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# Monitoring compliance with sulphur content regulations of shipping fuel by in-situ measurements of ship emissions

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Received: 12 March 2015 – Accepted: 1 April 2015 – Published: 15 April 2015

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Published by Copernicus Publications on behalf of the European Geosciences Union.

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(scrubbers) is also permitted, as long as it provides the same level of protection against sulphur dioxide emissions as the use of low sulphur MGO. These alternative options have been deployed to some ships and first studies have documented their effectiveness and economic efficiency (Reynolds, 2011; Jiang et al., 2014), but they are still under development and not very widespread, and for the vast majority of ships the only option to meet the regulations is to use MGO.

With the regulations in place, the question remains on how to efficiently verify compliance of the ships. To date, compliance is checked by inspection authorities who enter ships at berth, review fuel log books and fuel quality certificates and when suspicion was raised take a fuel sample to be analysed at certified laboratories. With the results of these analyses, it is possible to verify compliance and if needed, take legal actions. However, these controls can check just a minor number of ships. It is also not possible to evaluate the performance and compliance of scrubber technology by sulphur prediction in bunker oil samples which would be problematic if this method becomes more popular and common in future. Another problem is to control ship fuel of ships on the open sea.

For these reasons, several studies have suggested the implementation of air quality measurement systems especially aiming at the surveillance of ship emissions. One simple but efficient method is direct and simultaneous measurements of pollution trace gases with in-situ instruments. These instruments can quite easily be adapted to measurement conditions on airplanes, research vessels and trucks and have been used in a variety of campaigns in recent years (Sinha et al., 2003; Schlager et al., 2006; Agrawal et al., 2009; Williams et al., 2009; Diesch et al., 2013; Balzani Lööv et al., 2014; Beecken et al., 2014b). Based on the experience from those studies, we have established a measurement station near the harbour of Hamburg to monitor ship emissions, to estimate sulphur contents of fuel on board of passing individual ships. Our ship emissions dataset from September 2014 to January 2015 documents the quality of implementation of the MARPOL VI regulation with respect to compliant sulphur content in

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shipping fuel used in SECAs and follows the recent strong tightening of the regulation on 1 January 2015.

## 2 Measurement site and methods

The measurements reported here were conducted as part of the Mesmart project, a cooperation between the University of Bremen and the German Federal Maritime and Hydrographic Agency.

### 2.1 Measurement site

Hamburg harbour is the third largest harbour in Europe and the 14th largest worldwide. In 2014, it had a 20 ft standard container throughput of 9.7 billion containers according to Hamburg port statistics. On average there are 800 calls per month, of which more than half are container vessels, and the other half consists mainly of Reefer vessels, tankers and bulk carriers. The harbour is located at the mouth of the river Elbe about 110 km inland, see Fig. 1.

Measurements were conducted next to the river Elbe in the town of Wedel, which is near Hamburg, on the property and with the support of the Waterways and Shipping Office Hamburg. The instruments were set up right at the northern banks of the Elbe, with an approximate line of sight distance to ships leaving and entering Hamburg harbour of 0.3 and 0.5 km respectively. The average main wind direction at this location is with a southerly component, so that most of the time within the measurement period, the exhaust plumes of the ships were blown to the instruments. The area in the main wind direction south of the measurement station and the Elbe River is rural and sparsely populated with no significant sources of air pollution. Thus the location of the monitoring site is optimal for relatively low background concentrations of nitrogen oxides ( $\text{NO}_x$ ) and  $\text{SO}_2$ .

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## 2.2 Instrumentation

The concentrations of SO<sub>2</sub>, NO<sub>x</sub>, CO<sub>2</sub>, and Ozone (O<sub>3</sub>) were measured continuously with individual instruments which are combined in a temperature stabilised box to ensure stable measurement conditions and at the same time provide a compact and transportable set-up. Data are stored in an integrated data logger with the time resolution of one minute. Despite different time resolutions of the instruments, we used data normalised to one minute which is sufficient for the analysis of emission events with a duration in the order of several minutes.

NO<sub>x</sub>, SO<sub>2</sub> and O<sub>3</sub> were measured with instruments from the Horiba AP-370 series which are certified instruments used by German authorities for standard air pollution measurements. CO<sub>2</sub> was measured with a Licor 840A analyser. The O<sub>3</sub> measurements were not used for this study and are just mentioned for completeness.

SO<sub>2</sub>: the Horiba APSA-370 is based on the UV-fluorescence method, using the excitation of SO<sub>2</sub> molecules by UV light and measuring the fluorescence which is a function of SO<sub>2</sub> concentration. The response time of the instrument is specified to be less than 120 s. Calibration was carried out with a standard gas mixture from Air Liquide with a concentration of 99.7 ppb SO<sub>2</sub> with an accuracy of 5%. In addition, a daily control was obtained by the measurement of zero gas produced with a scrubber, and span gas from an internal permeation source with 175 ppb SO<sub>2</sub>.

