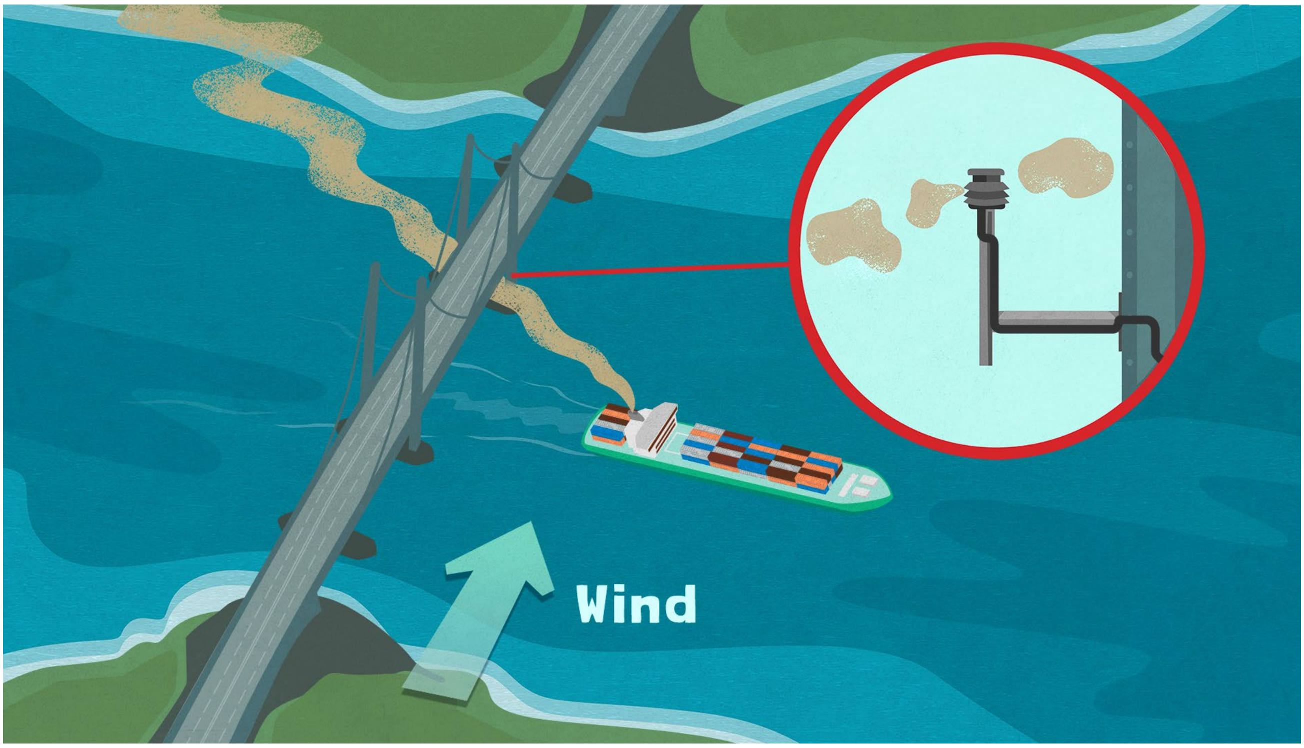
Best practice report on compliance monitoring of ships with respect to current and future IMO regulation



