

A case-study for the investigation of inland ship emissions in real world plume dilution at the Rhine river in Duesseldorf, Germany

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Abstract: In this case-study we used several measurement techniques to measure and investigate single exhaust plumes from ships passing by with a measurement truck standing on a plateau on the northern banks of the Rhine river near to the city of Duesseldorf, North-Rhine-Westphalia. We used a combination of an optical particle counter and a scanning mobility particle sizer to analyze the particle spectra in a size range from 5 nm up to 32 µm. Moreover, we used an aethalometer to investigate the proportion of soot in the particle spectra. Additionally, gaseous combustion species like nitrogen- and sulphur dioxide were measured. The data show a specific pollution characteristic for an individual ship. It could be found that the proportion of the pollutants in the exhaust plume vary for each ship. This effect is more dominated due to the engine load under which the ships are currently running than the type of ship or motor power.

Key-Words: inland ship emission, ultrafine particles, black carbon, sulphur dioxide, nitrogen dioxide

1 Introduction

Over the past decade air pollution in Germany is decreasing due to the use of modern techniques in emission control but is still a major problem in urban areas and bigger cities. Traffic is one of the major producers for air pollutants like fine particulate matter and ultrafine particles, nitrogen-, sulphur- and carbon dioxides and species from an incomplete combustion as unburnt hydrocarbons and soot. The main content of traffic emissions comes from road traffic, but also rail-, air traffic as well as shipping traffic play a role as polluters.

The amount of the inland water transport is stable over the last years. Due to the European Commission in order to increase the resource efficient transport system for achieving 60 % of greenhouse gas emissions, for transport distances greater than 300 km, more freight will be carried by rail or waterborne transportation, which will enhance the role of the inland water transportation as a polluter [1].

However, the International Maritime Organization (IMO) released the International Convention for the Prevention of Pollution from Ships (MARPOL) with the Annex VI from 19 May 2005 to set limits on sulphur dioxide and nitrogen oxide emissions from ship exhausts as well as to reduce the greenhouse gas emissions from ships by the use of technical and operational energy efficiency measures. Further-

more, so called Emission Control Areas (ECA) were accomplished in the coastal areas with more stringent emission standards.

The inland ships on German waterways run under the law of the Binnenschiffs-Abgasemissionsverordnung (BinSchAbgasV) based on the 2004/26/EG for the implementation of measures to reduce gaseous and particulate emissions from combustion motors for mobile machines. In the BinSchAbgasV [2] thresholds are given. Another approach is the use of alternative biogenic fuels [3] as well as to use further refined fuels with for e.g. a maximum sulphur content (§4, 10.BImSchV,2010) [4].

Also the operation of modern end of pipe exhaust gas treatments like e.g. the Selective Catalytic Reduction (SCR) investigated by Hallquist et al., 2012 [5] have a positive impact. In the context of the European research project – Clean Inland Shipping (CLINSH) - a fleet of 15 inland ships will be equipped with different emission-reducing-techniques or alternative fuels to investigate these measures.

Many studies have been performed in the past which describe in detail the kind and influence from ship emissions. Different engine studies on test rigs have been done for 2 and 4 stroke marine diesel engines [3,6,7,8] with a focus on the load depending emission. Other studies characterize shipping emission from maritime ships on sea, in coastal and harbor regions [3, 9, 10, 11]. Some studies have a look at the

impact from inland ship emissions [12,13,14,15]. Jonsson et al., [10] measured the exhaust plumes on maritime ships from a research vessel. Sinha et al. and Petzold et al. [16,17] did airborne measurements of the expanding ship plumes in the maritime boundary layer. Moreover, the influence of stationary parking ships was investigated by Vogel et al. [18].

In this case study we have a look at the role from the inland shipping emissions at the Rhine river in Duesseldorf, North-Rhine-Westphalia, Germany. Therefore, we use different measurement technique for several pollutants and try to measure and characterize single ship exhaust plumes.

The Rhine is one of the most important and busiest inland waterways in Europe. Round about 80 % of the inland water transportation is shipped via the Rhine. According to the Federal Association of Inland Shipping, the river section next to Duesseldorf has a traffic volume about 200,000 ships a year, which are around 550 ships per day [23].