NO<sub>x</sub>: the Horiba APNA-370 measures the chemiluminescence of NO molecules reacting with O<sub>3</sub>. To obtain information about the NO<sub>2</sub> concentration, the device contains a deoxidation converter to transfer NO<sub>2</sub> molecules to NO. The NO<sub>2</sub> concentration is calculated by the difference of total NO, representing NO + NO<sub>2</sub>, and NO without conversion. The response time for measurement of both gases is 90 s. The instrument is calibrated with an Air Liquide standard gas mixture with a concentration of 216.0 ppb NO and an accuracy of 5%. A daily control with scrubber produced zero gas and a NO<sub>2</sub> span gas of 105 ppb is also implemented.

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CO<sub>2</sub>: the Licor 840A is a non-dispersive infrared gas analyser. It has a response time of 1 s and was calibrated with two Air Liquide standard gas mixtures with 306.6 ppm and 990.0 ppm CO<sub>2</sub> with an accuracy of 2 %.

The trace gas measurements were complemented with measurements of wind, temperature, air pressure and precipitation by a compact weather station (Lufft WS600). With an AIS (Automatic Identification System) receiver the information transmitted by passing ships was collected, which includes identification number, name and type of the ship as well as position, course, and speed.

### 3 Data analysis

To obtain the sulphur content of ship fuel in use, the enhancement of SO<sub>2</sub> and CO<sub>2</sub> in measurements affected by exhaust gases is measured, and the ratio of these SO<sub>2</sub> and CO<sub>2</sub> peaks is used to calculate the fuel sulphur content. The combination of the trace gas peak time, the wind direction, and the AIS information enables the identification of the peak related ship.

When wind conditions are favourable for measurements, the exhaust plumes of ships passing the instrument leave a distinctive enhancement of the measured component against background concentrations. Since this enhancement is most significant in NO measurements, and NO is an indicator for recent combustion processes, these NO peaks are used to identify the time stamp of a ship emission event. For these time stamps peaks in CO<sub>2</sub> are then identified, which is more complicated because background concentrations are larger and more variable due to the surrounding vegetation. Only for those events with a significant CO<sub>2</sub> peak, SO<sub>2</sub> signals are analysed. For all peaks the peak area above the background concentration is determined. This accounts for the difference in peak width for each gas due to different time resolutions of the respective instruments.

With the assumption that fuel contains  $87 \pm 1.5$  % carbon (Cooper et al., 2003) and 100 % of the sulphur and the carbon content of the fuel are emitted as SO<sub>2</sub> and CO<sub>2</sub>

respectively, the sulphur fuel content (SFC) mass percent can be calculated as follows:

$$\begin{aligned} \text{SFC [\%]} &= \frac{\text{S [kg]}}{\text{fuel [kg]}} \\ &= \frac{\text{SO}_2 \text{ [ppm]} \cdot A(\text{S})}{\text{CO}_2 \text{ [ppm]} \cdot A(\text{C})} \cdot 87 \text{ [\%]} \\ &= \frac{\text{SO}_2 \text{ [ppb]}}{\text{CO}_2 \text{ [ppm]}} \cdot 0.232 \text{ [\%]} \end{aligned} \quad (1)$$

5 where  $A(\text{S})$  is the atomic weight of sulphur and  $A(\text{C})$  of carbon. With this formula it is easy to calculate the sulphur content for each set of peaks. For a discussion about the uncertainties of this formula see Sect. “Uncertainties”.

The second part of the data analysis is the attribution of the identified emission events to individual passing ships. Within 30 min before each event, which is characterised by the time the emissions arrive at the instruments, the AIS data is analysed for ship positions close to the measurement site. In combination with wind information it is in most cases possible to identify individual ships having caused the emission. The time the exhaust plume travels from being emitted to being analysed is about 2 to 10 min depending on wind speed and direction. However, there are cases where there are two or more ships too close to each other, or where no AIS signal was received, so that no single ship can be associated to the signal. These events are excluded from the data set.

## Uncertainties

20 There are several aspects that influence the accuracy of the calculated values of the sulphur content for each ship. The SFC-formula (Eq. 1) assumes a 100 % conversion from sulphur to  $\text{SO}_2$  during combustion, which is only true for an idealised combustion process. There is a range of uncertainty of how much sulphur is oxidised and how much is released as particles. Studies found that there could be an underestimation of the

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it should be noted that this study did not include uncertainty considerations (Beecken et al., 2014a), 90 % of 255 ship plumes and 97 % of 211 ship plumes (Beecken et al., 2014b). However, a study of Diesch et al., 2013, that describes measurements with a mobile laboratory along the Elbe River near our measurement site, found for 139 ship plumes a compliance of nearly 100 %. This could possibly be credited to the special location of Hamburg harbour where ships have to go up the Elbe for more than 100 km.

