The impact of shipping emissions on urban air quality in Europe — a port/city analysis

This article summarises the results of a modelling study undertaken to assess the influence that shipping emissions have on air quality in European port cities. The study compared the influence of both international and inland shipping on NO_2 concentrations both in seaports and in cities located close to the ports. It found that international shipping contributes significantly to NO_2 concentrations in Europe, while inland shipping generally has a low influence on NO_2 with only a few exceptions.

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Introduction

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 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.[1] Moreover, nitrogen deposition in soils and water bodies leads to eutrophication and biodiversity loss, and sulphur dioxide can contribute to acidification which can harm sensitive ecosystems.

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 recognised example of successful emission reduction is in SO_2. Due to abatement measures in power plants and desulphurisation of fuels, the atmospheric SO_2 concentration in European Union countries has declined by around 70% between 2000 and 2017[2] based on aggregated observations.

The strong emissions reductions in some sectors have inevitably shifted the focus to other sources with lower contributions, such as shipping for which the relative emissions contributions have a growing significance in terms of further reducing air pollutant concentrations.[3,4]

In this study, insights are gained with respect to the influence of shipping emissions on air quality in Europe and in major ports and cities. Using the chemical transport model (CTM) LOTOS-EUROS and its source apportionment capabilities, the contribution of international and inland shipping emissions to atmospheric air pollutant concentrations in 19 European port cities is computed and put into context compared to the relative contribution of other sources.

The methodology used in the study is described in the following section, which provides details about the model and the data that are used as input to perform the simulations of the atmospheric concentrations. The results of the study are presented on pages 8–13. The CTM provides labelled atmospheric concentrations over the simulation domain. Using the simulation results, the contributions of various sectors to air quality in port cities of interest are computed. The main findings are presented in the final section of this article.

Methods

Model description

LOTOS-EUROS is a 3-D chemical transport model developed by TNO. The offline Eulerian grid model simulates air pollution concentrations in the lower troposphere, solving the advection-diffusion equation on a regular latitude-longitude grid with a variable resolution over Europe.[5]

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, excluding the stacked boundary layers on top, extends to 5 km above sea level. The height of the layers on top of the 25-metre surface layer is determined by heights in the meteorological input data.

Gas-phase chemistry is simulated using the TNO CBM-IV scheme, which is a condensed version of the original scheme.[6] The LOTOS-EUROS model 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).[7] For aerosol chemistry the thermodynamic equilibrium module ISORROPIA II is used.[8] Dry deposition fluxes are calculated using the resistance approach as implemented in the DEPAC (DEPosition of Acidifying Compounds) module.[9] Furthermore, a compensation point approach for ammonia is included in the dry deposition module.[10] The wet deposition module accounts for droplet saturation following.[11]

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 peer-reviewed publications.[12,13,14]

Source apportionment

TNO has also developed a system to track the impact of emission categories within a LOTOS-EUROS simulation based on a labelling technique.[15] 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 used extensively in previous studies.[14,16,17]

As well as calculating the total concentrations of each pollutant, 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 oxidised) or S atom, as these are conserved and traceable.

Emissions and meteorology

The LOTOS-EUROS model is run with ECMWF ERA5 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. Examples of typical inputs required by LOTOS-EUROS include surface and air temperature, cloud cover, wind speed and direction, precipitation and relative humidity.

Quality-assured monthly updates of ERA5 (1959 to present) are published within three months of real time and are available through the Climate Data Store.[1] Preliminary daily updates of the dataset are available to users within five days of real time.

The CAMS-REG emission inventory data for the year 2018, version 5.1 REF2,[18] was used in this study for anthropogenic trace gas emissions. At the time of performing the study, this was the latest available dataset (an update with more recent data was published in December 2023). The inventory uses the official emissions data reported by European countries. However, for international shipping, the dataset is replaced with emissions from the Finnish Meteorological Institute (FMI) STEAM model.[19] Additional information that explains the choice of using the STEAM model to create the shipping emission inventory instead of using the officially reported European emissions data is provided below.