Johan Mellqvist and Vladimir Conde

Chalmers University of Technology, 41296 Göteborg, Sweden

Date 20/03/2021

Summary

Since 2015, new rules from the International Maritime Organization (IMO) and legislation from EU and the US allows ships to run with maximum fuel sulfur content (FSC) of 0.1 % m/m on northern European and US waters, respectively, or use appropriate abatement technique. In addition, since 2020, there is a global cap of 0.5 % for the FSC. From 2021, northern Europe is a NO_x emission control area, requiring at least 80 % emission reduction (Tier III) for all ships built from this year and onward, compared to ships built between 2000 and 2010 (Tier I). There is also a discussion within IMO how to control particle emission of black carbon (BC). This report focuses on best practice in remote compliance monitoring of FSC without stepping on board of the ship. Similar measurements for NO_x are also shown, with a discussion whether these can be used for compliance monitoring. Some examples of remote measurements of BC are provided. Remote measurement methods for compliance monitoring of FSC in ships have been developed during the last 10 years within national and European projects (EnviSum and Compmon) and furthermore implemented in national monitoring in Belgium, Denmark, Germany the Netherlands and Sweden. The measurement methods are generally based on *sniffer systems* measuring the exhaust gas concentrations of SO_2, NO_x and particulate matter (BC), respectively, against CO_2. There are systems with varying sensitivity that are operated at different distances from the ships (50 m to 2 km) and from different platforms, i.e. fixed, shipborne and airborne (manned and unmanned). There are also optical systems measuring the ratio of SO_2 against NO_2, as an indicator of the FSC, primarily used from manned aircraft. The focus in this report is on standard sniffer systems, based on generally available equipment for air quality monitoring. Such systems have been used extensively during the last 5 years for operational compliance monitoring from both fixed and airborne platforms. A summary of FSC measurement results for multiple operators and platforms shows that the noncompliance level has decreased significantly over the last 5 years at different parts of Europe, i.e. from 5-13 % in 2015 to below 1 % in 2020. The highest noncompliance levels were found at the SECA border in the English channel and in the middle of the Baltic sea. The measurement data, interpreted with ship modelling data from the Finnish Meteorological Institute, indicates that remote compliance monitoring of NO_x should work reasonably well for ships operating at high loads (above 40 % load). For slow steaming ships the measurements are associated with larger uncertainties and care should be taken in the interpretation of then results here and further ship emission modelling is needed to assess this. The remote measurements of BC work well to identify high emitters and groups of polluting ships. However, the BC emissions have a strong load dependence are intermittent by nature and it is therefore difficult to make short term measurements.

Contents

1 Introduction

In 2015 new rules from the International Maritime Organization (IMO), European directives (EU 1999; 2012)) and US legislation requires ships to run with maximum fuel sulfur content (FSC) of 0.1 % m/m on northern European (Figure 1) and US waters. Scrubber ships usually need to monitor their SO_2/CO_2 emission and report exceedances. Since 2020 ships worldwide are only allowed to operate with a maximum FSC 0.5 % outside the sulfur emission control areas. From 2021 northern Europe is a NO_x emission control area, requiring Tier 3 (more than 80 % NO_x reduction) for all ships built (keel laid) from this year and onward, compared to ships built 2000-2010. There is presently a discussion within IMO how to control particle emission (black carbon).

Figure 1. The European SECA which requires fuel with FSC less than 0.1% (non scrubber ships). From 2021 this area is also a NOx emission control area, requiring Tier 3 (approx. 90 % NOx abatement) for all ships from this year and onward.

For NO_x, the control of diesel engine emissions is achieved through the survey and certification requirements leading to the issue of an Engine International Air Pollution Prevention (EIAPP) (NOx Technical Code resolution MEPC.177(58) and MEPC.251.(66)). The NO_x control requirements apply to installed marine diesel engine of over 130 kW output power, Figure 2.

The regulation corresponds to varying engine emission limits depending on ship build year and engine type. The engine type is defined according to the rated engine speed (crankshaft revolutions per minute). The emission level is given as an emission factors (EF) with unit gram NO_x (as NO_2) per axial power in kWh. It corresponds to a weighted average of emission factors at 4 engine operation modes with different engine load (P). The average depends on engine type but generally it is constructed according to Eq.1.

$$\overline{EF}_{NOx} = 0.2 \cdot EF_{Nox}(P_{100\%}) + 0.5 \cdot EF_{Nox}(EP_{75\%}) + 0.15 \cdot EF_{Nox}(EP_{50\%}) + 0.15 \cdot EF_{Nox}(EP_{25\%}) \qquad \text{Eq.1}$$

