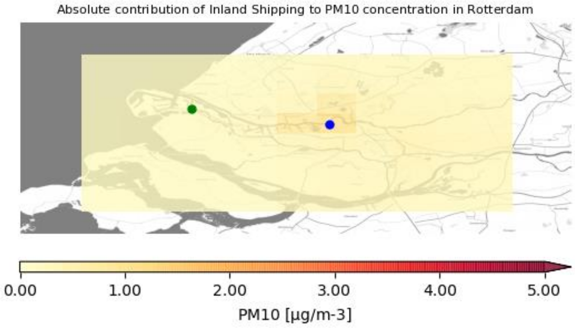

Absolute contribution of International Shipping to PM10 concentration in Rotterdam


Relative contribution of International Shipping to PM10 concentration in Rotterdam


PM10 in Rotterdam city

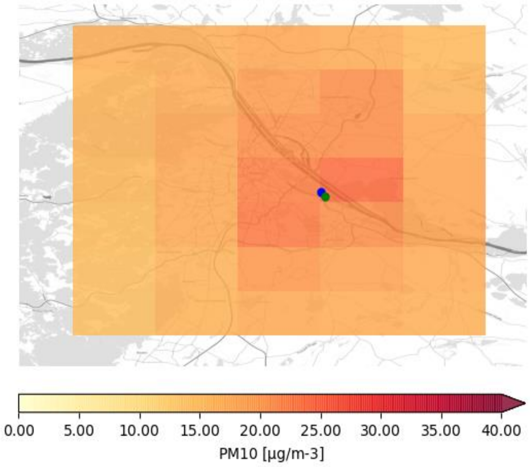
PM10 in Rotterdam port


Total concentration of PM10 in Rotterdam

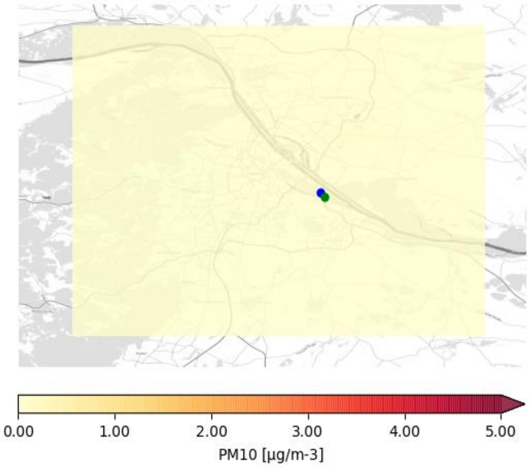

Absolute contribution of Inland Shipping to PM10 concentration in Rotterdam

7.3.3.12. Vienna

Total concentration of PM10 in Vienna

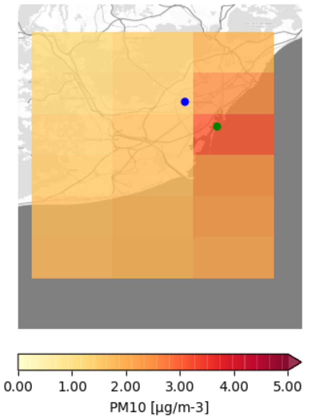


Absolute contribution of Inland Shipping to PM10 concentration in Vienna

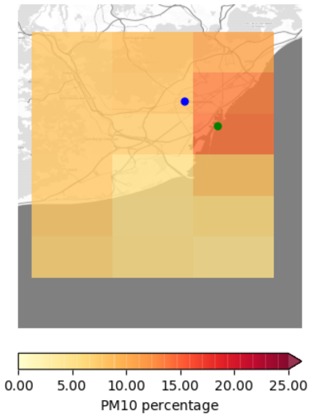


7.3.3.13. Barcelona

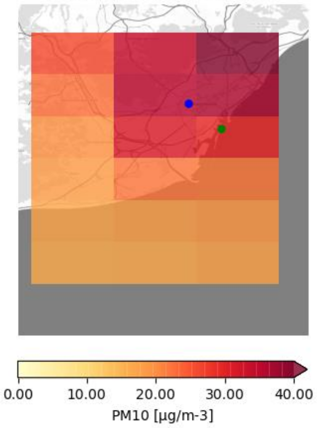
Absolute contribution of International Shipping to PM10 concentration in Barcelona



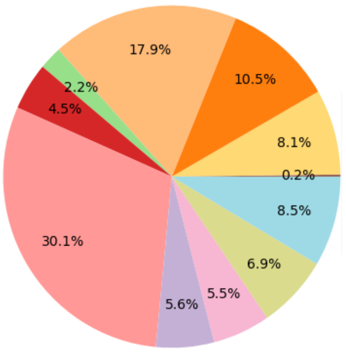
Relative contribution of International Shipping to PM10 concentration in Barcelona



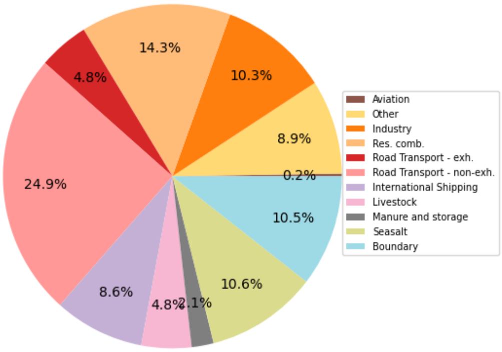
Total concentration of PM10 in Barcelona