The importance of the emission inventory

As mentioned above, the CAMS-REG emission inventory data for the year 2018, version 5.1 REF2,[18] is used in the air quality calculations as the latest available dataset. Generally, the CAMS-REG emissions datasets are based on the officially reported emissions from the EU Member States.

To ensure robustness in the air quality calculations, it is necessary that the emissions of all sources are geographically distributed in an accurate way. However, according to reporting conventions[20] the inventory totals as reported by countries do not contain all shipping emissions (and they are not geographically 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 a so-called memo item, 'International maritime navigation'.[21] 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 geographically referenced). In addition, the methodology used to calculate and report 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 differentiate between 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 it is not possible to calculate the split between inland and maritime use.

In order to overcome these inconsistencies and increase the accuracy of the emissions dataset used, 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.[19] This model is based on actual ship movements as registered by the Automatic Identification System (AIS) data and, moreover, they are geographically 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 are complemented by the spatial distribution of the emissions as calculated by the STEAM model.

[1] https://cds.climate.copernicus.eu/#!/home

Model set-up

Figure 1 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 conditions 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), covering the following ports that were studied in more detail:

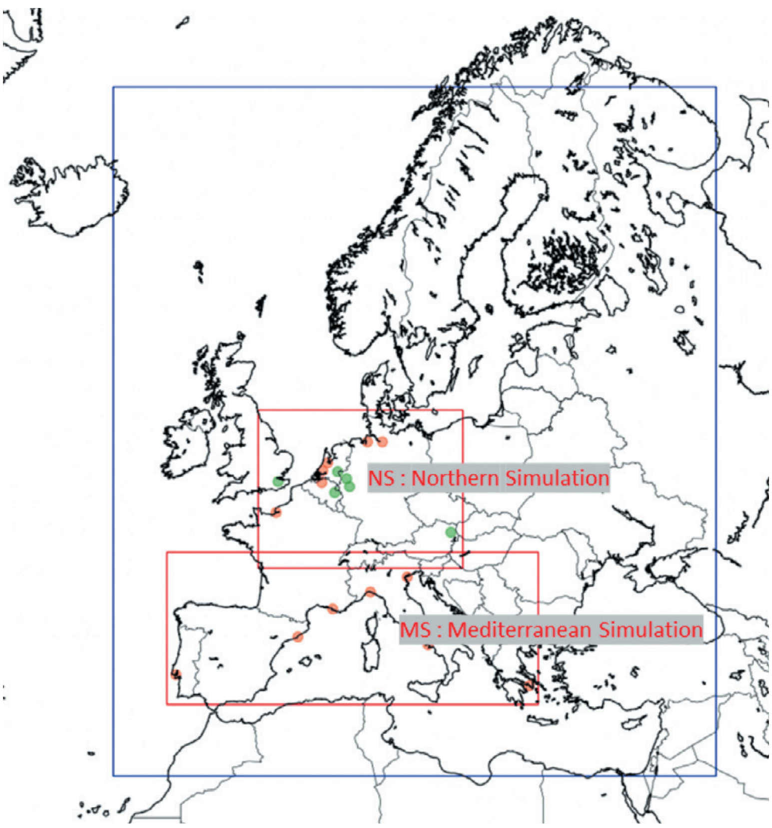
Seaports:

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)

Inland ports:

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

Figure 1: Display of the simulation set-up domains: the port/cities of interest are displayed as dots on the map (orange for seaports and green for inland ports)