Different levels (*tiers*) of control apply based on the ship construction date and the engine's rated speed given as crankshaft revolutions per minute. *Tier I* apply for ships built in 2000-2010, *Tier II* apply to ships built after 2011 and *Tier III* apply to ships operating in special emission control areas (Northern Europe and North America). In more detail Tier III applies to marine diesel engine that is installed on a ship (keel laying date) after Dec 31 2015 for ships in North American ECA and the United States Caribbean Sea ECA and after Dec 31 2020 for ships operating in the Baltic Sea ECA or the North Sea ECA.

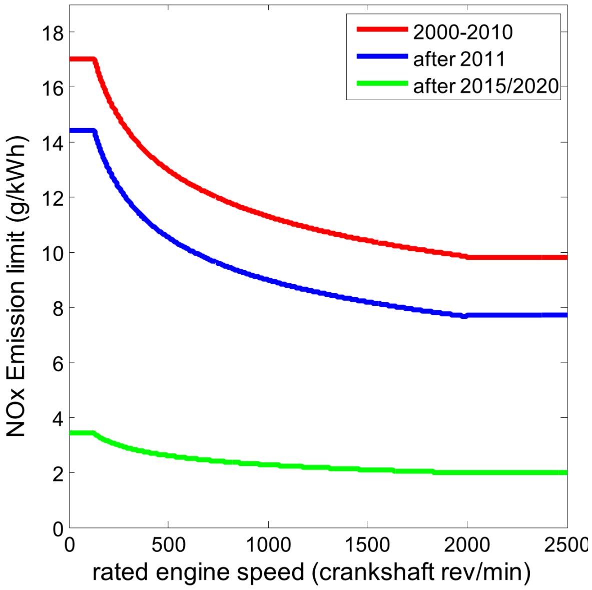


Figure 2. The IMO annex VI NO_x emission limits for ship engines. The emission levels depend on ship build year, divided int thee tiers, and engine type. The engine type is defined according to the corresponding rated engine speed. The emission corresponds to g NO_x per axial power in kWh, corresponding to a weighted average of several engine loads. Tier III applies in ECAs in north America (ships built after 2016) and northern Europe (ships built after 2020).

Port State Control (PSC) authorities have the right to inspect ships on internal waters (harbors, inland waters) and can also carry out enforcement actions such as detaining ships in harbors and even imposing civil penalties. The enforcement actions and penalties vary from country to country, although the states have tried to harmonize their control according to the Paris MoU, and other similar agreements. When ships are outside internal waters but in the exclusive economic zone, onboard inspection can only be carried out if there are clear grounds to suspect that the ship is not respecting the regulations, according to the United Nations Convention on the Law of the Sea (UNCLOS 1982) and the MARPOL code. On international waters inspection control is not possible but instead a complaint to the flag state should be field, if there are grounds for violation of the IMO code.

To inspect that the FSC legislation is complied with, on board fuel sampling is carried out by port state control authorities for ships at berth. For NO_x this is not possible and instead the engines are required to be type approved. According to European sulfur directive, it is required to inspect 10 % of the ships every year and 40% of these should be further checked with fuel sampling. Hence only a minority of the ships (4 %) is being controlled, and none while under way on open waters (2015/253/EC Article 3).

When using advanced monitoring strategies such as remote measurements or onboard monitoring with XRF (Xray Fluorescence), it is allowed, according to the European sulfur directive, to reduce the number of fuel sample analyses by up to 50 %.

The high extra cost for low sulfur fuel (+50%) and the relatively small risk of getting caught, creates a risk that unserious ship operators will run with on high sulfur fuel. In order to promote a level playing field within the shipping sector there is hence a need for measurement systems that can help make the compliance control effective and guide port state control authorities on which ships the fuel sampling should be carried out. There is a penalty system in place for noncomplying ships. Some countries enforce sulfur rules by fees (Sweden), others legal prosecution (Denmark) (up to 50 kEuro). Some countries may detain ships (Belgium). In the US they have a fee system based on economic benefit and gravity.