In accordance with the practice in use that fuel samples analysed in laboratories are considered as exceeding the 0.1 % sulphur limit in a legally binding way above the value of 0.149 %, we suggest to use a corresponding value of 0.15 % as a limit value for discussing the compliance of the ships in our January 2015 data set. This is in consistence with the formerly stated measurement uncertainties. In Fig. 4, a more detailed graph of the January 2015 data is shown. The red line shows the 0.1 % limit with the shaded area indicating a conservative 30 % measurement uncertainty. The blue line indicates the suggested 0.15 % limit for compliance discussion. Of all the ships measured in January 95.4 % were complying with the new regulation.

Color-coded in the Figs. 3 and 4 are the lengths of the ships in 50 m size steps. Even before the regulation change ships smaller than 100 m did not use fuel with sulphur values higher than 0.2 %, most likely because their engines cannot process such fuels or storage capacity for two different kinds of fuels is not available. After the regulation change, those smaller ships still do not use the fuels that reach up to the allowed 0.1 % limit. If one considers only those ships larger than 100 m that could choose which fuel to use and had to change their way of operation, the compliance drops to 93 %.

The number of ships that can be detected for compliance depends strongly on the wind conditions. Assuming the average number of calls in Hamburg harbour according to Hamburg port statistics of 800 ships per month means that 1600 emission events happen at our measurement station of ships on their way in and out of the harbour. For months with good wind conditions like December 2014 and January 2015, we can

detect about 30–40 % of those events, for month with unfavourable wind conditions like November 2014, this value drops to less than 10 %.

## 5 Conclusions

In this study, we have used the method of in-situ measurements of trace gases to implement a system to monitor compliance of ships with sulphur fuel content regulations. This has been discussed and suggested before (Balzani Lööv et al., 2014). Here we present a suitable location for permanent stationary measurements near Hamburg harbour, one of the largest harbours in Europe, and demonstrate a measurement approach that successfully characterises emissions from passing ships. We describe the method used to identify ship emission events and the corresponding ships and present a large data set on fuel usage of ships of altogether 1413 analysed ship plumes. This includes the first data after the most recent regulation change in the North Sea SECA, where fuel sulphur content limits were reduced from 1 to 0.1 % on 1 January 2015.

Our data shows that the vast majority (95.4 %) of ships measured are indeed complying with the new regulation of 0.1 % sulphur fuel content. Compliance has dropped slightly compared to the value of more than 99 % observed for the 1 % sulphur limit in fall 2014. It should be noted that the global oil price and thus MGO costs for the needed sulphur quality in January 2015 was the lowest since 2009, but we hope that not only economic issues influence the decision whether to comply with environmental legislation or not.

With the described method it is possible to easily and reliably identify those ships that do not comply. It is possible to check 10–40 % of all ships entering and leaving the harbour, depending on wind conditions. This should be interesting to government agencies in charge of the control of the SECAs.

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*Acknowledgements.* The project was funded by the German Federal Maritime and Hydrographic Agency. The authors thank the Waterways and Shipping Office Hamburg for their help and support.

- 5 The article processing charges for this open-access publication were covered by the University of Bremen.

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**Figure 1.** Location of the measurement station on the northern bank of the river Elbe, near Hamburg harbour. On the right: picture of instrument box. Map source: OpenStreetMap.