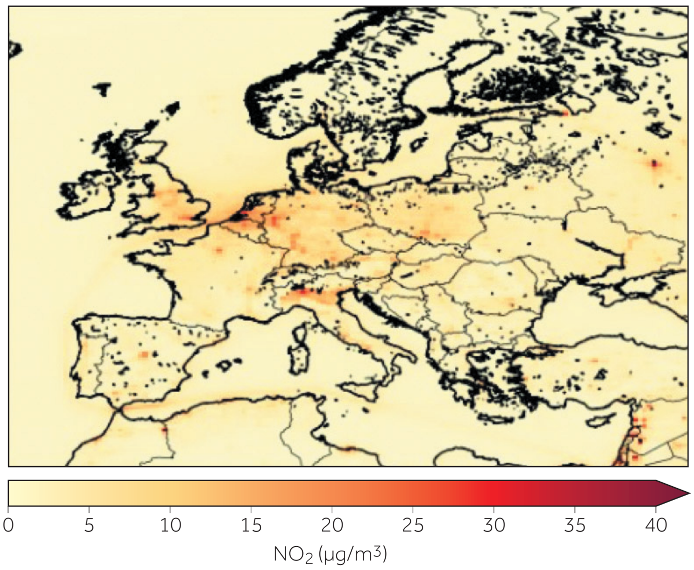
Results

Contribution of shipping emissions to air quality in Europe

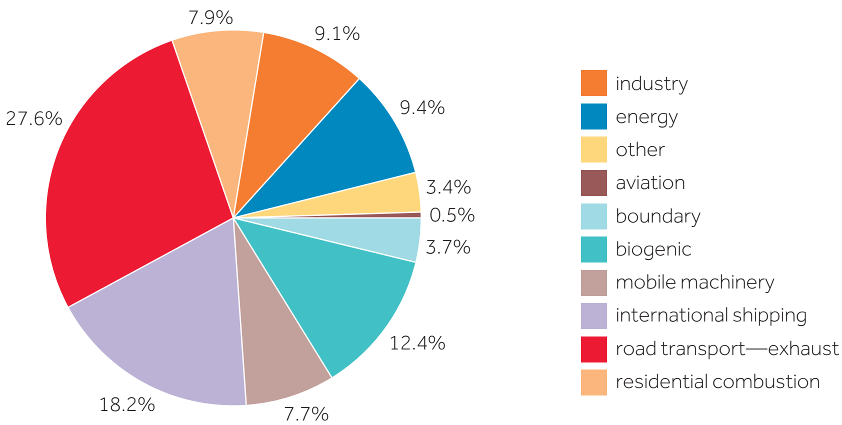
Figure 2 shows the predicted annual average surface concentration of NO_2 in 2018 for the European domain, together with the source apportionment results of the whole domain. High NO_2 concentration values are calculated in the central part of Europe (Benelux, Germany, UK) and in the Po Valley (north of Italy) with the biggest contributions, on average over Europe, being attributed to road transport (exhaust) and international shipping. The relative contribution of inland shipping is < 0.5% which is a small contribution in the European domain.

Figure 2: The annual average NO_2 surface concentration for 2018 in the simulation domain of the coarse (25 x 25 km) resolution LOTOS-EUROS simulation (a), and the relative contributions from the various labelled sectors to the surface concentration of NO_2 for the entire simulation domain (b)