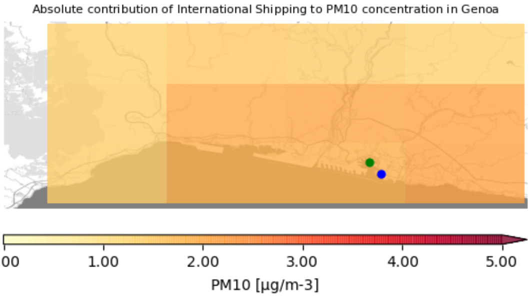
PM10 in Barcelona city

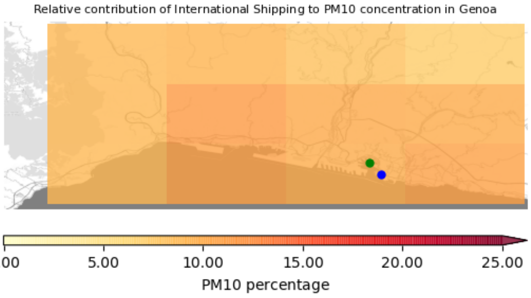


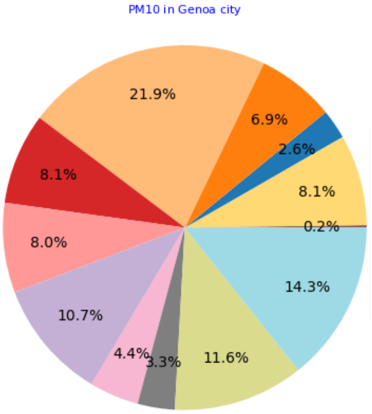
PM10 in Barcelona port

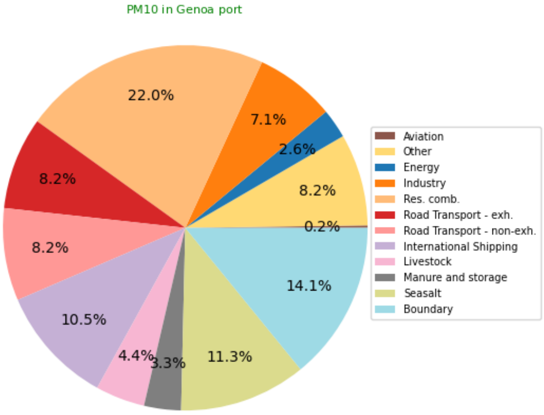


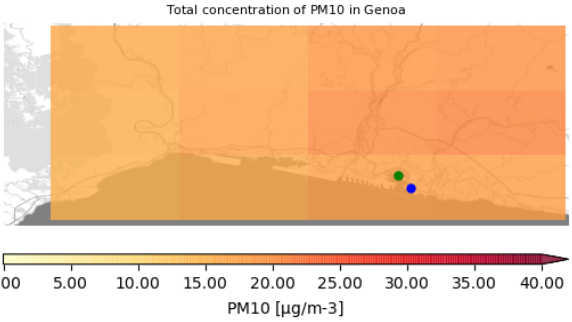
7.3.3.14. Genoa


Absolute contribution of International Shipping to PM10 concentration in Genoa

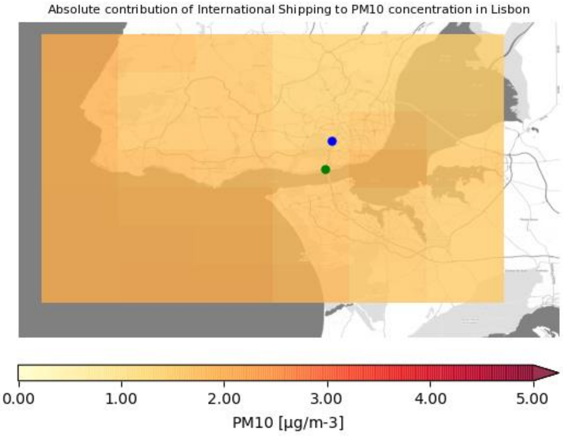

Relative contribution of International Shipping to PM10 concentration in Genoa

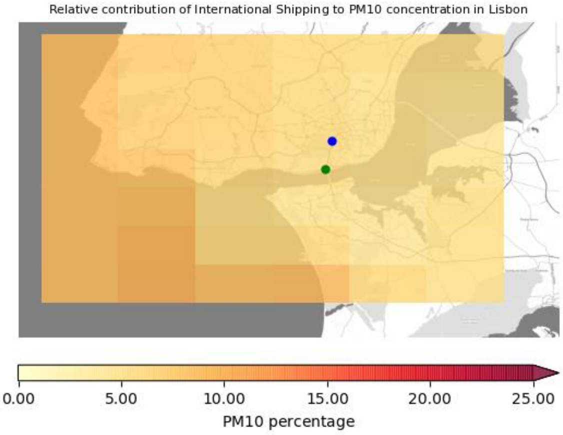

PM10 in Genoa city

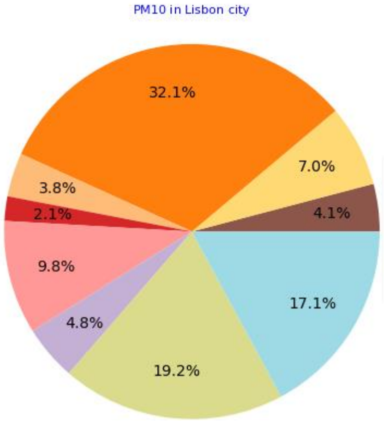

PM10 in Genoa port

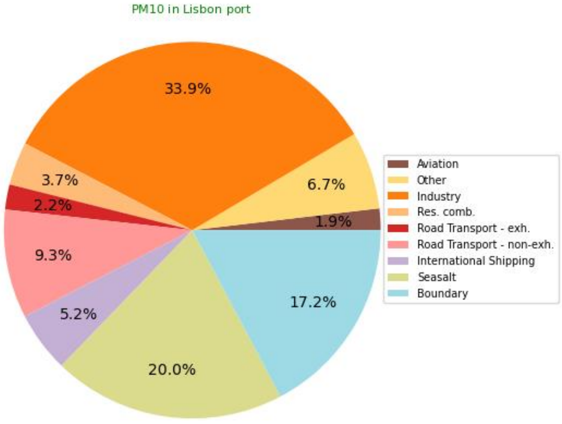

Total concentration of PM10 in Genoa

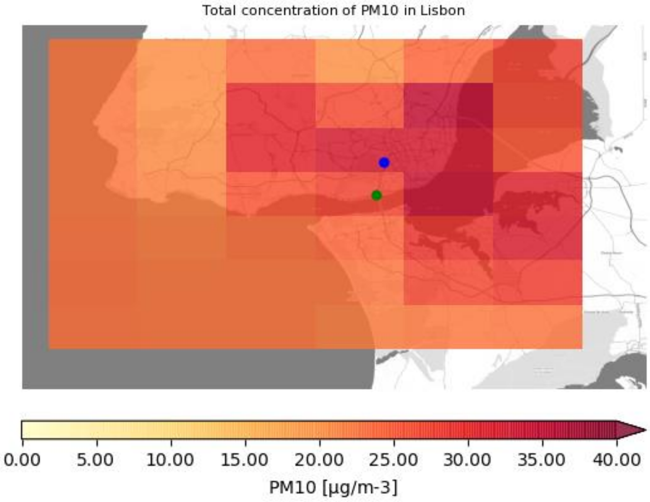
7.3.3.15. Lisbon





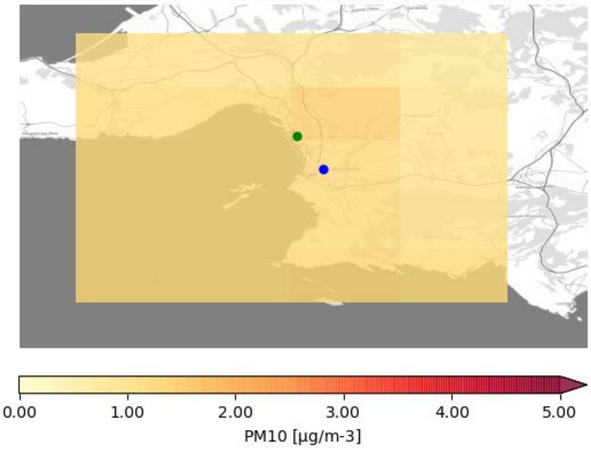




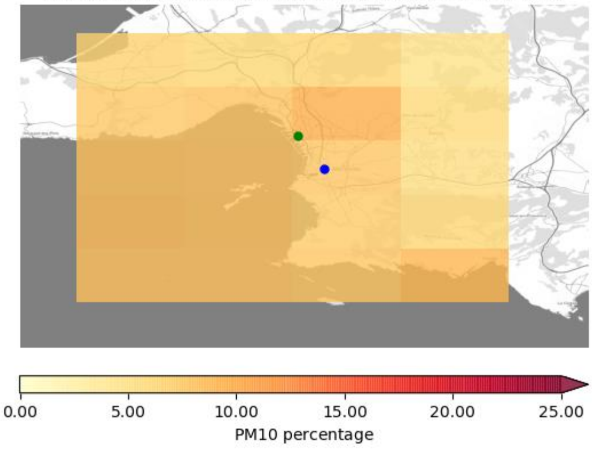


7.3.3.16. Marseille

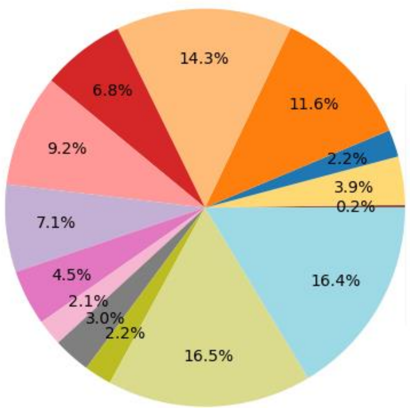
Absolute contribution of International Shipping to PM10 concentration in Marseille



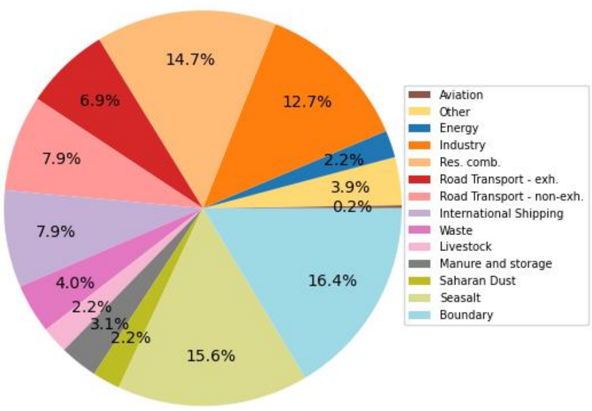
Relative contribution of International Shipping to PM10 concentration in Marseille



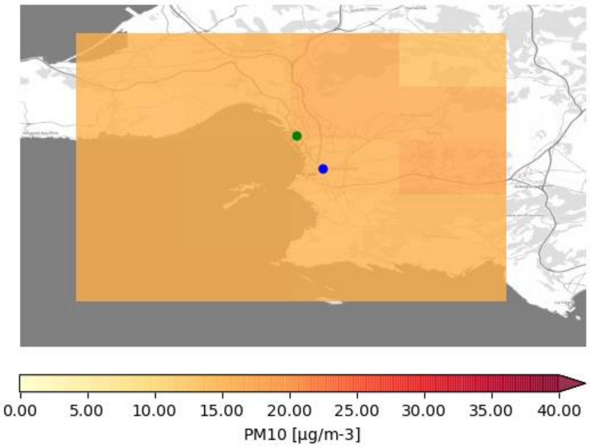
PM10 in Marseille city



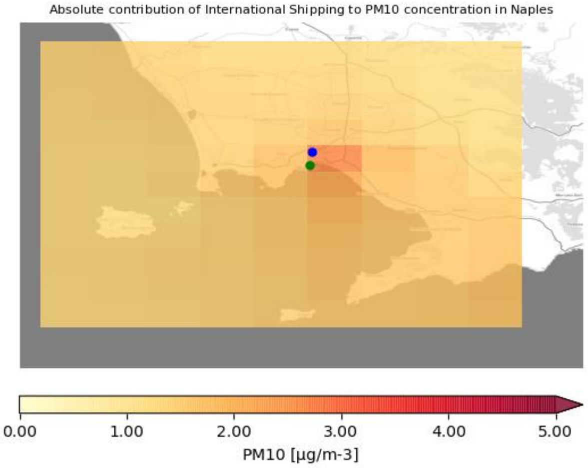
PM10 in Marseille port

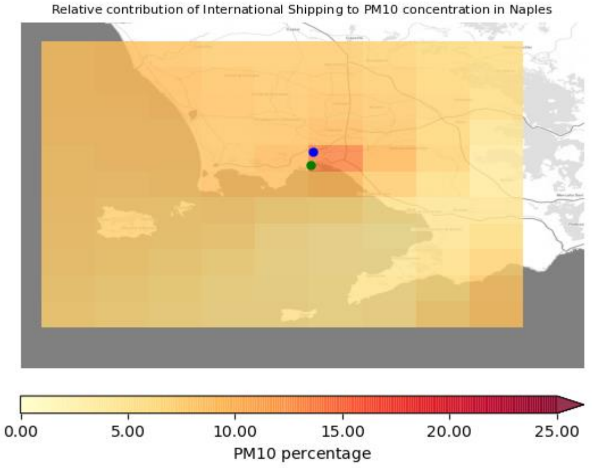


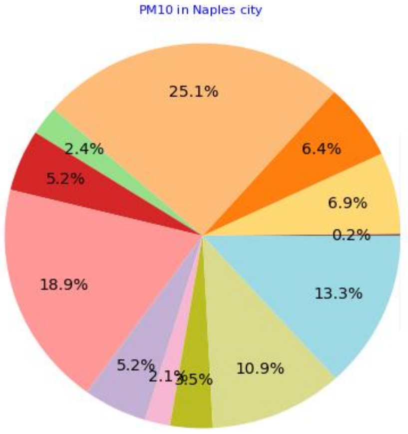
Total concentration of PM10 in Marseille

