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VERIFYING SHIPPING EMISSIONS BY COMPARING MODELLED AND MEASURED SULPHUR DIOXIDE CONCENTRATIONS IN THE PORT OF ROTTERDAM AREA

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Abstract: Shipping emissions are notoriously uncertain due to the high variability of engines, engine ages and maintenance situations and fuel types. In the port of Rotterdam area shipping is a substantial source and less understood than other dominant sources such as industrial and traffic. Furthermore, where other sectors are foreseen to reduce emissions, shipping was expected to rise due to increasing world trade a slow technology development in the sector (though the latter is about to change under influence of proposed IMO regulation). To study the shipping emission we look at SO_2. Contrary to NO_x or PM, shipping is the main SO_2 source in addition to a few stationary sources (refineries, power plants).
In a previous study we modelled all sources and analysed the modelled and measured pollution roses. The gap between measured and modelled concentrations indicated that SO_2 emissions were underestimated. By looking at the pollution roses, shipping and mainly ships at berth were identified as the probable cause. Recently the emission inventory was updated, leading to considerable spatial shifts in emissions. The new emission inventory is based on actual measurements of the position and speed of individual ships with a high spatial and temporal resolution. The absolute level of the emissions didn't change substantially. In this study we repeat the analysis with the new emission inventory. We compare measured and modelled pollution roses to see if the current inventory adequately describes the spatial pattern of the emissions. In addition we use linear regression to assess whether the modelled (daily averages) fields for shipping, industry correctly describe the observed variation on a number of monitoring sites.
Combining the pollution rose analysis and the regression technique improves the assessment of the current emission inventory.

Key words: *Shipping emissions, SO_2, reverse modelling.*

INTRODUCTION

SO_2 emissions and concentrations

SO_2 concentrations have declined spectacularly in the Rotterdam port industrial area over the past 40 years. This was mainly due to dramatic emission reductions in stationary sources (refineries, power plants) and the introduction of low sulphur fuels. The SO_2 emissions from seagoing ships where rising due to rather stagnating engine and fuel technology in that sector, in combination with growing world trade. This makes shipping an important (and the only growing) source of SO_2 in coastal areas and ports. The introduction of the so-called sulphur emission control areas (SECA) by the international maritime Organisation and the EU in 2007 slowed this emissions increase as the sulphur content of fuel was limited to 1.5%. The proposal to reduce S-content in fuel to 0.1% by 2015 should result in a further reduction of SO_2 levels. Current concentrations in the Rijnmond area are around 10 μgm^{-3} and pose no environmental problems. The regional SO_2 monitoring network that once comprised over 30 monitoring stations has now been scaled back to 8 sites. SO_2 is a known precursor for secondary inorganic aerosol. Test simulations with a chemical transport model indicate that reductions of the current SO_2 would decrease the $PM_{2.5}$ concentrations in the port area with 0.1 μgm^{-3} only (Weijers pc.). As such the SO_2 concentrations are of minor concern. However shipping is a source of concern and we use SO_2 as an indicator to analyse shipping emissions.

Emission uncertainties

The Netherlands relies heavily on air quality modelling for its annual air quality reporting obligations to the EU. Modelling is done on a 1x1 km scale by the national assessment agency (see: www.pbl.nl/nl/themasites/gcn/ index.html). Local authorities use these 1x1 km concentrations as background for detailed local modelling of industrial point sources or roads. These two sources categories have attracted considerable attention and research over the past decade. In the port of Rotterdam industrial area the situation is more complex. There are numerous small and big sources and not all of them are well known. Shipping is a substantial source, but one with relatively large uncertainties. The location of the emissions, their magnitude and the dispersion characteristics are poorly known. DCMR, the regional EPA, and national organisations are collaborating to improve the knowledge of this important source. Detailed modelling of shipping emissions in the port of Rotterdam area started in 2002 with the Urbis model. Elshout *et al.* (2005) concluded that shipping was responsible for some 30% of the regional NO_x emissions and for concentration contributions up to 60% of NO_2 (depending on the location). In this paper we briefly describe recent developments in describing the shipping emissions and, in particular, we present a modelling study that was done to assess how well the current emissions describe the monitored SO_2 concentrations.