a) Annual average NO_2 concentration in Europe

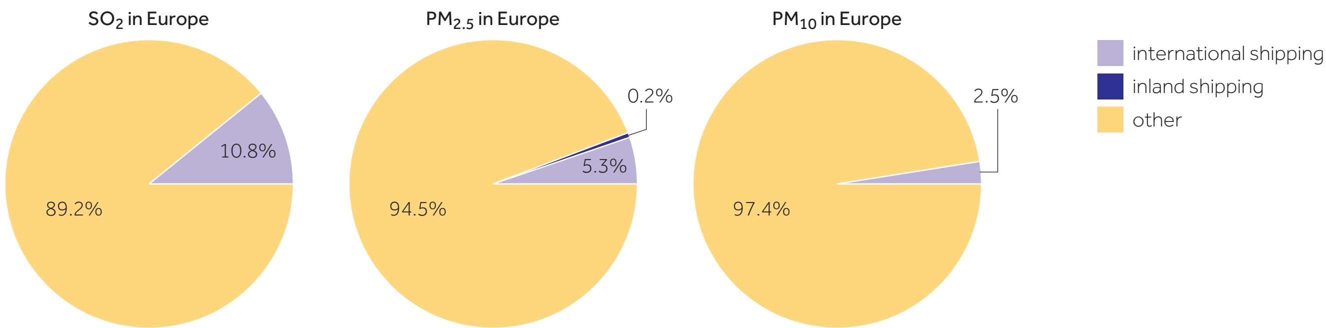


b) Contributions of the various labelled sectors to NO_2 in Europe



For the remaining pollutants examined in the study, the predicted contribution of shipping emissions compared to other sectors is shown in Figure 3. It is evident from the results that shipping has the largest relative contribution for NO_2 compared to other pollutants (Figures 2, 3). For SO_2 the contribution from international shipping is still significant (11%), while for PM the shipping contribution is somewhat smaller. In addition, inland shipping is predicted to be a negligible contributor to atmospheric pollutant concentrations on average in Europe.

Figure 3: The predicted relative contribution from international and inland shipping to SO_2, $PM_{2.5}$ and PM_{10} (annual average surface concentrations over Europe in 2018)



Contribution of shipping emissions for each port

Because the highest contribution of shipping is found for NO_2, the results of the calculated shipping contribution to NO_2 levels near the ports are presented and discussed here in more detail. Illustrative examples are used for three cases:

a) a port located near to the city centre (i.e. Piraeus);

b) a port located close to the city (i.e. Antwerp, ~10 km distance); and

c) a port located far from the city (i.e. Rotterdam, ~30 km distance).

Detailed results for all ports and pollutants can be found in the appendix of the full Concawe report of this study.[22] 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 on Figures 4 to 6. For these locations of interest, the concentration fields were calculated as a weighted average of the four nearest grid points in the simulation domain (inversely with distance from the grid point to the coordinates of the location of interest).

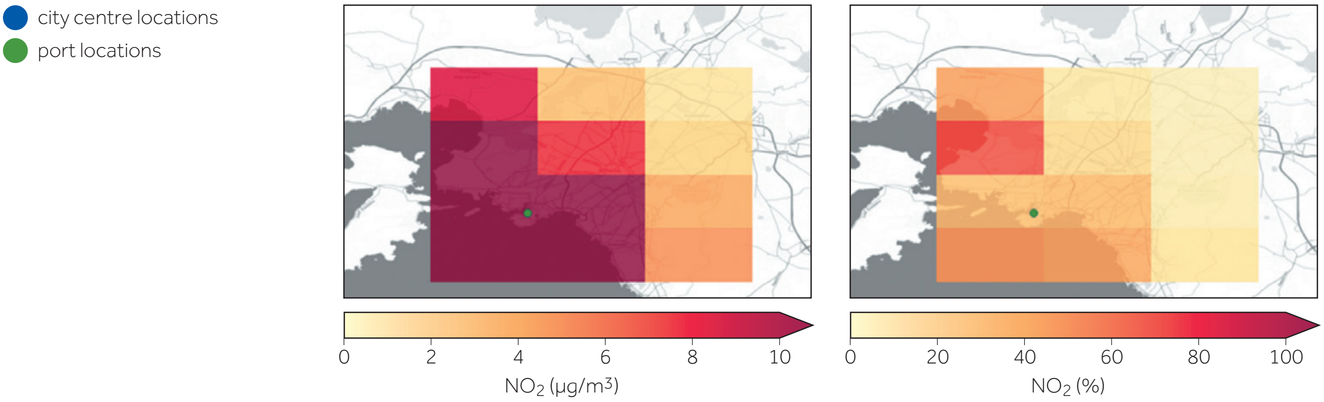
Piraeus

Figure 4 shows the absolute and relative contribution of international shipping to NO_2 annual average surface concentrations. The upper left portion of the figure shows that the absolute contribution of international shipping exceeds 5 μg/m^3 in most of the surrounding areas, and can reach up to 10 μg/m^3 or higher at the seaport. The port is located at the city centre, which causes the green and blue dots 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, and is the dominant source closely followed by exhaust emissions from the road transport sector.