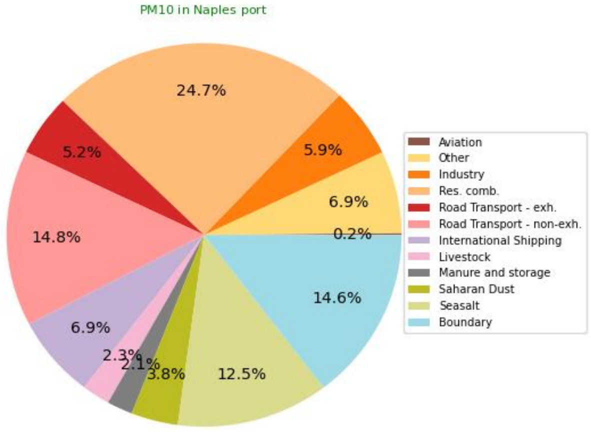


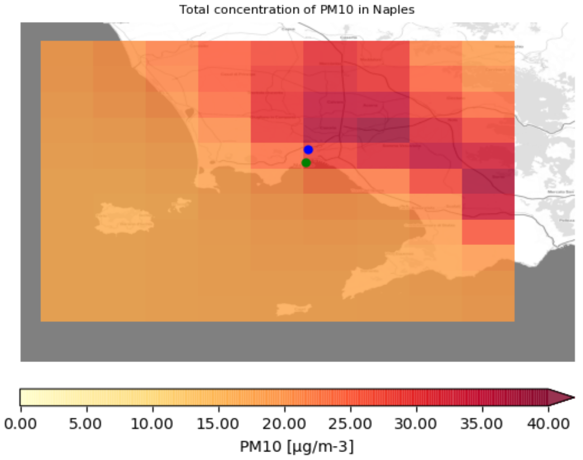
7.3.3.17. Naples



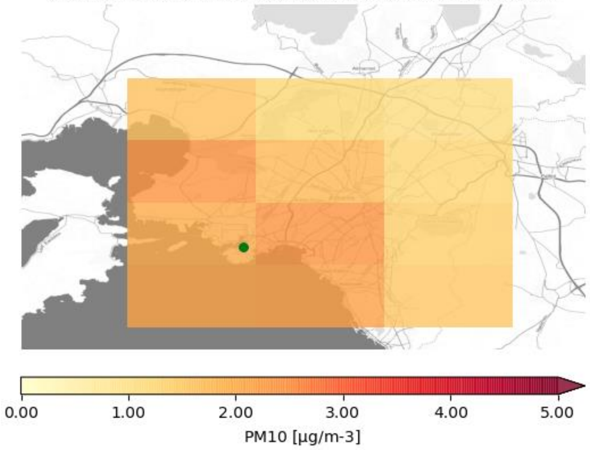


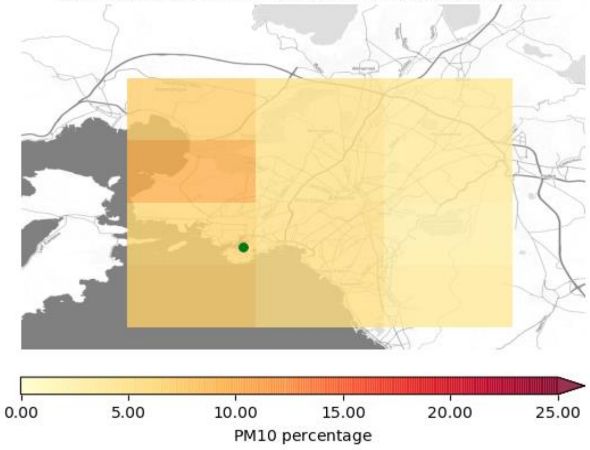


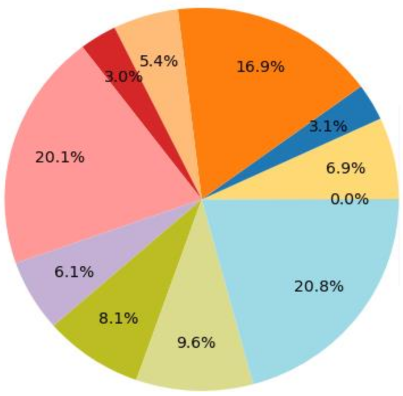


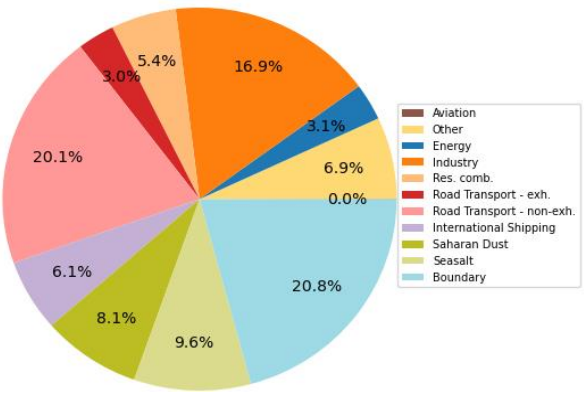


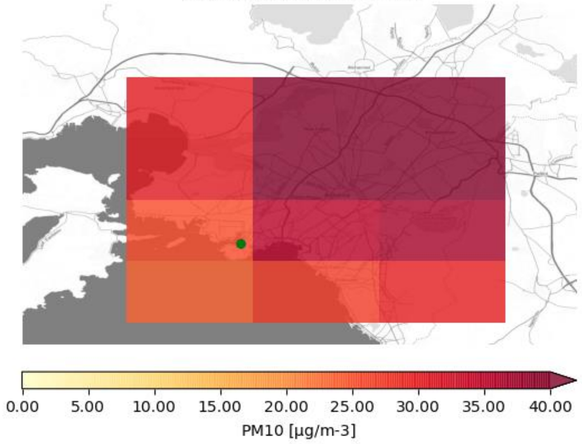
7.3.3.18. Piraeus


Absolute contribution of International Shipping to PM10 concentration in Piraeus


Relative contribution of International Shipping to PM10 concentration in Piraeus

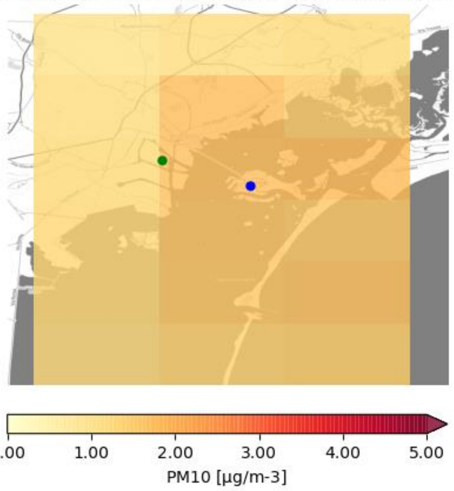

PM10 in Piraeus city


PM10 in Piraeus port

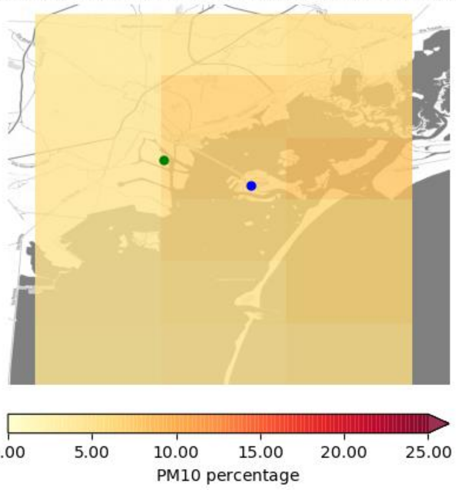

Total concentration of PM10 in Piraeus

7.3.3.19. Venice

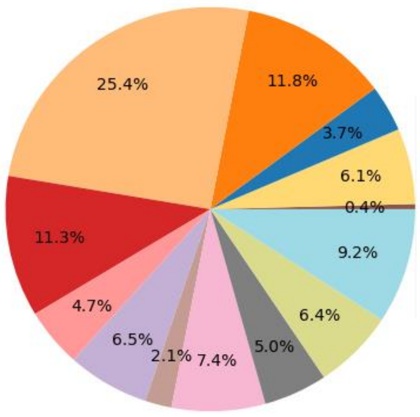
Absolute contribution of International Shipping to PM10 concentration in Venice



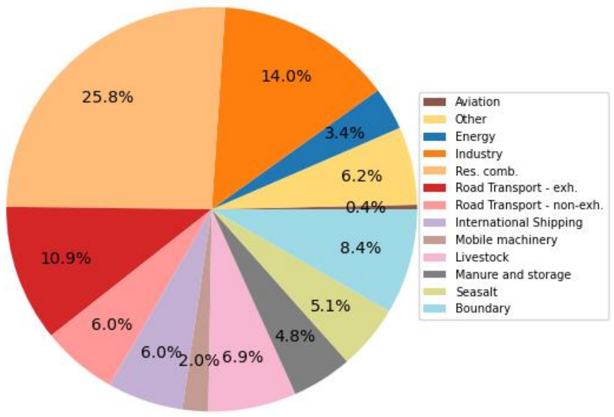
Relative contribution of International Shipping to PM10 concentration in Venice



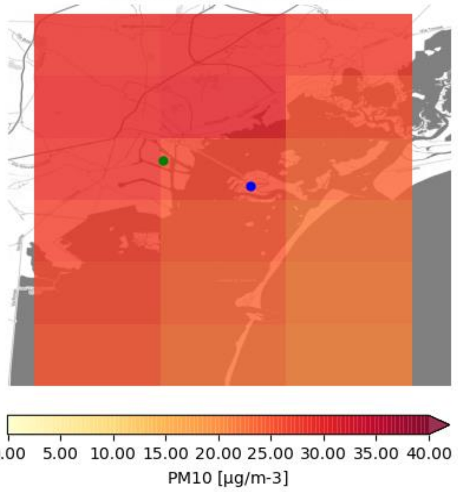
PM10 in Venice city



PM10 in Venice port

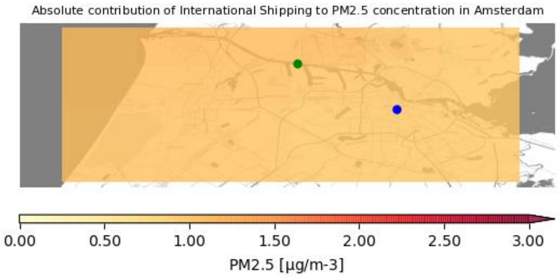


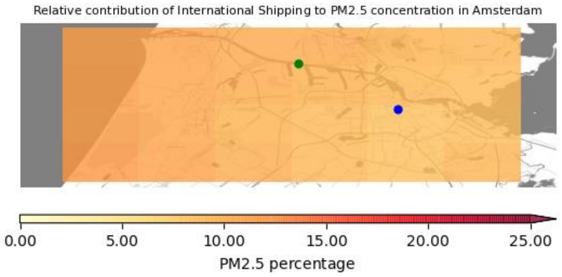
Total concentration of PM10 in Venice

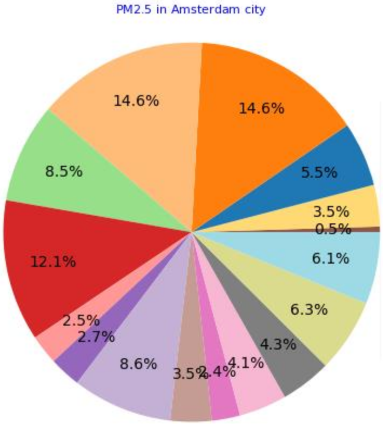


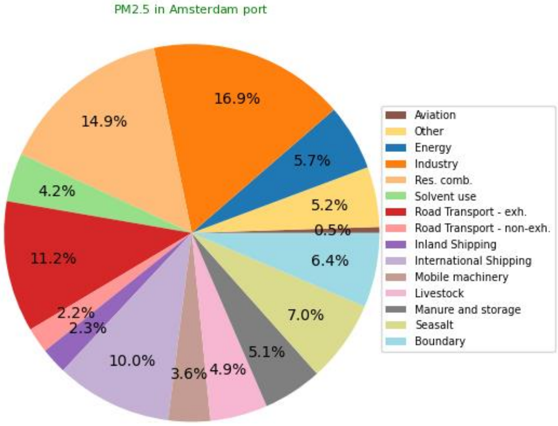
7.3.4. PM$_{2.5}$

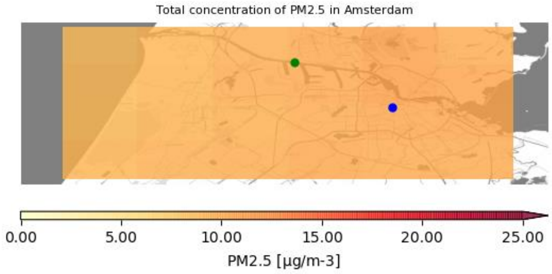
7.3.4.1. Amsterdam

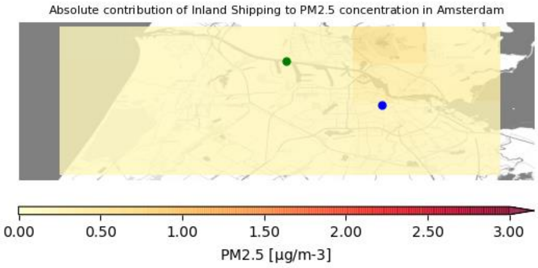

Absolute contribution of International Shipping to PM2.5 concentration in Amsterdam


Relative contribution of International Shipping to PM2.5 concentration in Amsterdam