2 Methods

For the investigations a measurement truck of the HSD was equipped with several measurement devices and meteorological sensors (see section 2.2) and was placed on a bypass road next to the Rhine river.

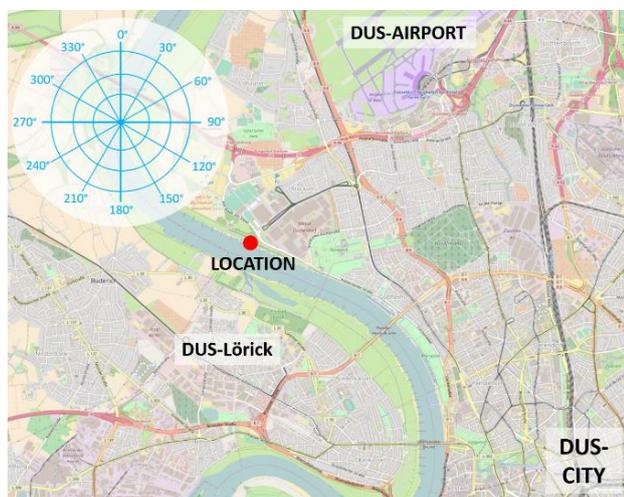


Fig. 1: Map section of Duesseldorf with the measurement site. (Source: Openstreetmaps)

The measurements were executed on days where the wind comes from directions between 120 – 280 °N. It was shown that wind direction from about 200 °N which is orthogonal to the shipping route at this site, are necessary to distinguish between single ship exhaust plumes. Winds from other directions are not further analyzed in detail, because one cannot differ between single ships, so that the plumes from several ships reach the site at the same time. Fig.1 shows a

map section of Duesseldorf. One can see the northern districts with the international Airport (DUS), the inner city in the south and the district Lörrick in the southwest. The measurement site is marked with a red dot and additionally a 360 °N scale is shown.

During the measurements, the time, distance and heading from the bypassing ships were registered. Additionally, a picture from each ship was taken for a better characterization of the ships in detail afterwards. During the measurements an inland ship fleet about 100 ships passed the measurement site. About 55 ships passed during these days with good wind direction, on which we focused in the analysis.

2.1 Measurement Site

Several potential locations were investigated with mobile measurement techniques before, to find an optimal place for the measurement campaign of the exhaust ship emissions from bypassing ships. The chosen measurement site is in the north of the center of Duesseldorf next to the Congress-Center and Duesseldorf Fair at Rhine kilometer 749.

This river section reveals a 3 km straight part, where the measurement site is in the middle of it located. At this site, the broadness of the Rhine is about 330 m. According to the Waterway and Shipping Authority Duisburg, the streaming velocity of the Rhine depends from the water gauge and shape of the Rhine. Here the water flows between 5 and 8 km/h but can reach up to 12 km/h at this part of the Rhine. The measurement site is located directly at the northern bank of the Rhine and offers several opportunities for these kinds of measurements. First, the measurement truck can stand on a plateau from a bypass road, which reaches about 40 m into the Rhine from its bank and therefore ships passing by in only a few ten meters distance. Second, in this part of the Rhine the shipping route from the upstream moving ships are mostly next to the northern banks and therefore next to the measurement site. Third, due to the fact, that we measured only under conditions, when the wind comes from southwest directions, there are no direct emission sources, which can have an impact on the measurements. In the southwestern area from the measurement site there is the district Lörrick, a suburban area, which is embossed as a low population density area with little traffic and almost no industry. The Environmental State Agency NRW (LANUV) operates an official air quality measurement station for the urban background, which is another advantage of this location.

2.2 Measurement Techniques

The truck we used for the investigation is a Mercedes Benz transporter with special platform housing on the back, which is air-conditioned and has a 19-inch rack inside for the measurement devices. Additionally it has a sampling inlet which can be extended about 80 cm above the top of the roof. The sampling inlet leads into the housing where the sampling air is distributed with a manifold to the single devices. Moreover, the truck is equipped with a pylon for the meteorological sensors and can be extended to the height of 7 m over ground. The truck has accumulators to run independently for several hours. On Fig. 2 one can see the truck during the campaign. The measurement techniques are explained in the next subchapter.