Figure 4: The calculated absolute contributions (a) and relative contributions (b) of international shipping to the annual average surface NO_2 concentration in Piraeus in 2018. The pie charts show the relative contributions of various sectors to the NO_2 concentrations in the city centre (c) and the port (d) — these are the same because the port is essentially located at the city centre.*

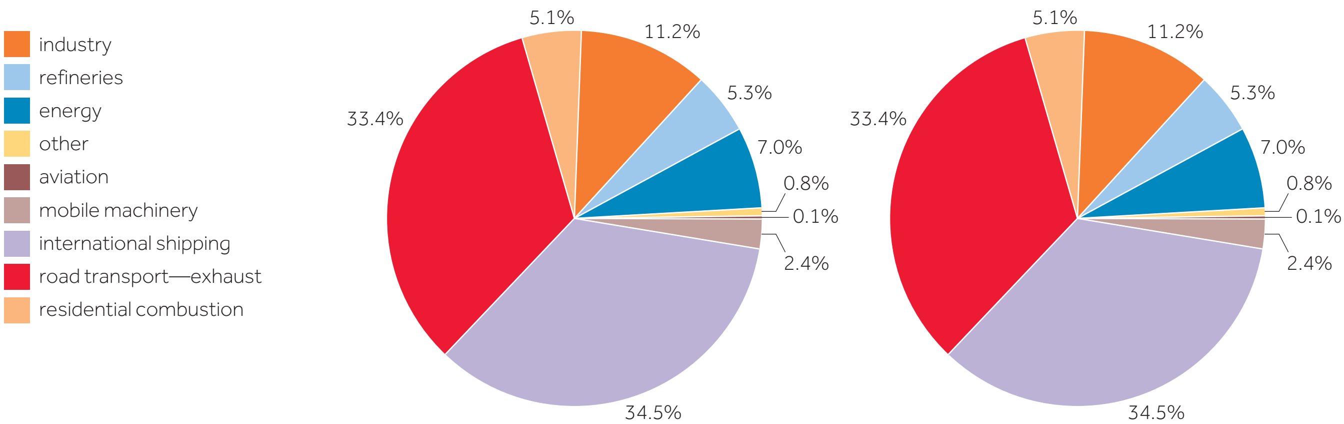
a) Absolute contributions of international shipping to NO_2 concentrations in Piraeus

b) Relative contributions of international shipping to NO_2 concentrations in Piraeus



c) Relative contributions of various sectors to NO_2 concentrations in the city centre*