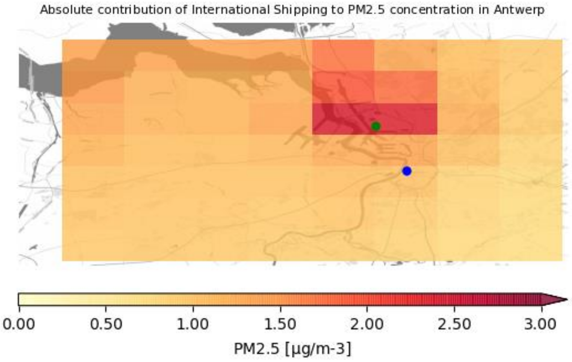

PM2.5 in Amsterdam city

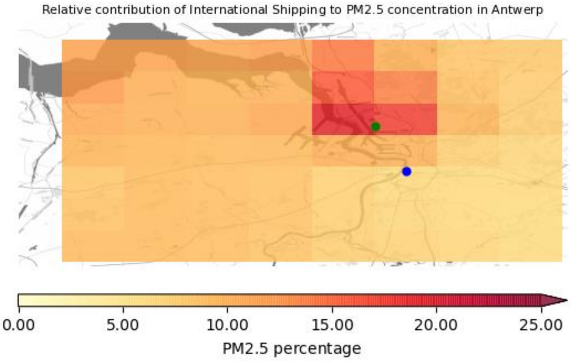

PM2.5 in Amsterdam port

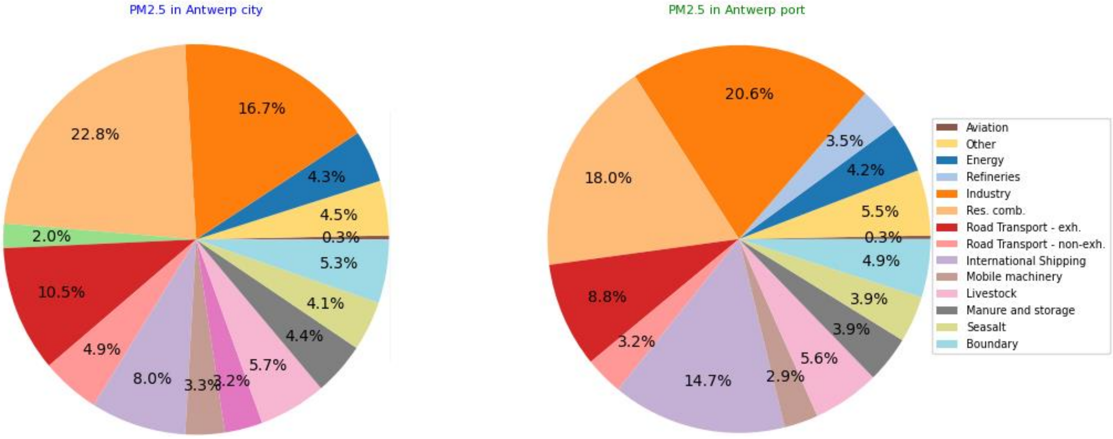

Total concentration of PM2.5 in Amsterdam

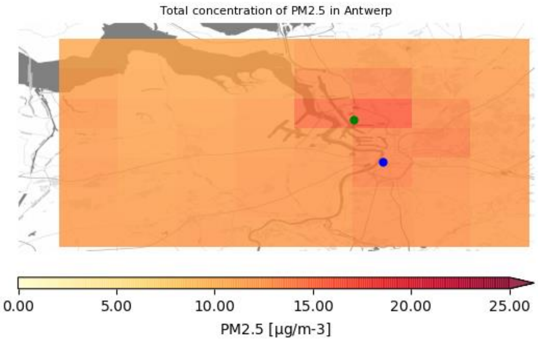

Absolute contribution of Inland Shipping to PM2.5 concentration in Amsterdam

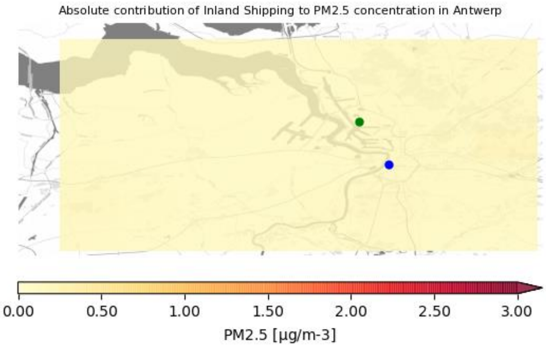
7.3.4.2. Antwerp



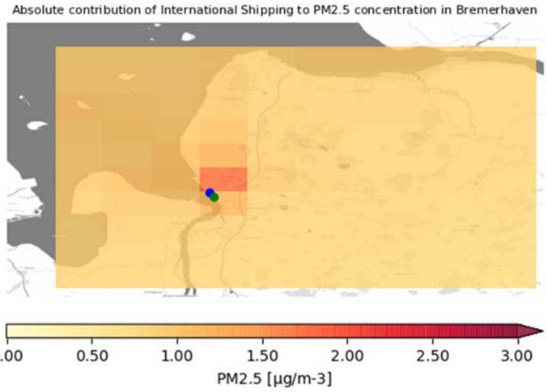


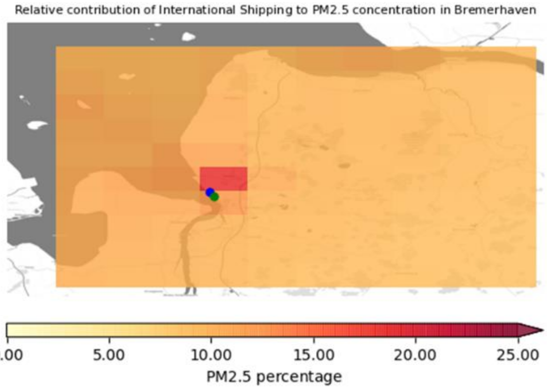


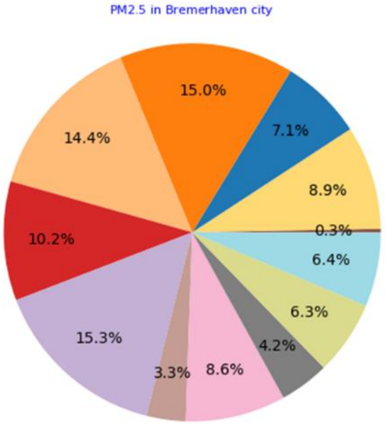


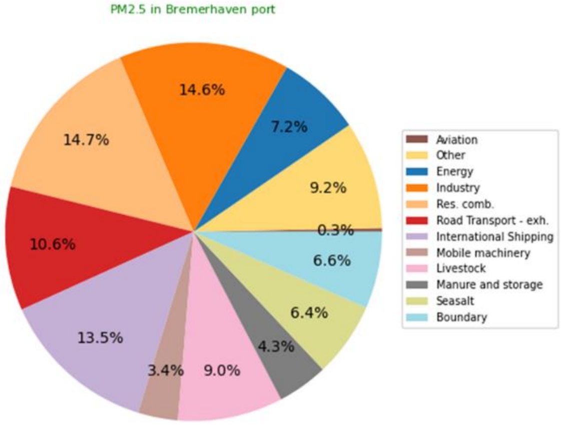


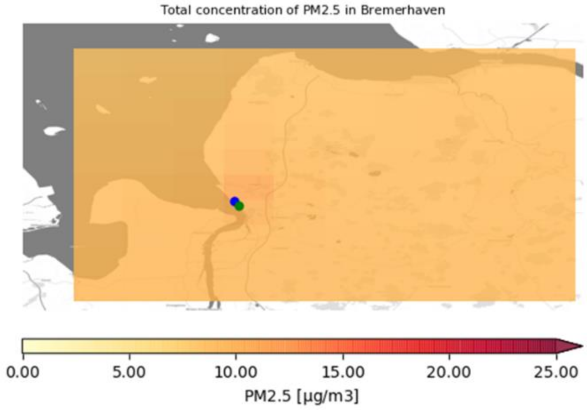
7.3.4.3. Bremerhaven

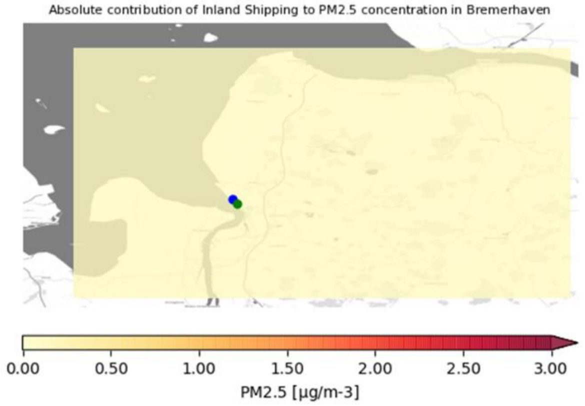

Absolute contribution of International Shipping to PM2.5 concentration in Bremerhaven


Relative contribution of International Shipping to PM2.5 concentration in Bremerhaven

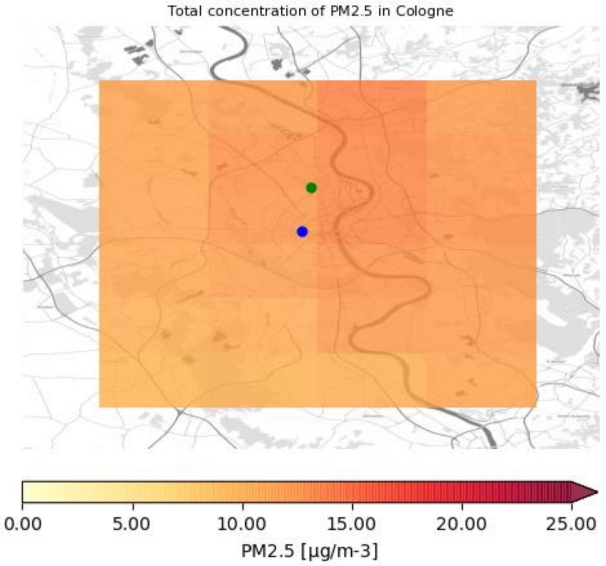

PM2.5 in Bremerhaven city

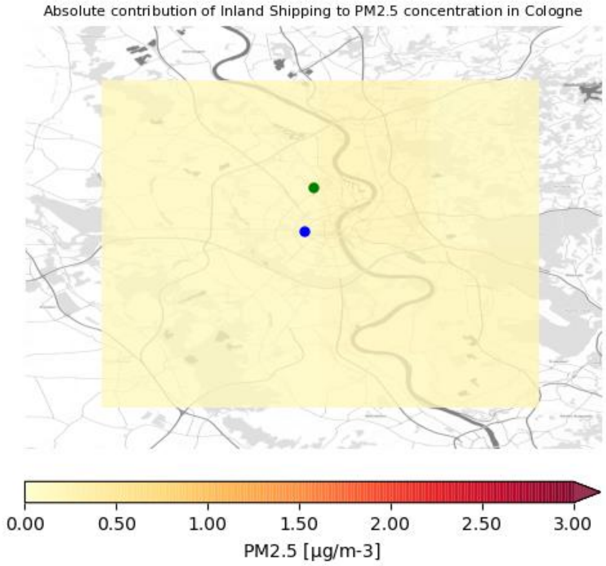

PM2.5 in Bremerhaven port


Total concentration of PM2.5 in Bremerhaven

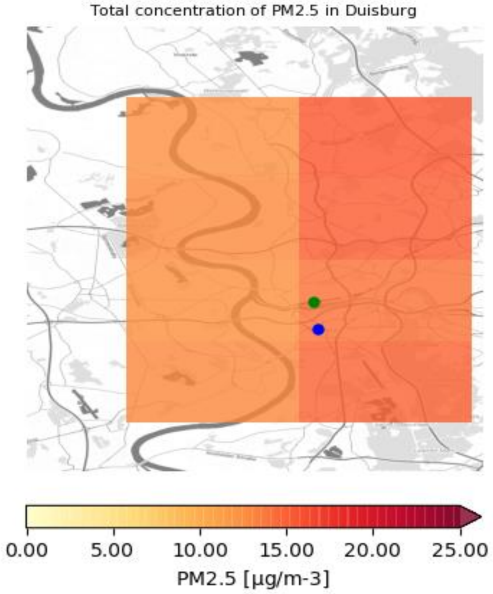

Absolute contribution of Inland Shipping to PM2.5 concentration in Bremerhaven

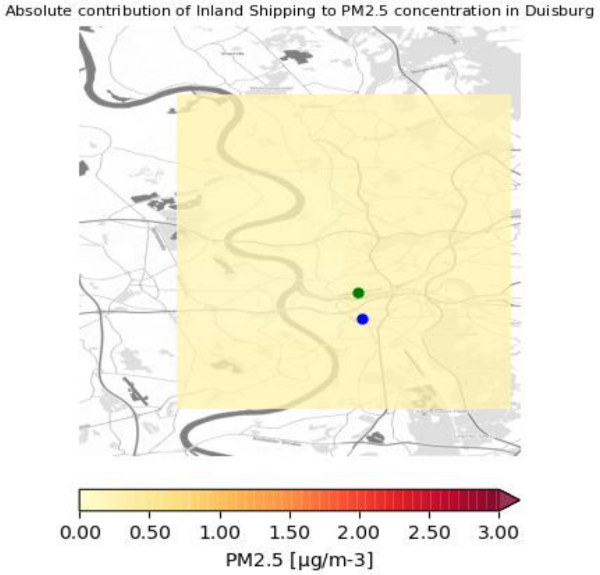
7.3.4.4. Cologne


Total concentration of PM2.5 in Cologne


Absolute contribution of Inland Shipping to PM2.5 concentration in Cologne

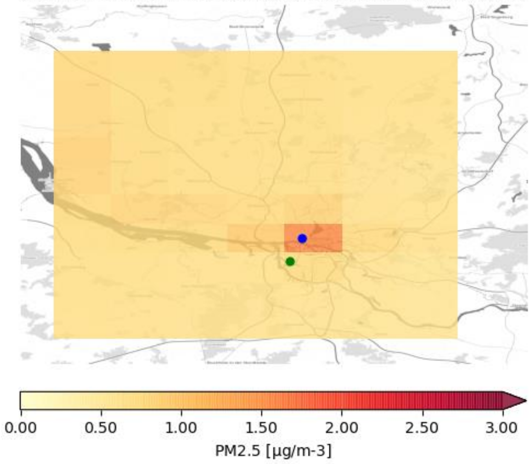
7.3.4.5. Duisburg


Total concentration of PM2.5 in Duisburg

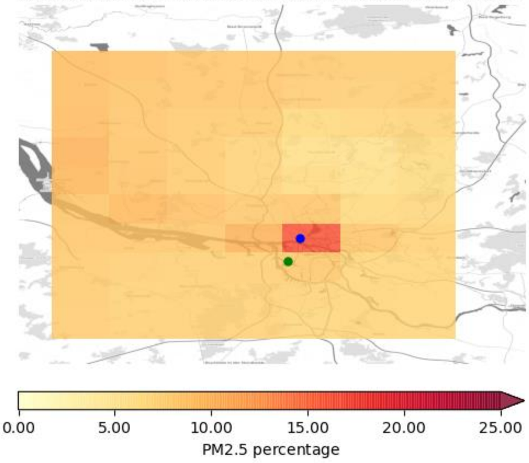

Absolute contribution of Inland Shipping to PM2.5 concentration in Duisburg

7.3.4.6. Hamburg

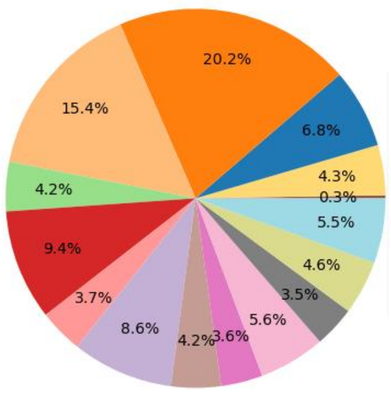
Absolute contribution of International Shipping to PM2.5 concentration in Hamburg



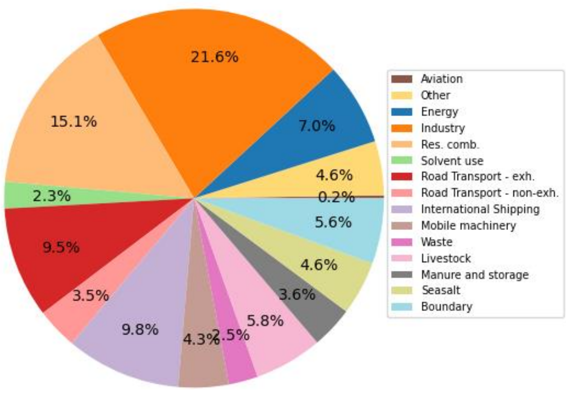
Relative contribution of International Shipping to PM2.5 concentration in Hamburg