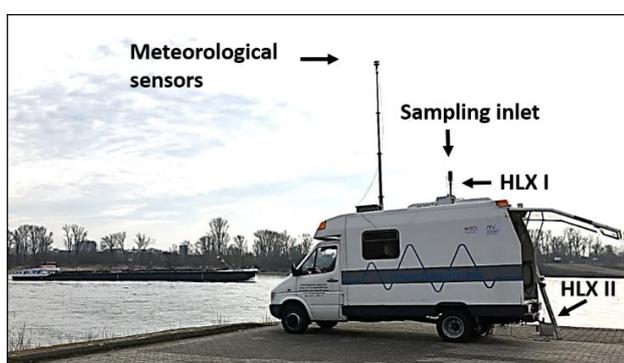


Fig. 2: Truck on measurement site.

2.2.1 Aerosol measurement techniques

For the detection of aerosol we use different techniques. Two Grimm HLX devices which are a combination of an optical particle counter (OPC) and a Faraday-cup aerosol electrometer (FCAE) are positioned on the top of the truck and additionally on the ground. Both Grimm HLX devices have a short and straight radial sampling inlet, so that the sampled aerosols in the coarse mode are not disturbed in the size distribution due to sampling losses in long sampling line. Inside the truck there are a scanning mobility particle sizer (SMPS) with a condensation particle counter (CPC) for the size resolved sampling of nanoparticles and an aethalometer for soot.

The OPC (Grimm Aerosol GmbH, type 1.109) classifies and counts aerosols by measuring the scattered light from single particles and has a time resolution of 6 seconds. The particles are classified according to their sizes in 31 channels from 250 nm up to 32 μm . From the number distribution obtained, the mass concentrations can be calculated. Therefore, a special calibration function is used, which is empirical evaluated for the measurement of environmental and urban aerosols. This kind of OPCs were already frequently used in the past by HSD, see e.g. in [20-22].

The FCAE (Grimm Aerosol GmbH, type NC1.320) detects ultrafine particles with a diameter ranging from 25 nm up to 300 nm by a unipolar diffusion charger with an electric potential and Faraday detector. The time resolution is 10 seconds.

The SMPS (Grimm Aerosol GmbH, type 5420) is a combination of a differential mobility analyzer (DMA, type Vienna) with a condensation particle counter. The DMA uses a high voltage to separate ultrafine particles with a specific diameter, which are counted afterwards with the CPC. With a known transfer function between voltage and particle mobility the device is able to classify particles from 5 nm up to 350 nm in 41 channels. The CPC uses a heated saturator with an oversaturated butanol atmosphere and a cooled condensation chamber. First the particles pass the saturator, where they adsorb some butanol. After that they pass the condensation chamber where the butanol condensates and because of this, the particles grow up by size and can be detected. Depending on the range and number of channels the time resolution is up to 4 min for a single scan over the whole range with 41 channels. One can reduce the range and number of channels to get a higher time resolution. After some premeasurements, we used 10 channels from 10 nm to 140 nm with a time resolution of 1 minute for this study.

The aethalometer (MAGEE Scientific/Aerosol d.o.o., type AE 33) is used for the determination of unburnt hydrocarbons as well as elemental carbon and soot. A defined volume flow is led through a filter tape, where the particles are deposited. Thus the light transmittance of the filter material is decreasing depending on the increasing load of particles. Laser diodes with 7 different wavelengths from 370 nm up to 950 nm are used as a light source for this instrument. Due to wavelength depending light absorption ability of different soot types, one can get additional information about which kind of soot is present. The temporal resolution can be adjusted variably to a minimum of one second.