d) Relative contributions of various sectors to NO_2 concentrations in the port*



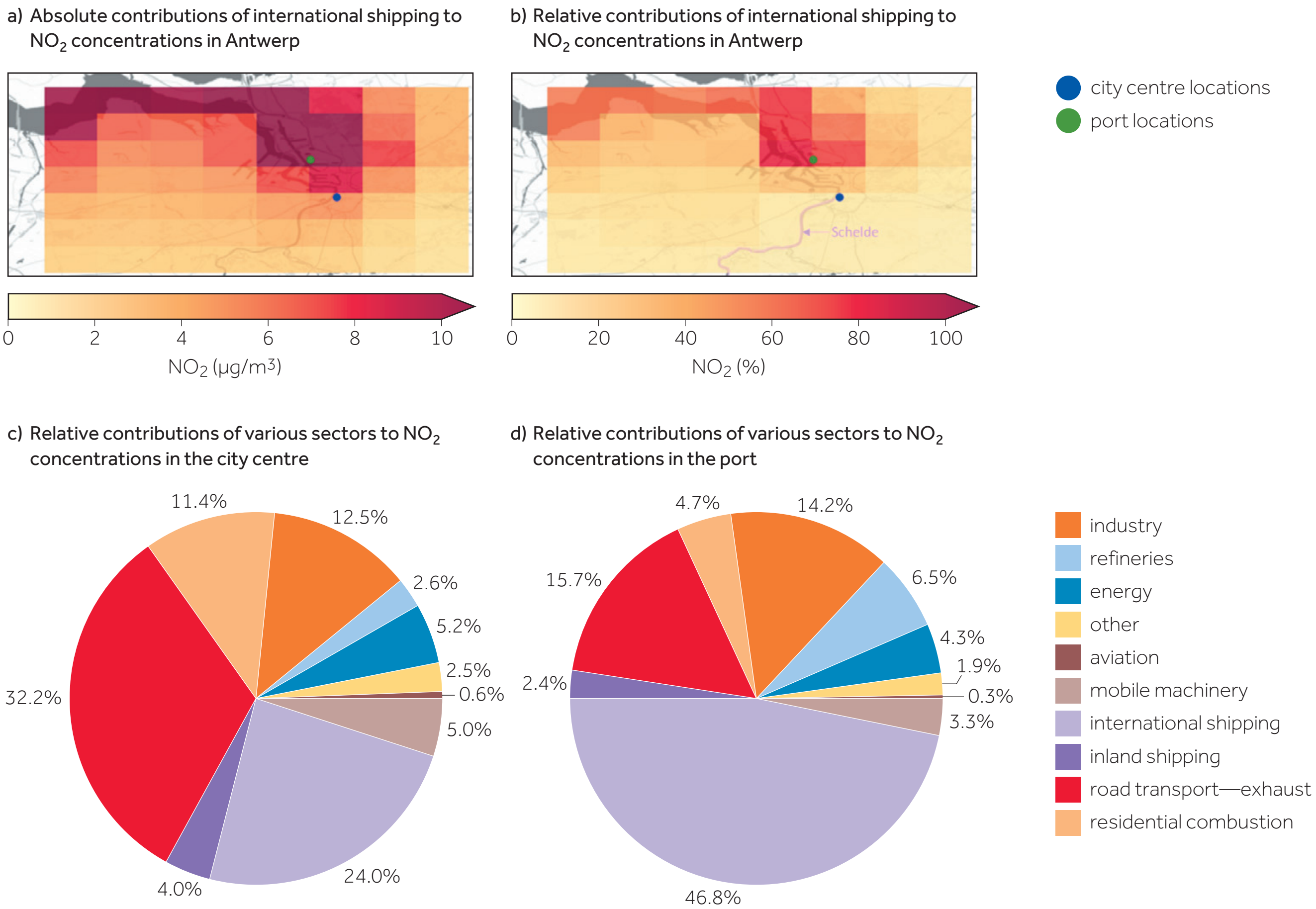
Note: Inland shipping is not shown in the pie charts as there is no contribution from this sector around Piraeus.

Antwerp

Antwerp is by far the biggest Belgian (sea) port, 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.

Figure 5 shows the contribution of international shipping to the NO_2 concentration in Antwerp. The absolute contribution of international shipping at the port of Antwerp (green dot) located at the delta of the Scheldt River is 16 µg/m^3 (47%). The relative contribution from international shipping to NO_2 concentration can go up to 70% following the Scheldt River further downstream. The NO_2 concentration in the ports assessed is predicted to also receive contributions from emissions from ships at berth in the ports. This also influences the air quality in the 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 5: The calculated absolute contributions (a) and relative contributions (b) of international shipping to the annual average surface NO_2 concentration in Antwerp in 2018. The pie charts show the relative contributions of various sectors to the NO_2 concentrations in the city centre (c) and the port (d).