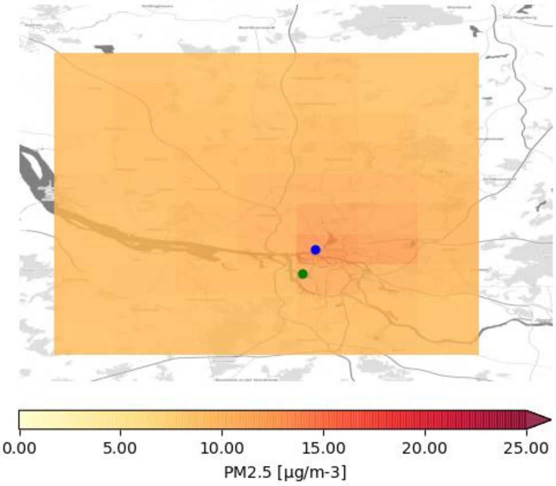
PM2.5 in Hamburg city



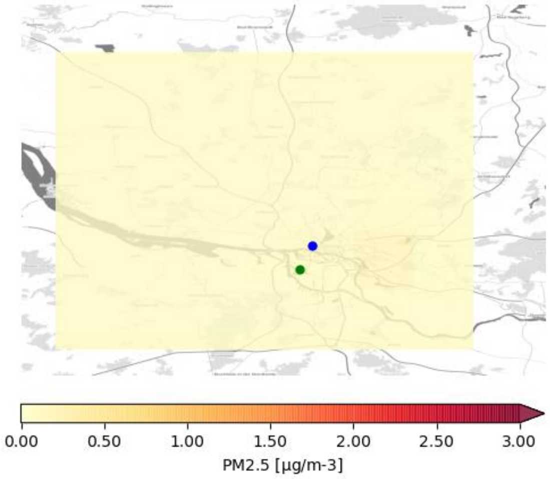
PM2.5 in Hamburg port



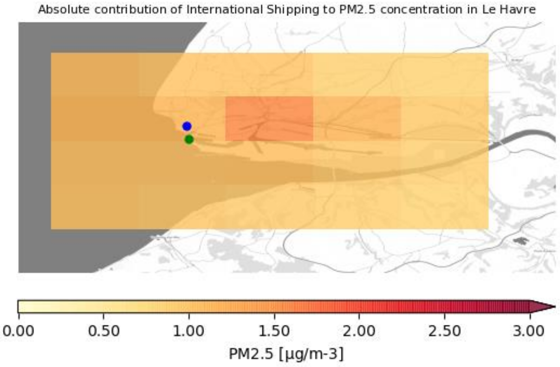
Total concentration of PM2.5 in Hamburg

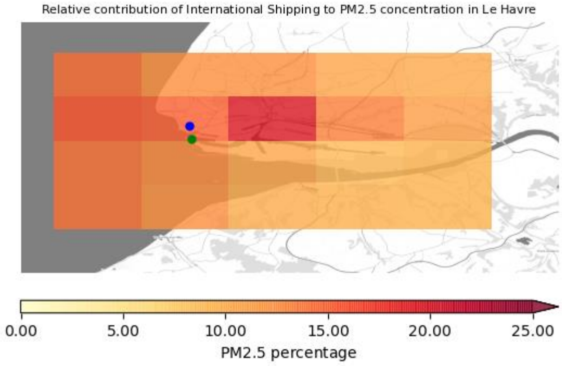


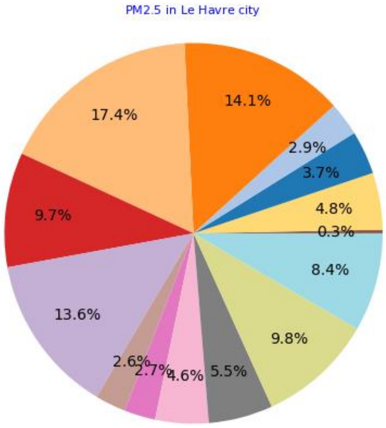
Absolute contribution of Inland Shipping to PM2.5 concentration in Hamburg