2.2.2 Gaseous measurement techniques

For the measurement of sulphur dioxide we use a standard UV fluorescence analyzer (Horiba, type APSA-370) The SO_2 molecules are excited by UV radiation and emit light at a particular wavelength when returning to their energetic ground level. The amount of emitted light is proportional to the concentration. The device has a time resolution of 5 seconds. However, it must be said that the response time (t_{90}) of the device is limited constructively to 15 seconds. For the measurement of nitrogen dioxide we use a cavity attenuated phase shift spectrometer (CAPS, Environnement s.a, type AS32M). The air is

lead into an optical cavity cell where an LED produces a square wave modulated light at 425 nm. At presence from NO₂ in the cell the leak of light from the cavity will be modulated, which is a quantity of the concentration. The time resolution is about one second, but the response time (t₉₀) is about 16 seconds.

3 Results

As mentioned before, only the days with wind directions from southwest were analyzed in detail. The following Fig. 3 shows the speed distribution observed from an amount of 1000 ships for the up- and downstream moving velocity in the environment of the measurement site based on the live online position tracking at www.marinetraffic.com.

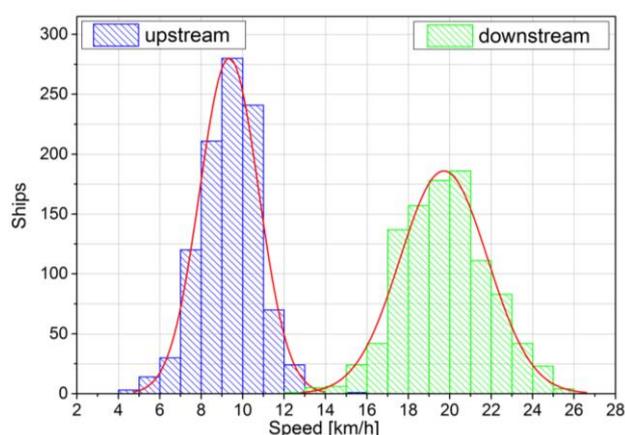


Fig. 3: Speed distribution from passing ships

One can see that the upstream moving ships have an average speed around 9.4 km/h. The downstream moving ships have an average speed around 19.5 km/h. Calculating the relative speed with the average streaming velocity of the Rhine at this site (7.5 km/h), ships have to accelerate to 16.9 km/h upstream and 12 km/h downstream. One can see that the relative speed from the upstream going ships is about 4.9 km/h higher and because of this, the motor load has to be higher respectively. The investigation shows a basic trend, that not all measured pollutants are emitted in an equal way for all the ships. One can classify the emitted pollutants in two categories: To the first category belong pollutants, which are emitted by each single ship like ultrafine particles, nitrogen dioxide and soot (see subsection 3.3). To the second category belong in contrast to that some other pollutants, e.g. particles in the coarse mode described in the mass fractions PM₁₀, which cannot be assigned directly to ship emissions. Particles in the upper accumulation mode can only be observed for a few ships, as well as for sulphur dioxide (subsection 3.4).

3.1 Assignment of the exhaust plumes to a particular ship

In a first step we assign the measured peaks of the ship emissions to a particular ship. With the known distance from a passing by ship in the orthogonal direction to the measurement site, the actual wind speed and direction at this time, one can calculate the theoretical time, when the exhaust plume from a single ship should reach the site. In nearly almost cases, one can clearly differ between the exhaust plumes from single ships. In some cases, even when more than one ship passes or are nearby the site, it is possible, that the plumes are overlapping and reaching the site at the same time. In this case one gets a bulky plume from different ships and therefore it is not possible to assign the plume to a particular ship.

3.2 Data assimilation

For each graph we subtracted the background level with a spline function, so that only the peaks produced by the ship emissions were evaluated. To reduce spikes in the BC data, a 10 second moving average was used. All other data were not modified.

3.3 UFP, BC and NO₂

The following Fig.4 shows the results of a two hour extract of a measurement. During the two hours an amount of 21 ships passed the site. Nine ships are moving downstream and twelve ships are moving upstream.

In the upper graph the wind speed in m/s (red dotted line) and the wind direction in °N (green line) are shown. The next graph shows the concentration of nitrogen dioxide in ppb (purple line). The third graph shows the concentration of soot in ng/m³ divided into the different absorption parts in the ultraviolet (blue line) as well as in the infrared region (red line). The fourth graph shows the concentration from the ultrafine particles in #/cm³ (black line). The fifth graph shows the distance and the moving direction (blue symbol for upstream and green symbol for downstream) from passing by ships. The last graph presents a colored contour plot from the size distribution of the SMPS data from 10 to 140 nm.