Improving the assessment of shipping related air pollution

The improvement in the assessment of the impact from shipping was approached from different angles:

- Duyzer *et al.*, (2006) used shore-based measurements to evaluate the emission factors of ships entering the port of Rotterdam. The emission factors in use for NO_x were correct and those for PM_{10} were found to be slightly too high.
- Hulskotte and Dernier van der Gon (2010) improved emission estimates for ships at berth.
- Tak and Hulskotte (2008) used ships' transponder data to identify the exact place of the emissions, and derive other emission characteristics e.g. type, actual speed, engine, age, etc. Emissions are directly proportional to speed so this study improved the emission assessment. This study confirmed that the spatial distribution of the emissions had become outdated over the years. The port activity had mainly grown in the western, deepwater, part and had (relatively) decreased in the more inland part of the port. Figure 1 shows an example of the differences in modelled NO_2 concentrations using the old and the new emissions database.

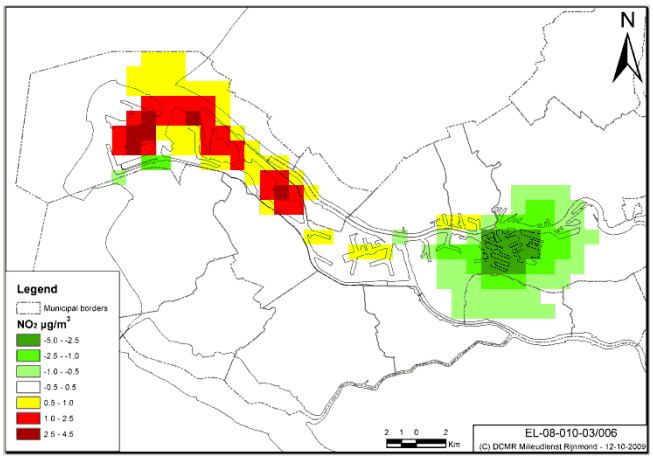

Figure 1. Influence of updated shipping emission inventory on NO_2 concentrations

Though advances in the emission inventory contribute to a better assessment of the impact of shipping, the knowledge on how to model the dispersion of shipping emissions also remains inconclusive. DCMR evaluated the approaches in use and found substantial differences in the results. This has led to a national working group that is currently making recommendations on how to model shipping emissions for regulatory purposes in the Netherlands.

Aardenne *et al.* (2002) compared model calculations and measurements to assess the accuracy of emission inventories. De Gier *et al.* (2008) compared wind direction dependent measured and modelled SO_2 concentrations in the port of Rotterdam and observed substantial deviations. From the pollution roses they concluded that the emissions of ships at berth were probably underestimated. With the new information that has become available we decided to verify if the emission update better described the observed measurements. Denby (2007) describes linear regression as a basic data-assimilation tool that removes model bias. Laupsa *et al.* (2009) apply multiple linear regression (MLR) in a source apportionment study. Similarly we apply an MLR to estimate to what extent the modelled concentration fields (daily averages) of the source categories (shipping, point sources) describe the measured daily average concentrations.

METHODOLOGY

Monitoring stations

In this study the data of six monitoring stations of DCMR EPA in the Port of Rotterdam area are used. Four of them are located on the north bank of the river, and two of them on the south bank. Data from two background monitoring stations of the National Air Quality Monitoring Network are used as well. See Table 1 and figure 2.