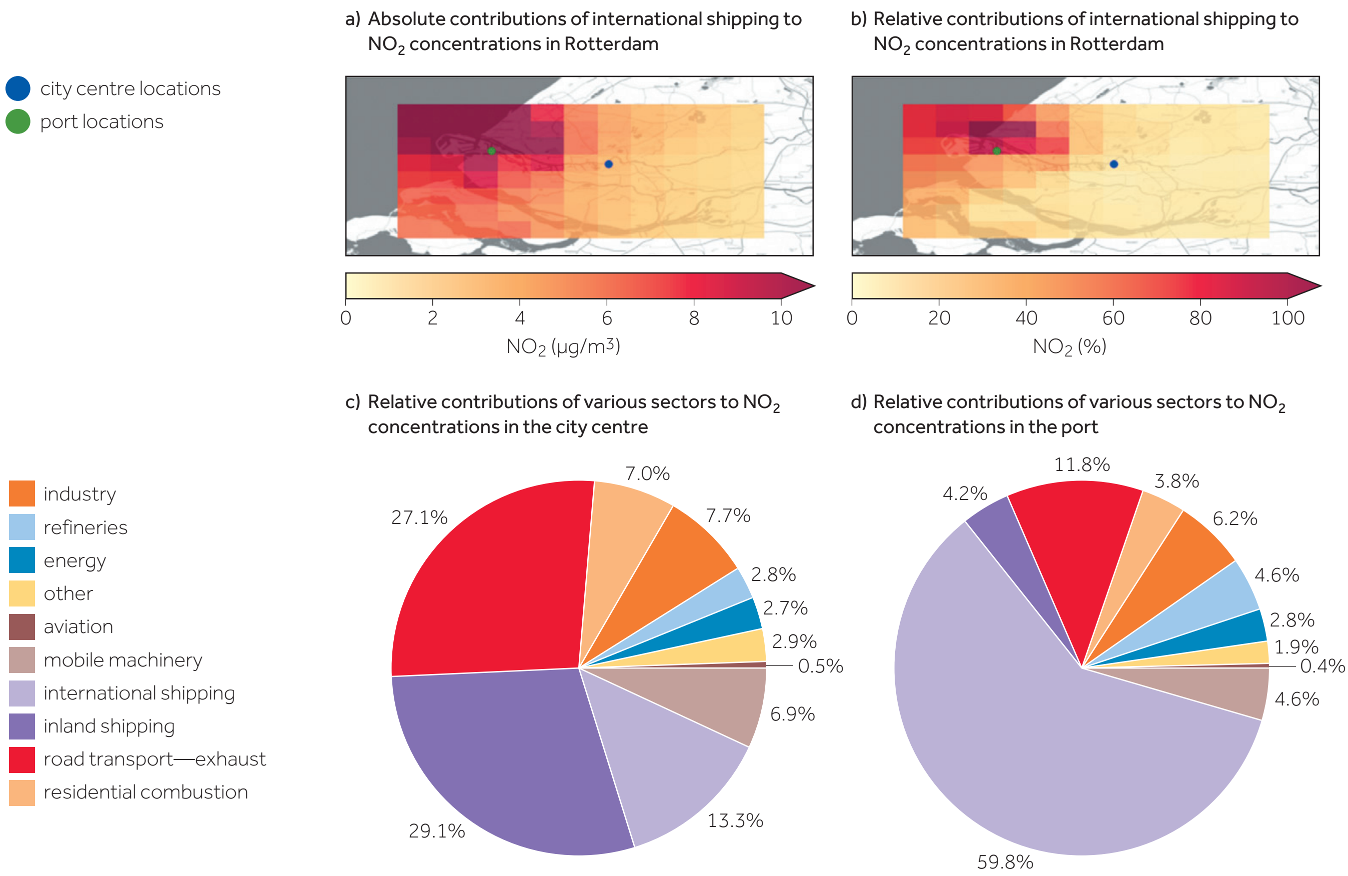


Rotterdam

The distribution of the contribution of international shipping to the annual average NO_2 surface concentration in the Rotterdam area for 2018 is shown in Figure 6. The pie charts show 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 µg/m^3 (60%) at the port entrance at sea (green dot), while even at 35 km to the north, in the centre of Rotterdam (blue dot), contributions of 3.7 µg/m^3 (13%) are found. The absolute contribution, however, decreases between the port and the city centre due to dilution upon transport and the lifetime of NO_2 (the distance between the port and the city is approximately 30 km). In contrast, the absolute contribution from inland shipping is larger in the city centre 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 centre before exhaust emissions from the road transport sector.