As a first result it can be stated that the emission amount from the downstream moving ships are less distinctive compared to the emissions from upstream moving ships. This can be explained due to the higher relative speed and because of this a higher engine load. This result is in contrast to the behavior from maritime diesel engines which have a cleaner combustion, if they drive under higher load and therefore produce less emissions [5,17]. Another fact

is that the duration from the upstream passing ships next to the site is longer and therefore the plume can better be detected by the measurement techniques. Furthermore, it can be stated, that the distance from the ships has a clear impact to the measurement results. Due to a greater distance, there is a higher dilution of the plume. Probably the temperature of the hot exhaust gases causes a rise of the plume, so that the plume from ships at a greater distance moves above the sampling inlet of the measurement truck and cannot be determined, which happened in a few cases.

One conspicuity which can be observed for each ship plume is, that the proportion from the individual pollutants (e.g. UFP, BC, NO₂) differ significantly. In Table 1 the peak values from 7 different ships, also numbered in Fig.4, for UFP, BC and NO₂ are shown as examples. Additionally, the ratio between the BC_{IR} to BC_{UV} is given. Three of the ships (1, 2, 4) have a similar characteristic for a high emission of BC and NO₂ and only an average rate for UFP emission. Although the ships have a similar emission characteristic, the technical data from the ships differ. For example, the year of construction varies from 1959 (ship 3) to 2001 (ship 2). Furthermore, the motor power varies from 480 hp. (ship 4) to 2028 hp.

(ship 2). The ship (5) has high emission on UFP and NO₂ but almost no emission of BC. The emission from ship 6 has high values for UFP and BC but less for NO₂. Ship 3 emits UFP, BC and NO₂ on an equal but moderate level.

To give an overview of the whole fleet during the campaign, the minimum and maximum values for the pollutants are given. The range for UFP is between 190 and 96,000 #/cm³. The BC concentration are between 330 and 13,990 ng/m³ and for NO₂ between 9 and 65 ppb. Moreover, averaged values of the pollutants for down- and upstream moving ships of the whole fleet are given. One can see that there is a three times higher emission for UFP and BC of the upstream moving ships. The amount of emitted NO₂ is about 65 percent higher.

The size resolved data from the SMPS only works adequate for upstream moving ships. In most of the cases, the duration for detecting the plumes seems to be long enough. Nevertheless, shorter plume durations (<1 min) may cause a bias and thus show an incomplete or disturbed particle size distribution of the plume. The use of three or more parallel operating SMPS, where each SMPS scans only a part of the whole particle spectra can help to improve the time resolution for a whole scan and therefore get an