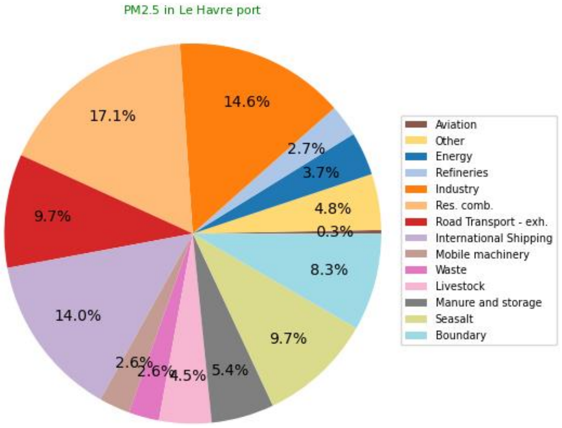


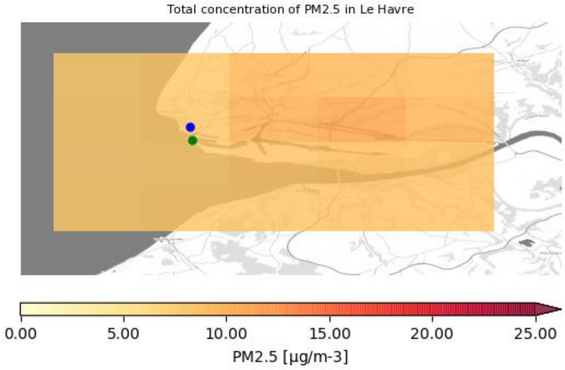
7.3.4.7. Le Havre

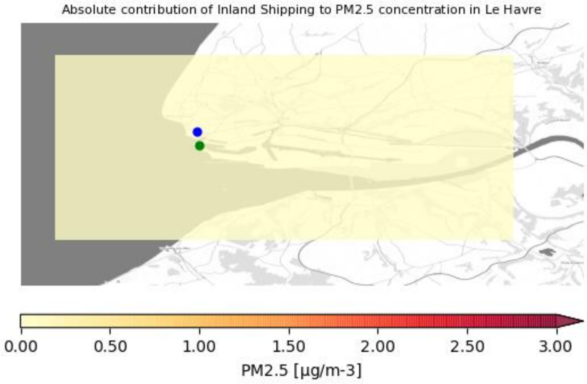




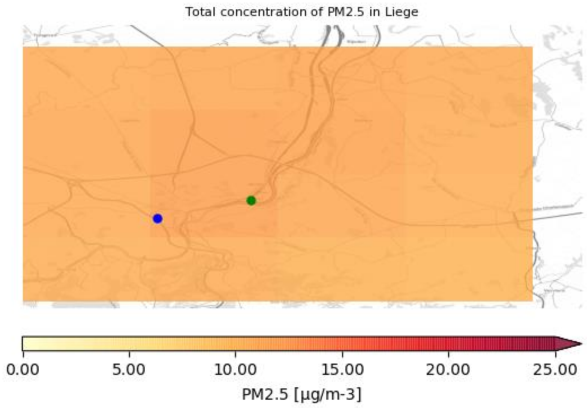


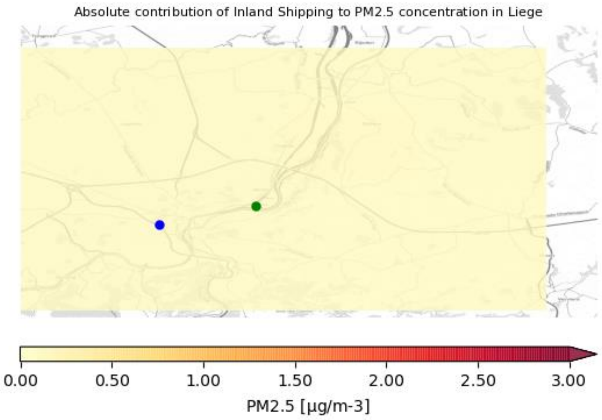




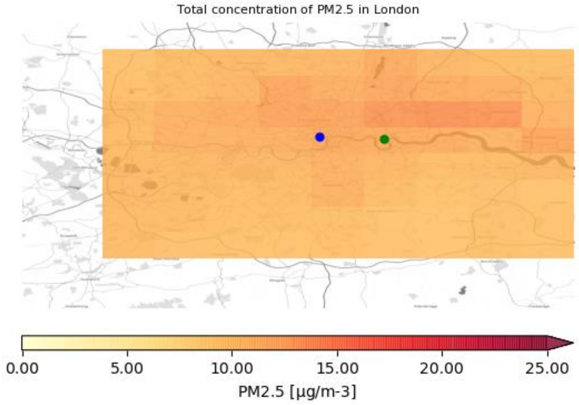


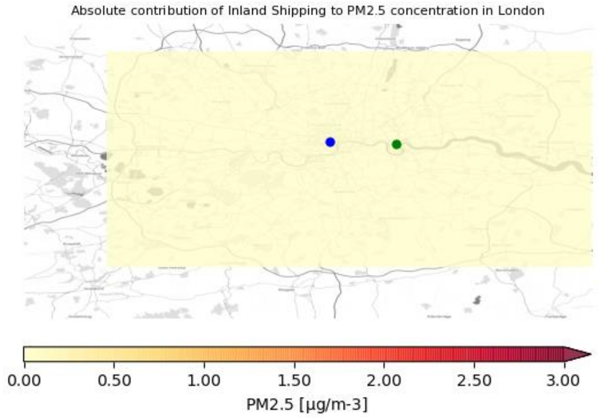
7.3.4.8. Liege


Total concentration of PM2.5 in Liege

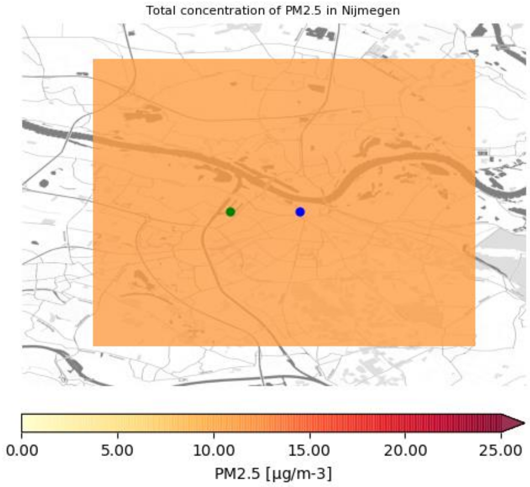

Absolute contribution of Inland Shipping to PM2.5 concentration in Liege

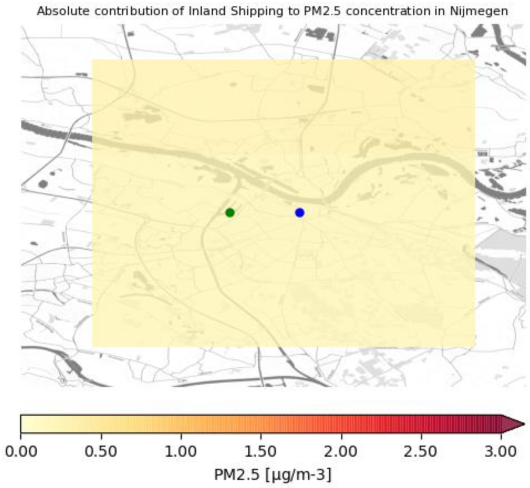
7.3.4.9. London


Total concentration of PM2.5 in London

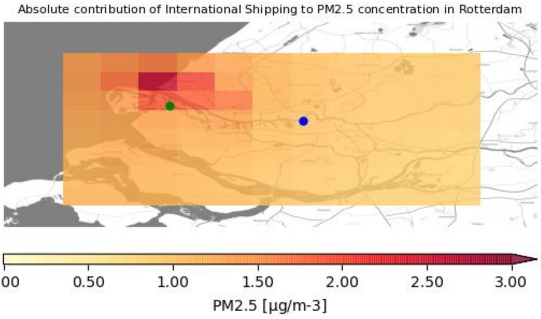

Absolute contribution of Inland Shipping to PM2.5 concentration in London

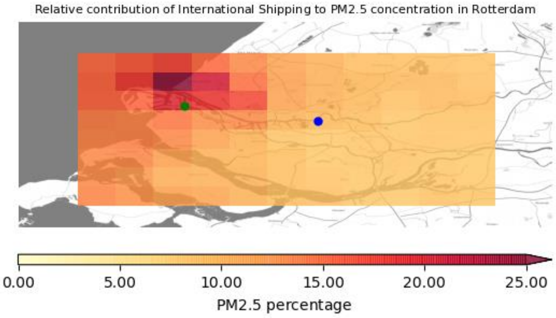
7.3.4.10. Nijmegen

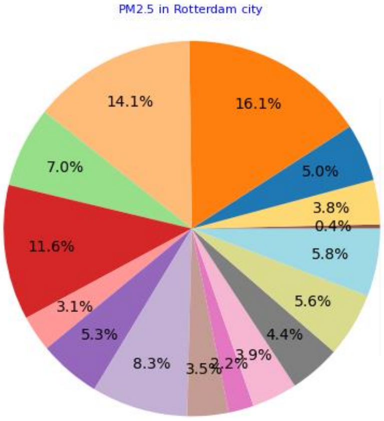

Total concentration of PM2.5 in Nijmegen

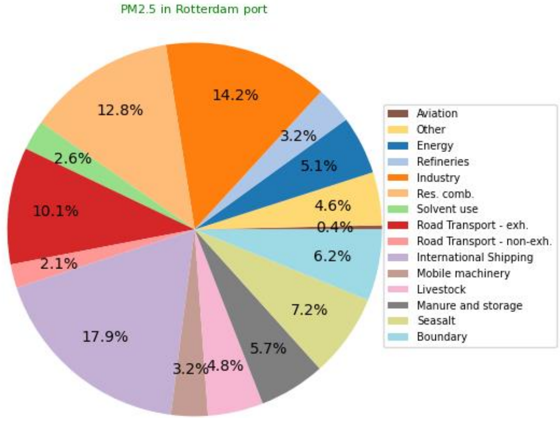

Absolute contribution of Inland Shipping to PM2.5 concentration in Nijmegen

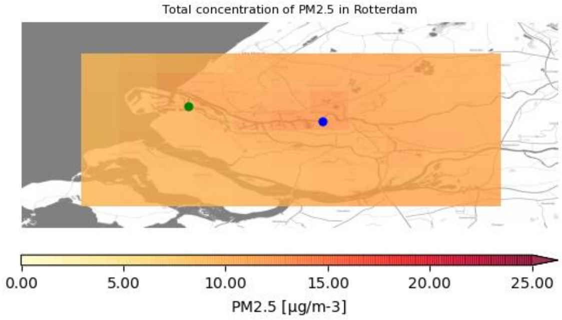
7.3.4.11. Rotterdam

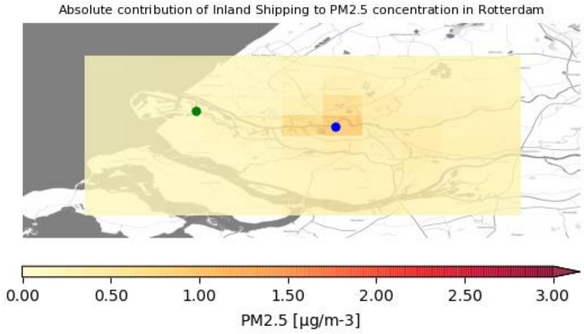

Absolute contribution of International Shipping to PM2.5 concentration in Rotterdam


Relative contribution of International Shipping to PM2.5 concentration in Rotterdam

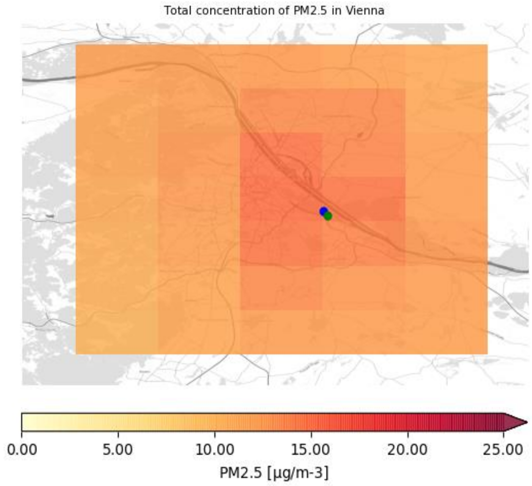

PM2.5 in Rotterdam city

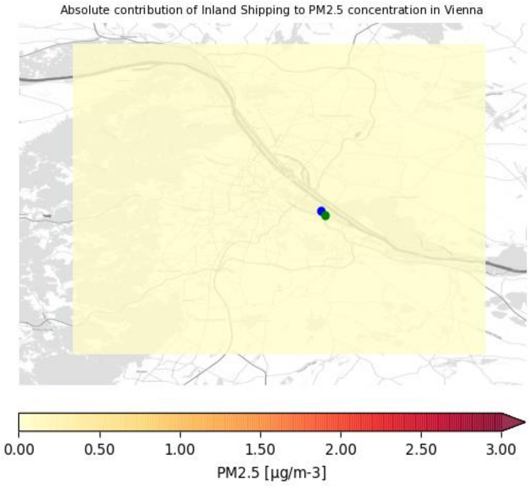

PM2.5 in Rotterdam port


Total concentration of PM2.5 in Rotterdam

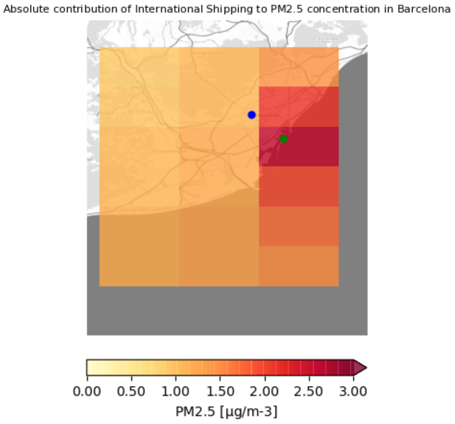

Absolute contribution of Inland Shipping to PM2.5 concentration in Rotterdam

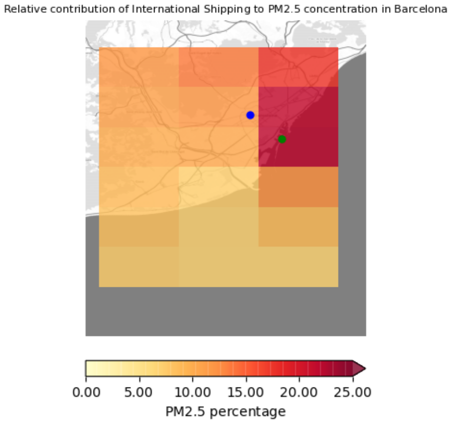
7.3.4.12. Vienna

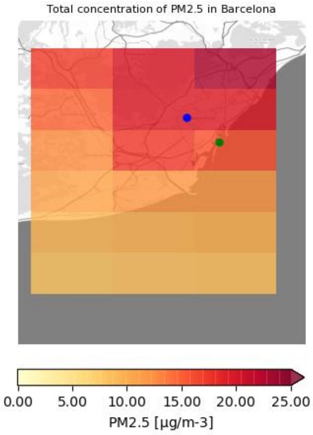

Total concentration of PM2.5 in Vienna

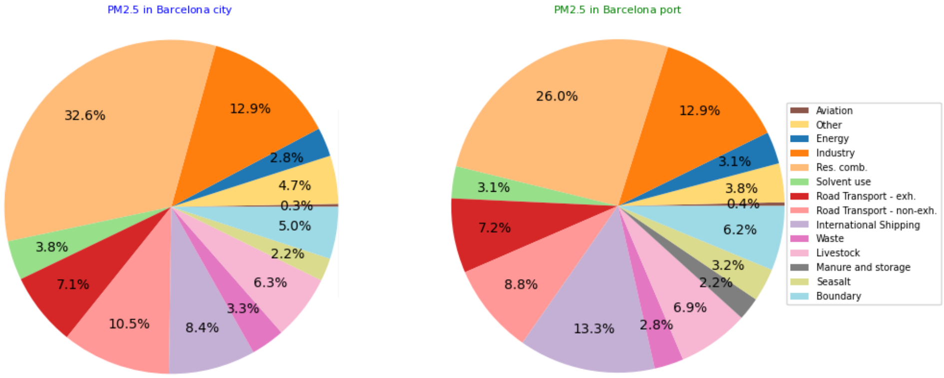

Absolute contribution of Inland Shipping to PM2.5 concentration in Vienna

7.3.4.13. Barcelona

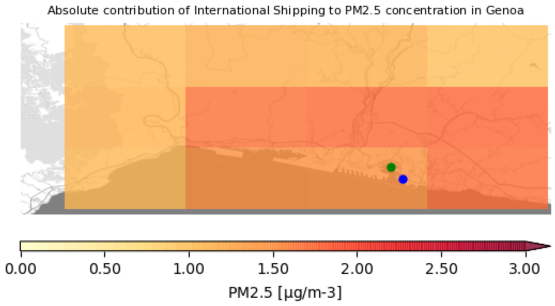

Absolute contribution of International Shipping to PM2.5 concentration in Barcelona

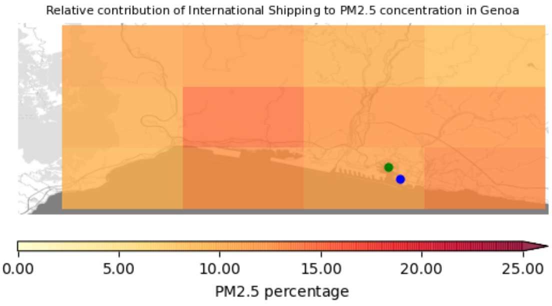

Relative contribution of International Shipping to PM2.5 concentration in Barcelona

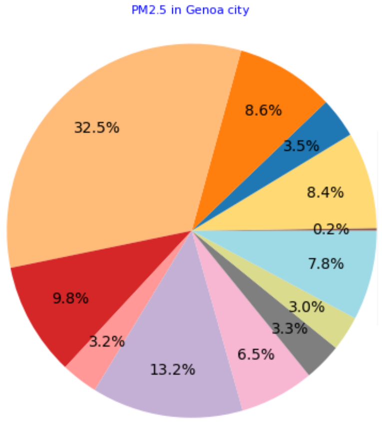

Total concentration of PM2.5 in Barcelona

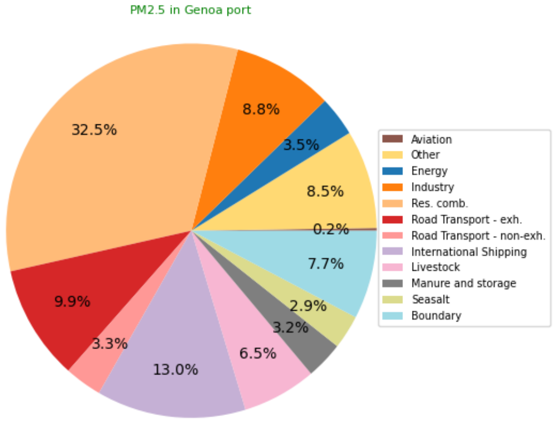

PM2.5 in Barcelona city
PM2.5 in Barcelona port

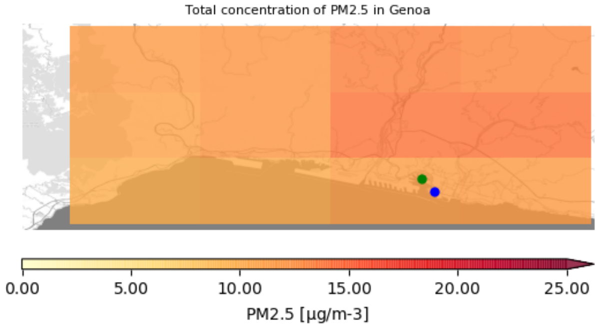
7.3.4.14. Genoa


Absolute contribution of International Shipping to PM2.5 concentration in Genoa
0.00
0.50
1.00
1.50
2.00
2.50
3.00
PM2.5 [µg/m-3]


Relative contribution of International Shipping to PM2.5 concentration in Genoa
0.00
5.00
10.00
15.00
20.00
25.00
PM2.5 percentage

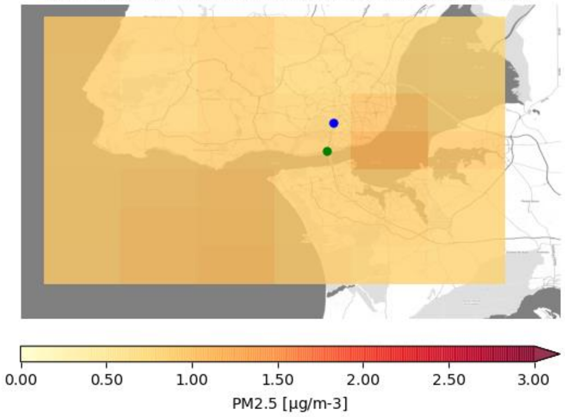

PM2.5 in Genoa city
32.5%
8.6%
3.5%
8.4%
0.2%
7.8%
3.0%
3.3%
6.5%
13.2%
3.2%
9.8%