Table 1. Characterisation of monitoring stations

Name	**Type**	**SO_2 sources with substantial impact on SO_2 concentrations**
Botlek	Harbour	Located on major shipping routes; 800 m northeast of harbour Botlek: refineries and ships; 400 m north of 3e Petroleumhaven: refineries and ships
Hoek van Holland	Shipping and background	East of the entrance of Port of Rotterdam; 5 km east of the Maasvlakte harbour, the harbour where the largest ships arrive.
Maassluis	Urban background	240 meters northeast of major shipping route; 2.3 km northeast of harbour 7e Petroleumhaven: ships
Pernis	Urban background	1 km east of harbour: ships and refinery; south and west of shipping route and harbour
Schiedam	Urban background	2.5 km north of major shipping route; 2.0 km north and northeast of harbours
Vlaardingen	Urban background	630 m northwest of major shipping route; 1.3 km north west of 1e and 2e Petroleumhaven: refinery and ships
Schipluiden	Background	About 11 km north of the Port of Rotterdam area.
Westmaas	Background	About 14 km southeast of the Port of Rotterdam area

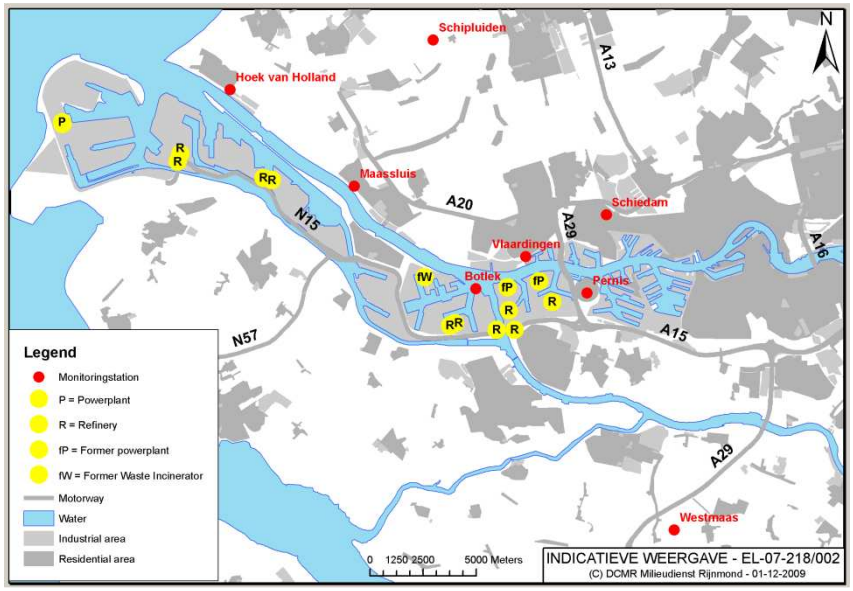

Figure 2. Location map monitoring sites and SO_2 point sources

Sources

In the previous study (De Gier *et al.*, 2008) we modelled several source categories individually and observed a large gap between measured and modelled concentrations ranging from 25 to 55% of the measured concentration. An analysis of the wind directions with the greatest differences pointed to ships at berth. In Table 2 we summarize the results but this time we use shipping concentrations based on the improved emission inventory. The gap is still large (between 32 to 47%) but the variation is smaller, indicating an improved geographic distribution of the emissions.

The two background sites (bottom part of the table) show that there is a difference in the background concentrations, with the northern site being higher than the southern one. With dominant winds from the south-west this is again an indication that the local sources are underestimated, or (less likely), that there are unknown sources in the port-industrial area. Apparently 1.2 μgm^{-3} is the true background concentration once we correct for local influences. In this study we therefore focus on shipping and local industrial point sources and treat the rest as background.

Table 2.Year average results of the first modelling study (de Gier *et al*., 2008); shipping data based on the 2008 and the current study.