This report focuses on best practice in remote compliance monitoring of FSC, i.e. measuring the fuel sulfur content without stepping on board of the ship. The report also discusses whether the same method can be applied to investigate whether ships comply with the NO_x IMO limits.

A description about the available methods will be given together with compliance monitoring results obtained during the last 10 years within the projects EnviSum (Repka et al, 2019), Compmon (Mellqvist, 2017a) and by national monitoring in Belgium (Van Roy, 2019, Mumm), Denmark (Mellqvist 2020b; Explicit 2021; Explicit 2020), Germany (Weigelt, 2019), the Netherlands (pers comm Jan Duyzer, TNO) and Sweden (Mellqvist, 2017b, Swedish Transport Agency).

Figure 3. Illustration how the enforcement is carried out today. 10% of the ship are controlled once by port inspection annually, and for 40% of these a fuel control is also carried out.

2 Methods

Remote measurements to enforce the new IMO sulfur regulations can be conducted in several ways as shown in Table 1. Here three types of sniffer systems are shown (ultra sensitive, standard and mini) in addition to an optical system. The focus in this report will be on the standard sniffer system which is based on standard equipment for air quality monitoring. Such systems have been used extensively during the last 5 years for operational compliance monitoring from both fixed and airborne platforms, see Figure 4 and frontpage. Technical details about the systems used are provided in the next section. Mini-sniffer systems are also used operationally by a few actors (commercial and research) although these systems are less mature than the standard ones, still requiring improved quality assurance work and estimation of measurement uncertainties.

Figure 4. Airborne monitoring of FSC and NO_x in ship exhaust. The ratio of SO_2 and CO_2 and NO_x and CO_2, respectively, is used to deduce the emission factor from the ship. A similar approach is illustrated on the front page for fixed measurements.

Table 1. Sensor systems for remote FSC and NOx emission measurements. Also particulate matter, e.g. Black Carbon, and other pollutants can be measured in a similar fashion.

Sensors	Typical sensitivity	Platforms	Dist. from ships	FSC principle	Meas priniple	Interference	Accuracy in FSC+-2 σ (95% conf)
Ultra sensitive sniffer	SO_2: 0.1 ppb CO_2 200 ppb	Airborne, shipborne and fixed	>1 km	$\Delta SO_2/\Delta CO_2$	Laser absorption		+-0.02%*
Standard sniffer	SO_2: 2 ppb CO_2 200 ppb NO_x 0.5 ppb	Airborne, shipborne and fixed	1 km	$\Delta SO_2/\Delta CO_2$	UV fluorescense NDIR Chemiluminiscence	+1.5% NO VOCs	+-0.08%
Mini sniffer	SO_2: 10 CO_2: 10000 NO/NO_2: 10	Drone	50 m	$\Delta SO_2/\Delta CO_2$	Electro chemical NDIR	-100% NO2 RH, T -100% O3	0.05%*
Optical Sensors	SO_2 1 ppmm NO_2 1 ppmm	Airborne shipborne and fixed,	1 km	$\Delta SO_2/\Delta NO_2$	DOAS 300 -450 nm		+-0.3%*

- Preliminary assessment from own data.

Optical measurements have been demonstrated during the last years to for identification of high sulfur ships, forinstance at the SECA border in the English Channel, as part of the Compmon project (Mellqvist 2017a). Here measurements with both sniffer and an optical sensor were carried out with good agreement as seen in the results section. In addition, infrared imaging measurements have been tested by several actors, but with only few reported results so far. Ultra sensitive sniffers, based on laser spectroscopy, are under development and presently being tested and shows great promise for more precise measurements than the standard system.