PM2.5 in Genoa port
32.5%
8.8%
3.5%
8.5%
0.2%
7.7%
2.9%
3.2%
6.5%
13.0%
3.3%
9.9%
Aviation
Other
Energy
Industry
Res. comb.
Road Transport - exh.
Road Transport - non-exh.
International Shipping
Livestock
Manure and storage
Seasalt
Boundary

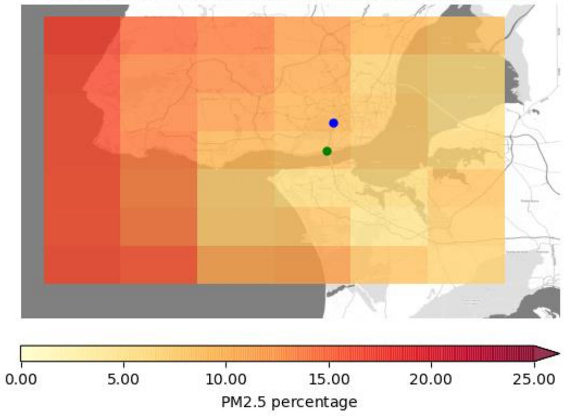

Total concentration of PM2.5 in Genoa
0.00
5.00
10.00
15.00
20.00
25.00
PM2.5 [µg/m-3]

7.3.4.15. Lisbon

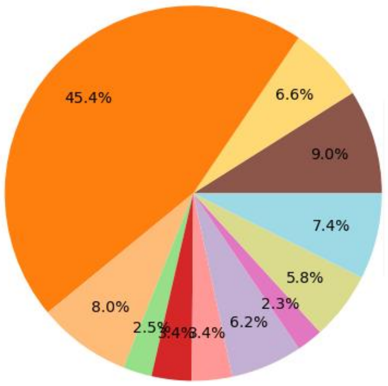
Absolute contribution of International Shipping to PM2.5 concentration in Lisbon



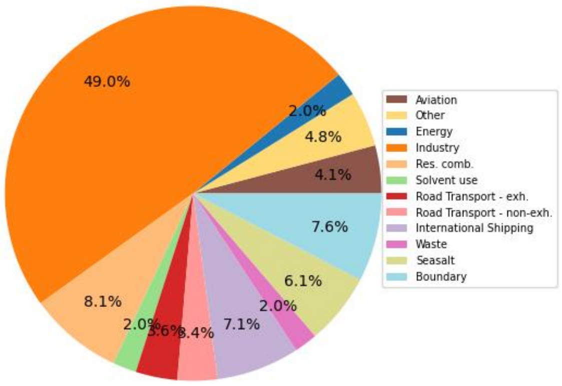
Relative contribution of International Shipping to PM2.5 concentration in Lisbon



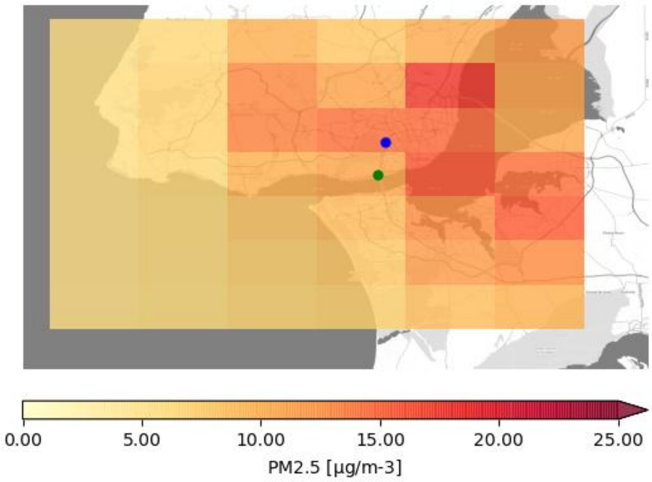
PM2.5 in Lisbon city



PM2.5 in Lisbon port

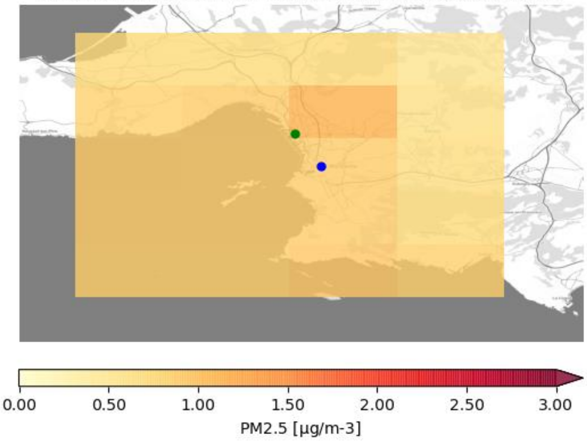


Total concentration of PM2.5 in Lisbon

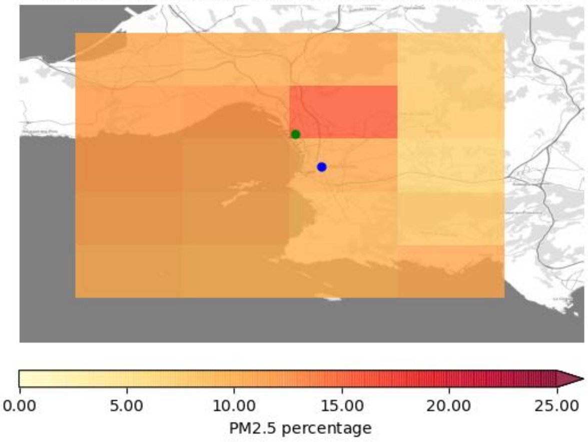


7.3.4.16. Marseille

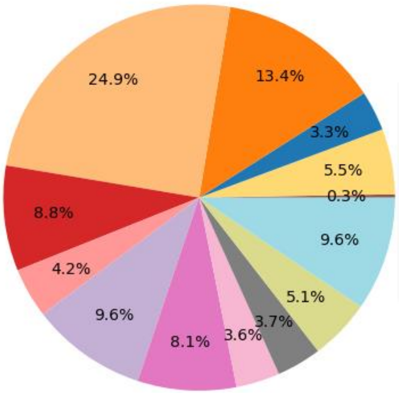
Absolute contribution of International Shipping to PM2.5 concentration in Marseille



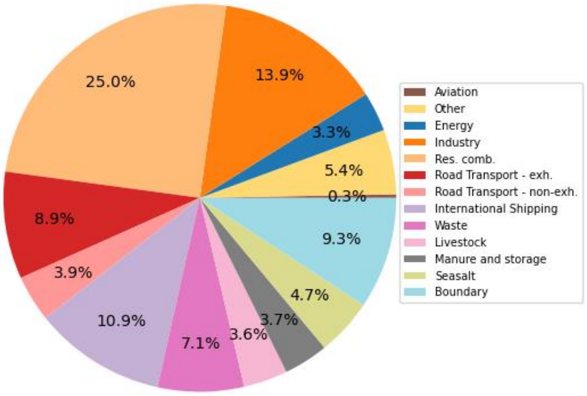
Relative contribution of International Shipping to PM2.5 concentration in Marseille



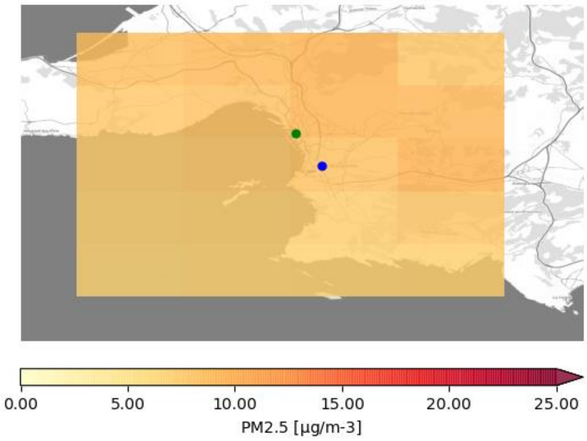
PM2.5 in Marseille city



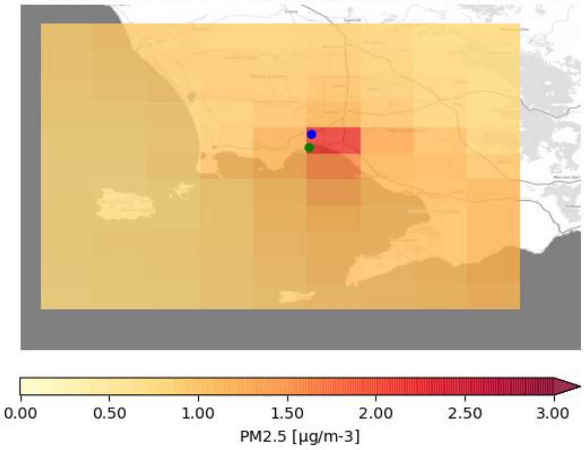
PM2.5 in Marseille port

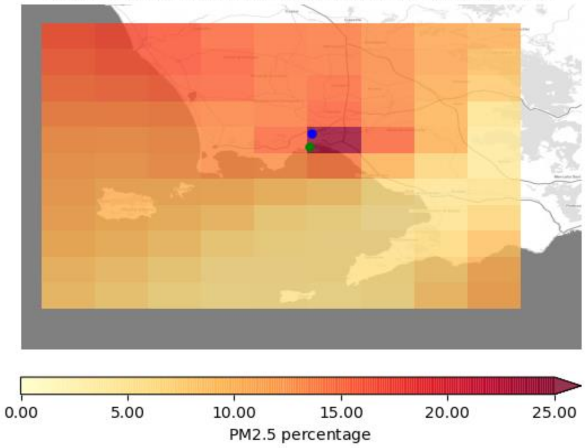


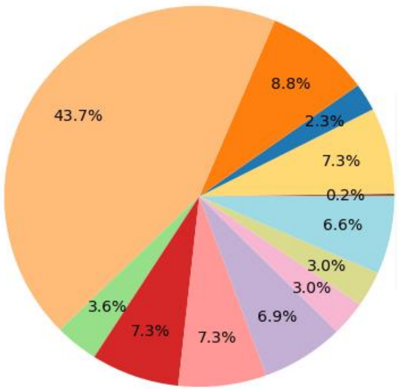
Total concentration of PM2.5 in Marseille