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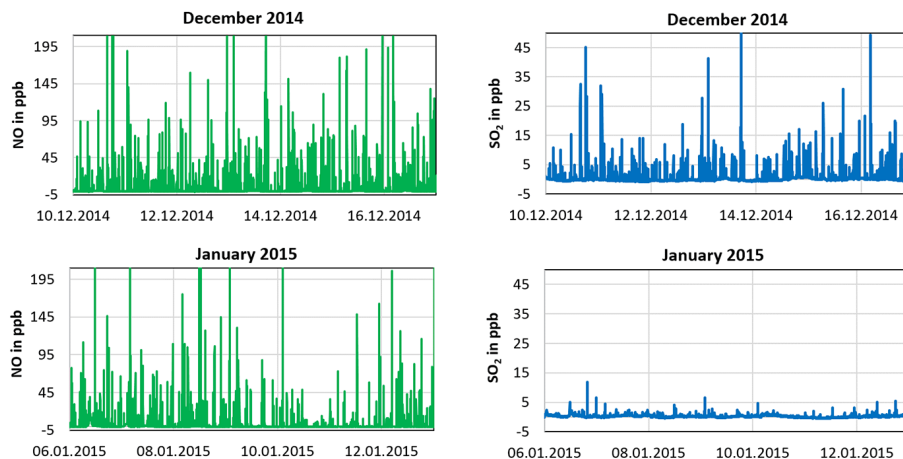
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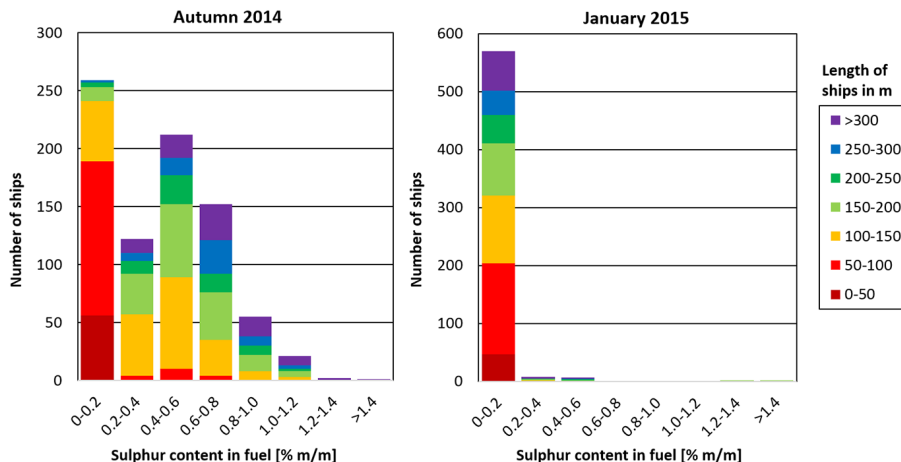


**Figure 2.** Comparison of absolute NO and SO<sub>2</sub> volume mixing ratio values measured over two weeks, one week in December 2014 and one in January 2015 with comparable wind conditions. Each peak belongs to one emission plume of an individual ship. The reduction in SO<sub>2</sub> in 2015 is obvious, while for NO no reduction can be observed.

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**Figure 3.** Sulphur fuel content in autumn 2014, and in January 2015, after the change of fuel regulations. Colour-coded is the length of the ships that have been analysed. While in 2014 only small ships had fuel sulphur contents below 0.2 %, nearly all ships fell into this category in January 2015.

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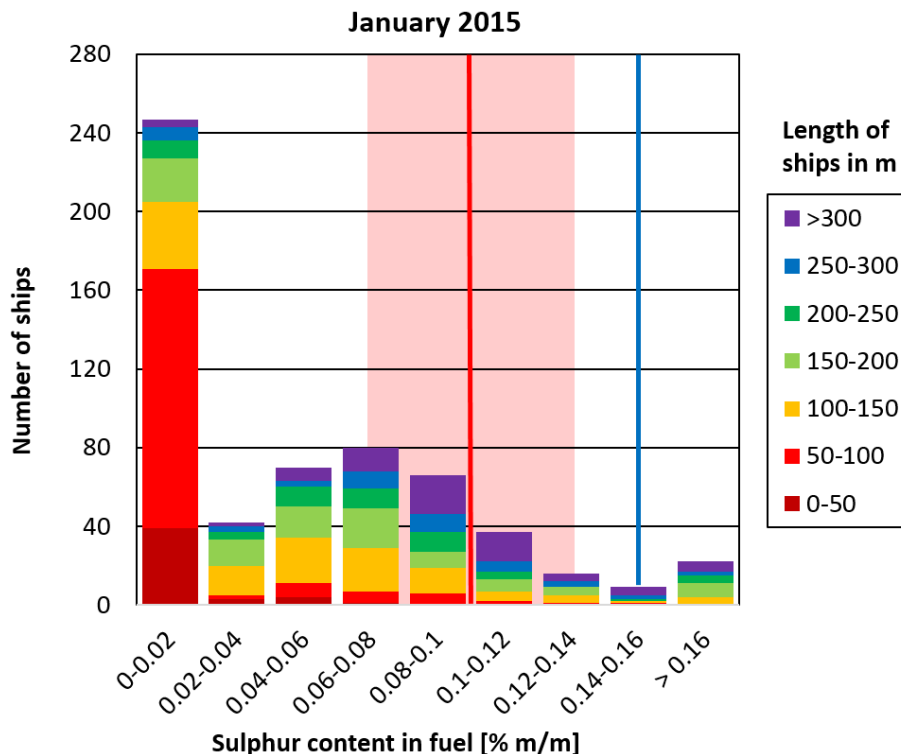
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**Figure 4.** Detailed view of the January 2015 data set. Colour-coded is the length of the ships; the red line indicates the 0.1 % limit with the shaded area representing the upper limit uncertainty of 30 %. The blue line indicates the suggested limit of 0.15 % for flagging ships as exceeding the allowed sulphur fuel content limit.

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