	Modelled SO_2 concentrations 2005 (μgm^{-3})					SO_2 concentrations 2005 (μgm^{-3})			
Monitoring site	local point sources	other sources	ships at berth new	sailing ships new	sum all known sources new	measured	back-ground	sum of sources + background	Gap measured - modelled
Botlek	2.5	1.6	2.9	1.6	8.5	17.0		9.7	7.3
H. van Holland	1.5	1.6	2.5	2.7	8.3	14.0		9.5	4.5
Maassluis	1.2	1.4	1.9	1.8	6.3	13.0		7.5	5.5
Pernis	2.0	1.5	2.1	1.1	6.7	12.0		7.9	4.1
Schiedam	2.1	1.4	1.7	0.9	6.2	14.0		7.4	6.6
Vlaardingen	2.5	1.4	2.1	1.4	7.4	15.0		8.6	6.4
Background sites:									
Schipluiden (N)	1.1	1.5	0.9	0.9	4.4	7.3	2.9	5.6	1.7
Westmaas (S)	0.5	1.8	0.5	0.3	3.1	4.3	1.2		

Dispersion models

STACKS (Erbrink, 1995) was used to model the industrial point sources and the shipping emissions (treated as point sources in a 100 x100m grid). We used a custom version capable of producing hourly output of relevant parameters and concentrations. The meteorology used was obtained from Rotterdam Airport. Since the study area is close to the sea, this meteorological dataset might not be correct for the whole area: wind speeds tend to be higher near the coast (this would have resulted in even lower calculated concentrations in H. van Holland).

In the previous study shipping emissions were modelled using generic information on stack height and heat capacity. With the use of the transponder data based emission database (Tak and Hulskotte, 2008) information about the ship type and engine was available. This way the heat capacity could be differentiated in different areas of the port, leading to a further improvement of the modelling. The use of individual ship emissions (> 2 million records) was not possible so the data were clustered into six classes based upon size and type of ship to estimate the heat capacity per class.

Table 3. Heat capacity per ship class (type and Gross Tonnage) main engines

Size	Type	Exhaust heat capacity sailing (MW)	Exhaust heat capacity manoeuvring (MW)
< 10000GT	Oil tanker, other tanker, bulk carrier	0.466	0.185
> 10000GT	Oil tanker, other tanker, bulk carrier	1.094	0.621
< 10000GT	Container ship, general cargo	0.551	0.196
> 10000GT	Container ship	2.785	2.902
< 10000GT	Roro, reefer, ferry, other	0.184	0.092
> 10000GT	Roro, reefer, ferry, other	1.025	0.541

Generally the heat output for manoeuvring is lower than for sailing. This is not always the case as some ships use the service of tugboats. The heat capacity for ships at berth was derived from the fuel use. The stack height was estimated at 25 m (same as used in the previous study) and was not differentiated per type. The Total SO_2 emissions in both studies were 1797, 467 and 3204 ton per year for sailing, manoeuvring and ships at berth respectively.

RESULTS

The measured pollution roses corrected for the influence of stationary sources pointed to port areas as sources of SO_2. See figure 3. The corrected line (black) points towards harbour areas with ships at berth. In the graphs the influence of the refinery (east of Pernis, and southeast of Schiedam) is removed from the measured pollution rose (red). Hence our attention to shipping, and in particular to ships at berth. If we subtract the modelled shipping contributions and the industrial contributions from the measured concentrations we obtain a residual concentration that has virtually the same shape as the pollution rose including the shipping but without the point sources (blue line). This is particularly strong in the Maassluis graph. This further suggests that we could be underestimating the shipping concentrations.