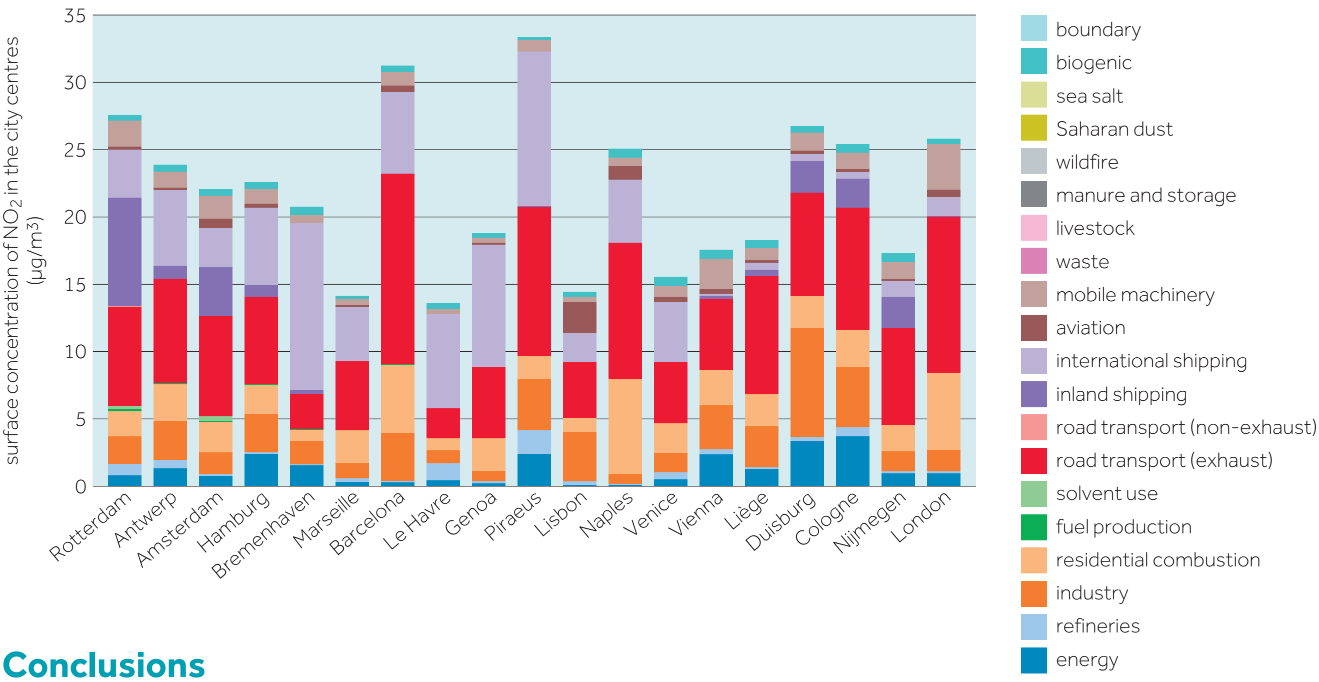
Figure 6: The calculated absolute contributions (a) and relative contributions (b) of international shipping to the annual average surface NO_2 concentration in Rotterdam in 2018. The pie charts show the relative contributions of various sectors to the NO_2 concentrations in the city centre (c) and the port (d).



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.

An overview of the absolute contributions from the labelled sectors to the centre locations of all cities examined in this study is given in Figure 7.

Figure 7: The predicted absolute contributions from the various labelled sectors to the annual average surface NO_2 concentration in 2018 for the city centres of the port cities of interest



Conclusions

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. The main findings from the study are summarised below:

- International shipping contributes significantly to NO_2 concentrations in Europe (18% on average).
- The contribution of shipping to other species is lower but still noteworthy (11% for SO_2, 2.5–5% for $PM_{2.5}/PM_{10}$).
- Locally in the seaports, the contribution of international shipping to NO_2 concentrations is higher and reaches up to 60% (Rotterdam).
- The contribution to NO_2 remains significant in all cities located near to the seaports, while in several cases, international shipping can be the dominant source (e.g. Piraeus, Hamburg).
- On average over the cities examined, the relative contribution from international shipping is 22%, whereas if only the seaport locations are considered, the contribution is higher with an average of 28%.
- Inland shipping generally has a low influence (0–4%) on NO_2, with only a few exceptions (Rotterdam, Amsterdam).

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