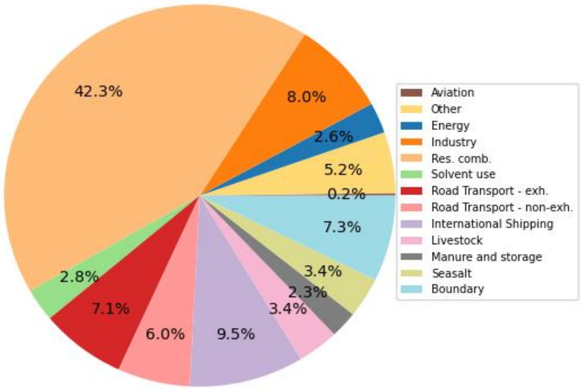


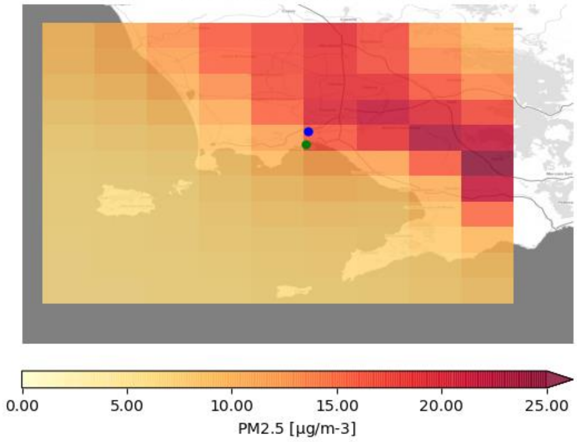
7.3.4.17. Naples


Absolute contribution of International Shipping to PM2.5 concentration in Naples


Relative contribution of International Shipping to PM2.5 concentration in Naples

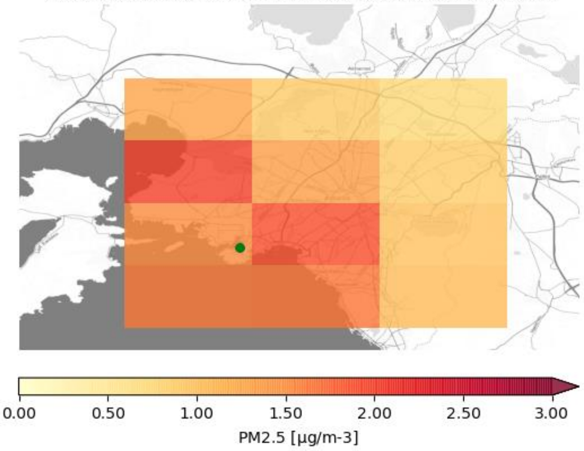

PM2.5 in Naples city


PM2.5 in Naples port

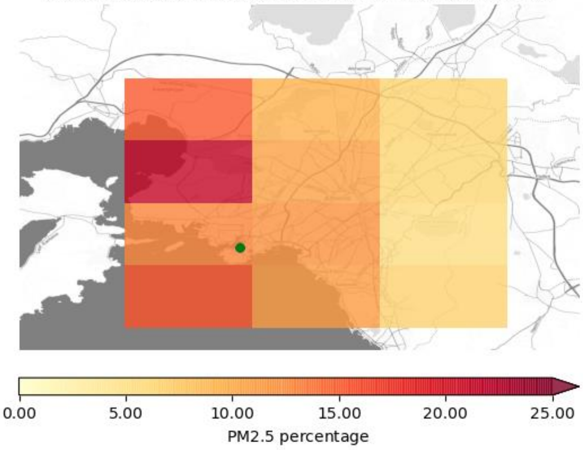

Total concentration of PM2.5 in Naples

7.3.4.18. Piraeus

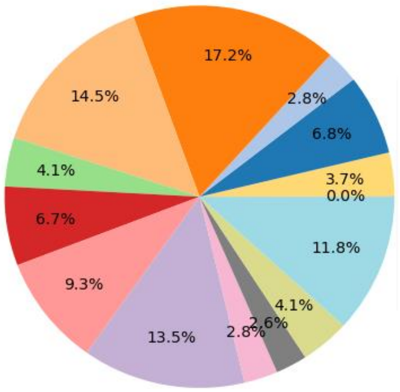
Absolute contribution of International Shipping to PM2.5 concentration in Piraeus



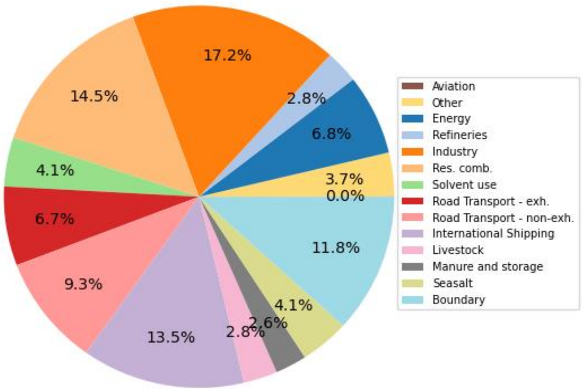
Relative contribution of International Shipping to PM2.5 concentration in Piraeus



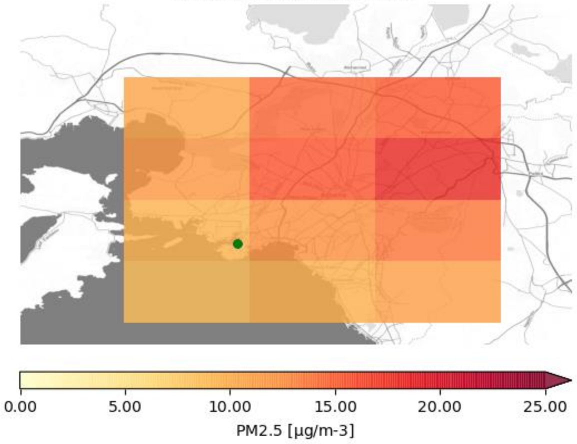
PM2.5 in Piraeus city



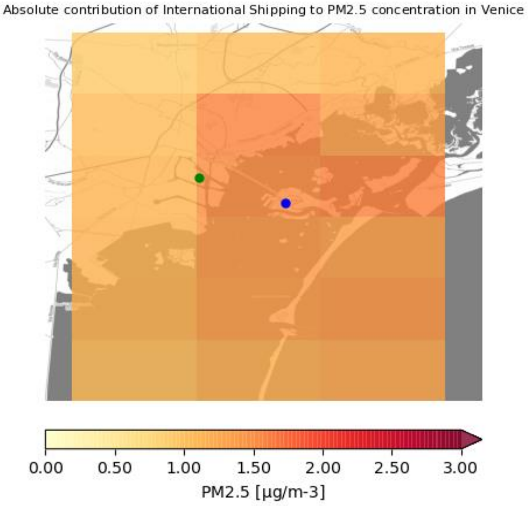
PM2.5 in Piraeus port

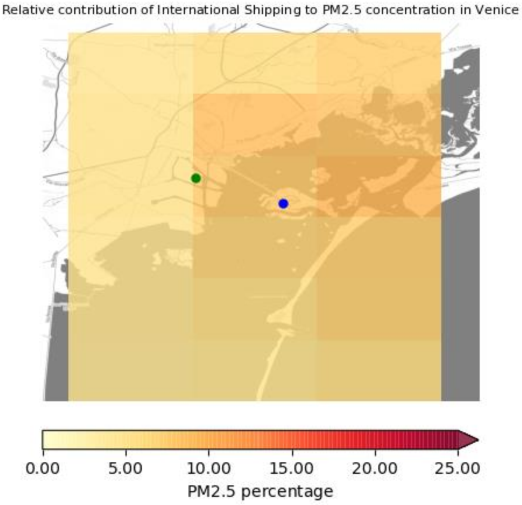


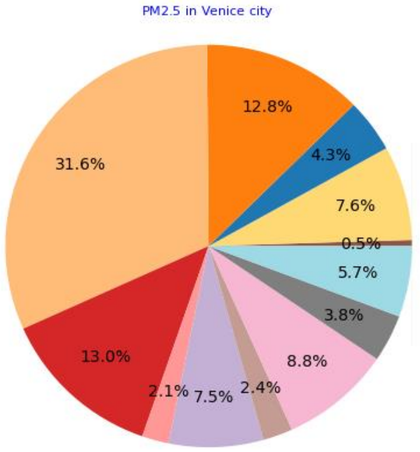
Total concentration of PM2.5 in Piraeus

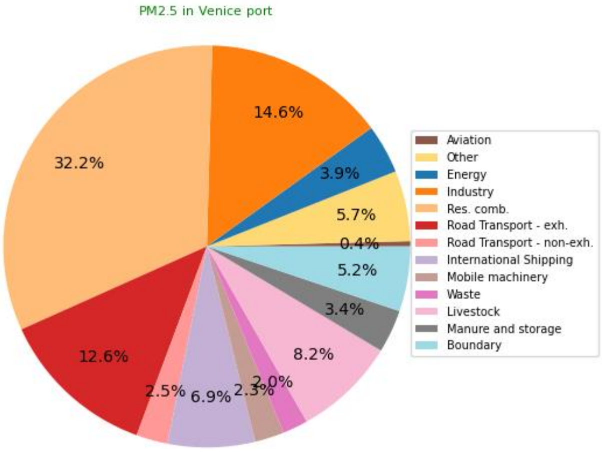


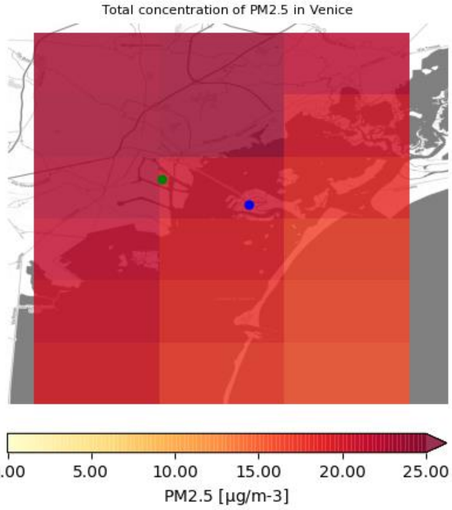
7.3.4.19. Venice


Absolute contribution of International Shipping to PM2.5 concentration in Venice


Relative contribution of International Shipping to PM2.5 concentration in Venice


PM2.5 in Venice city


PM2.5 in Venice port


Total concentration of PM2.5 in Venice

7.4. COMPARISON BETWEEN MODELS AND OBSERVATIONS FOR OTHER POLLUTANTS

The station annual mean values from observations and model results for SO_2, $PM_{2.5}$ and PM_{10} respectively are shown on the left panels and the underlying networks of stations with measurements for at least 50% of the days in 2018 on the right panels.

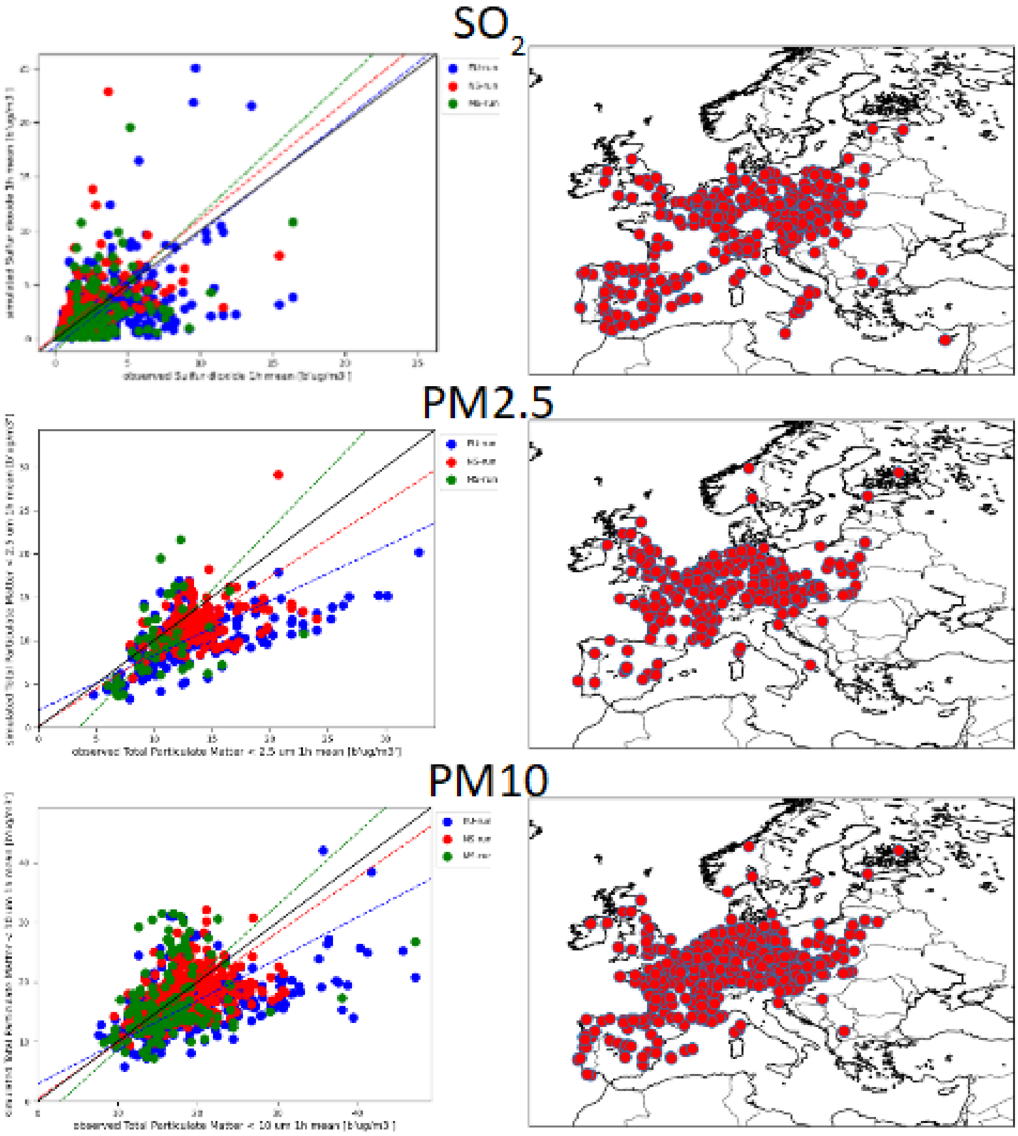


Figure 24 Observed vs modelled annual mean concentrations of SO_2 (top panel) $PM_{2.5}$ (middle panel) and PM_{10} (bottom panel) in 2018

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