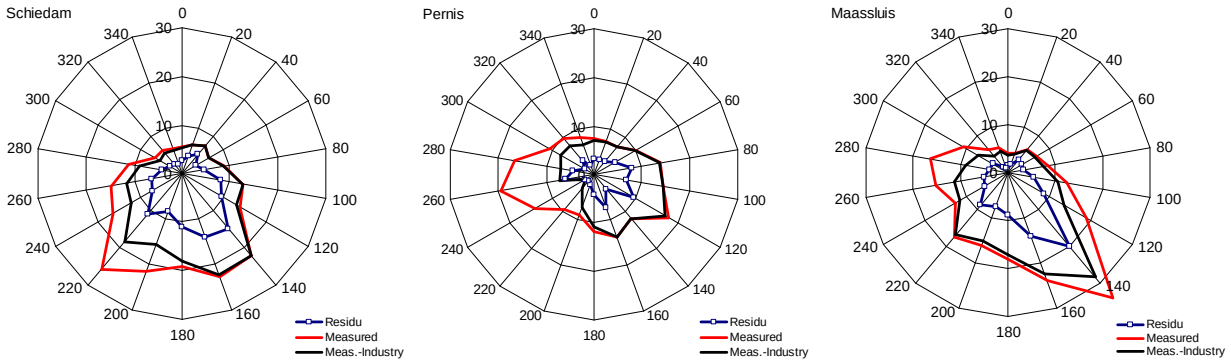

Figure 3. pollution roses showing measured, and residual (measured – modelled) concentration distributions

In the updated emission inventory the regional representation of the emissions improved though the gap between modelled and monitored data remains substantial. Similarly to work by Laupsa *et al.* (2009) and Denby (p.c.) we applied multiple linear regression to see if the modelled fields (daily averages) for ships at birth (SB), manoeuvring ships (MS), sailing ships (SS) and industrial point sources (IP) could explain the unaccounted emissions. A correlation matrix of the modelled shipping concentrations showed high correlations between SB and MS. The correlation coefficient with SB or MS and SS was still 0.5. This lack of independence of the variables makes multiple linear regression complicated, hence a total shipping (TS) variable was defined as well. The correlation between shipping and industry was fortunately very low. Spatially the activities occur side by side in some parts of the port so the pollution roses alone are not the best instrument to analyse the source contributions. The daily averaged concentration gap (C_G) is calculated as the observed concentration at a given point (C) minus the minimum of the two background concentrations at that point (corrected for industrial and shipping contributions in the background). So:

$$C_G = C - C_B \quad \text{and} \quad C_B = \min (C_{BSchip}, C_{BWest}) \tag{1}$$

with

$$C_{BSchip} = C_{Schip} - C_{SchipIP} - C_{SchipTS} \quad \text{and} \quad C_{BWest} = C_{West} - C_{WestIP} - C_{WestTS} \tag{2}$$

The regression model to be fitted is:

$$C_G = \beta 1 + \beta 2 * IP + \beta 3 * (SB+MS) + \beta 4 * (SS) \quad \text{or} \quad C_G = \beta 1 + \beta 2 * IP + \beta 5 * (TS) \tag{3}$$

One could argue whether an intercept ($\beta 1 \neq 0$) is justified. This assumes that there could be other unknown sources that explain part of the concentration gap. We tried models both with and without an intercept. The results are shown below. The models with intercept opt for a very high intercept and low regression coefficients as industry and shipping have only small explanatory relevance. See table 4. presenting the regression results.

Separating sailing ships and ships at berth, results in a negative coefficient for sailing ships. This is impossible and due to the strong correlation between the shipping variables. If the regression is forced with a zero intercept, the regression model indicates that the industrial sources are approximately correct and that the shipping emissions are underestimated. Again it was not possible to separate ships at berth from sailing ships: the regression coefficient for sailing ships in the third model is too low to be trustworthy.

Table 4. Regression results of models in equation 3.

Model \ coefficients	β1	β2	β3	β4	β5	RMSE
Intercept	6.3	0.8	1.5	-0.9		9.1
	6.3	0.9			0.7	9.2
No intercept	0	1.1	2.5	0.1		9.7
	0	1.2			1.7	9.8

CONCLUSIONS

We studied SO_2 concentrations in the port of Rotterdam area to verify if shipping emissions are accurately estimated. As there are few sources of SO_2 this is much easier than analyzing NO_x or PM_{10} emissions related to shipping. A 2008 study suggested that ships at berth could be responsible for the gap between measured and modelled concentrations. We repeated the analysis using a much more detailed emission inventory. Though this narrowed the gap a bit and reduced the spatial variation of the deviations, a considerable gap remained. Linear regression and the pollution roses both suggest that this is shipping related. The results are not clear enough to differentiate between ships at berth and sailing ships.

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