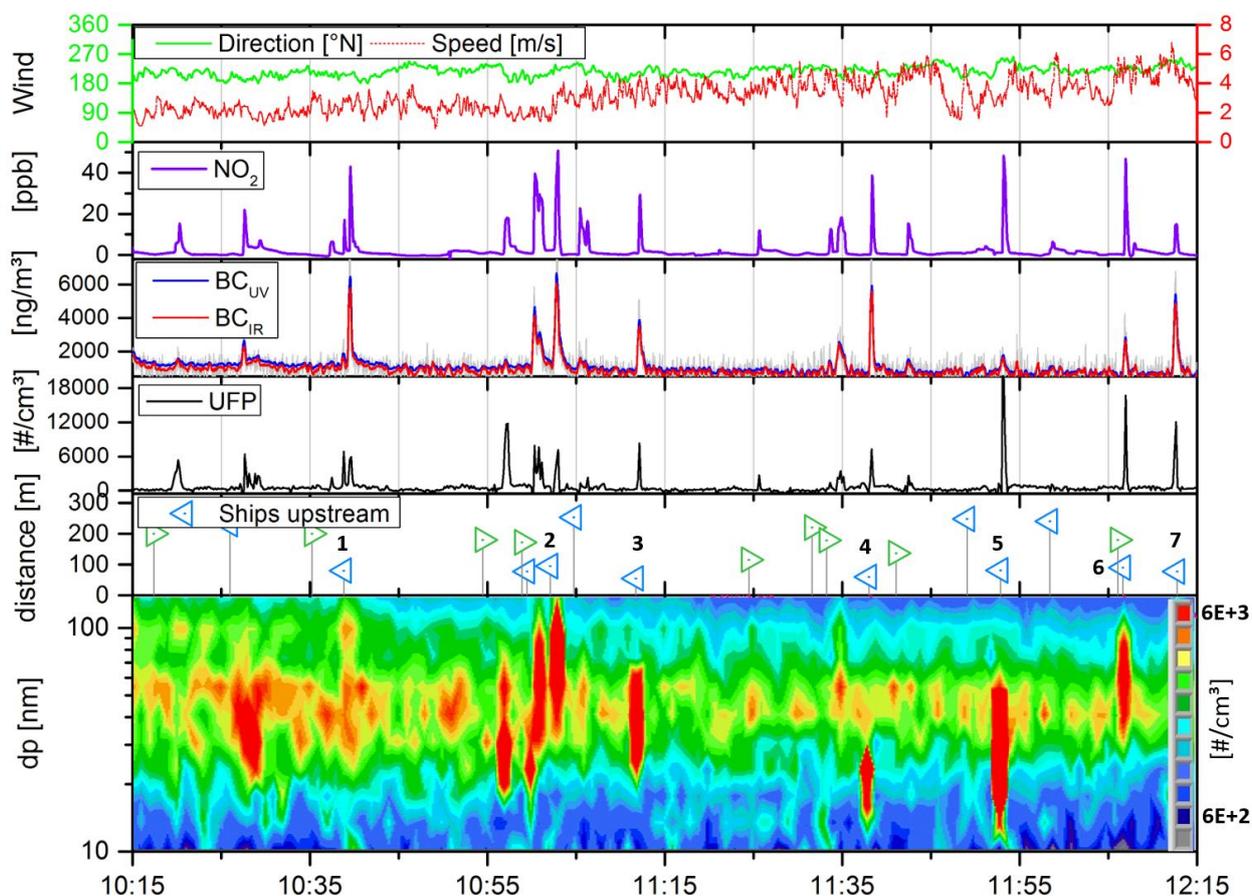


Fig. 4: Results of pollutants (UFP, BC, NO₂) directly emitted from ships. Additionally, meteorological and ship data. (2017.03.14).

accurate particle size distribution. Another way is to reduce further the size channels and the size range to reduce the scanning time, but here, the resolution from the particle spectra suffers.

Table 1: Examples of single ship plumes and summarized min, max and average concentration.

	UFP	BC	NO ₂
	[#/cm ³]	[ng/m ³]	[ppb _v]
1. Freighter (10:39), 1987, 1301 hp.	6890	3820	43
2. Freighter (11:02), 2001, 2028 hp.	7130	4365	50
3. Freighter (11:12), 1959, 730 hp.	5070	2390	29
4. Freighter (11:38), 1960, 480 hp.	7310	3815	39
5. Tanker (11:53), 2010, 2130 hp.	24,450	980	48
6. Tanker (12:07), 2004, 900 hp.	16,660	1730	47
7. Freighter (12:13), 1951, 862 hp.	12,500	3555	15
Minimum values (whole fleet)	190	330	9
Maximum values (whole fleet)	96,000	13,990	65
Average values (downstream)	5804	1070	21
Average values (upstream)	15090	3025	35

For the SMPS data one can state, that the main particle diameter of particles emitted from the ships are between 20 to 80 nm. Deviating to this range, one can see some plumes with particles with a lower diameter between 10 and 20 nm (ships 4 & 6) as well as a bigger diameter up to 140 nm (ship 2).

3.4 Fine particulate matter and SO₂

The next Fig.5 shows the results of a three hour extract from of a measurement. In the first graph one can see the mass concentration in $\mu\text{g}/\text{m}^3$ for fraction PM₁₀ (blue line) and PM₁ (red line). The next graph shows the particle number concentration in the measurement range from the OPC (0.25 - 32 μm) in $\#/ \text{cm}^3$. In the third graph the NO₂ concentration in ppb is shown. NO₂ data are shown here as an indicator for combustion plumes. In the fourth graph the sulphur dioxide concentration in ppb is shown followed by the distance of a ship and its moving direction in the last graph.

The graph for the coarse mode particles which are a major compound in the mass fraction PM₁₀ shows no direct correlation to single exhaust plumes. The trend is more dominated by the regional background level concentrations. In contrast to the PM₁₀ emissions from stationary emitting ships [18] e.g. in parking position or hotel ships, or for bigger diesel operated with heavy fuel oils [6] one is not able to detect coarse mode particles from passing by ships. However finer particles in the accumulation mode

(PNC_{0.25-32 μm} & PM₁) can be detected from only a few ships. This is in accordance with the literature [15].

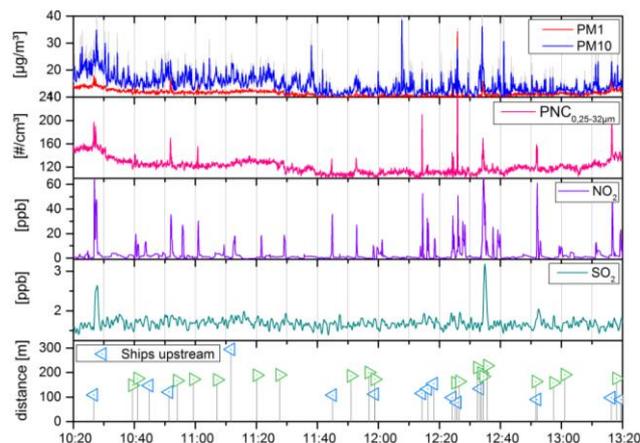


Fig. 5: Results for PM₁₀, PM₁, PNC_{0.25-32 μm} , SO₂ and NO₂ as well as ship data. (2017.03.29).

With the exception of two peaks, one cannot see any increased sulphur dioxide concentration which can be assigned to ship exhaust plumes. During the whole campaign, only three events with an increased sulphur dioxide content happened. The measurement results of this case-study indicate, that almost no significant amount of SO₂ is emitted by inland ships. The two peaks in the graph are emitted by a cargo vessel from 1982, build in Germany with a 1200 hp. MAK Engine, a total length of 105 m and a tonnage of 2936 and a push tow built in 1998 in Romania with a two 1345 hp. Wärtsila engines, a total length of 185 m and a tonnage of 4651. However, no SO₂ emissions could be found in the plumes of other ships with similar technical properties. Probably the use of fuels with a higher sulphur content could be an explanation for the increased SO₂ values of these two ships, but cannot be verified here finally.

4 Conclusion

Within this study we have shown, that it is possible to detect and analyze exhaust plumes from single river ships with measurement systems placed at the banks of the river. Orthogonal wind directions to the shipping routes which are about 200 °N are better to characterize single ship plumes. The more the wind directions differs from this heading, the more difficulties are to distinguish between single ships and due to that, only a bulk plume from more than one ship can be observed. During this study it turned out that the ship emission can be categorized into two categories. On one hand there are pollutants e.g. nitrogen dioxide (NO₂), ultrafineparticles (UFP) and soot which can be clearly detected for every single ship. On the other hand, there are pollutants like e.g.

coarse mode aerosols and sulphur dioxide emitted by only a few ships.

The maximum measured concentrations for UFP are 96,000 #/cm³, for soot 13,990 ng/m³ and for NO₂ 65 ppb_v (124 µg/m³). The data of the SMPS suffer a little because of the one-minute time resolution from the device. Only the slow and upstream driving ships offer enough time for a full size scan from the SMPS. Bias due to shorter present plumes leads to a distorted particle size distribution and offer a false plume characteristic. For the SMPS data it can be stated, that the main particle diameter of measured particles in ship exhaust plumes are between 20 to 80 nm. Deviating to this range, one can see increased particle size spectra down to 10 nm as well as up to 140 nm. The composition of the pollutants in the exhaust plumes vary from ship to ship and one cannot classify the kind of ship type due to the pollutant characteristics.

Further investigations are planned to analyze more ships of the inland fleet.

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