In the sniffer measurements, it is assumed that the SO_2 to CO_2 ratio is directly proportional to the sulfur to carbon content in the fuel, see Equation 2. In this equation the CO_2 is given in the unit ppm (parts per million) while SO_2 in the unit ppb (parts per billion) and it assumed that 87 % of the fuel corresponds to carbon and that all sulfur is converted to SO_2 in the combustion. It is necessary to subtract the background concentration from the measured concentration to determine the true ratio between the SO_2 and CO_2 in the exhaust gas. It is possible to determine the ratio remotely even 1-2 km downwind of the vessel.

$$\mathrm{FSC}\ \% = \frac{\mathrm{M(S)}\frac{g}{mol} \times \int [SO_2]_{ppb} - [SO_{2,bgd}]_{ppb} dt}{\frac{\mathrm{M(C)}\frac{g}{mol}}{0.87} \times \int [CO_2]_{ppm} - [CO_{2,bgd}]_{ppm} dt} = 0.232 \times \frac{\int [SO_2]_{ppb} - [SO_{2,bgd}]_{ppb} dt}{\int [CO_2]_{ppm} - [CO_{2,bgd}]_{ppm} dt} \qquad \text{Eq. 2}$$

The fuel specific emission of NO_x is obtained from the NO_x to CO_2 ratio, according to Equation 3 and here CO_2 is given in ppm while NO_x is given in ppb. It is assumed that all NO_x corresponds to NO_2, and to convert to the power specific emission (g NOx per kWh) as given in the IMO annex VI, the fuel efficiency of the specific engine is multiplied with the specific fuel oil consumption (SFOC), Equation 4. This value can vary from 160 g/kWh for slow stroke engines to 220 g/kWh for medium stroke engines and it also has a load dependence, with higher values at low loads. A default value of 200 g fuel per kWh is generally used. However, in this study data, an attempt has been made to use data from the ship emission model STEAM (Jalkanen, 2009; 2012) for the SFOC and to assess uncertainties caused by the fact that the power specific emission should be a weighted average according to Equation 1 and that the auxiliary engine exhaust mixes with the main engine exhaust in the remote measurements.

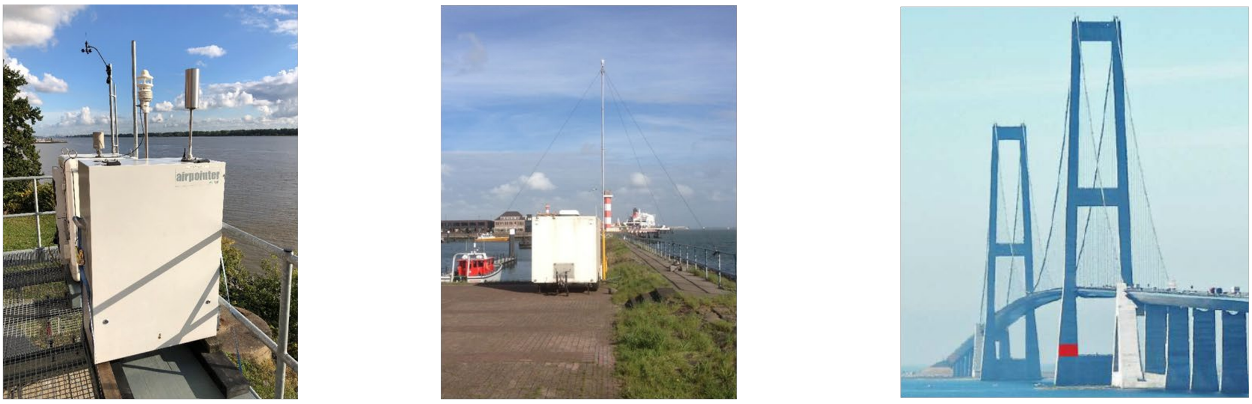
$$EF_{NOx}\left(\frac{g}{kg\ fuel}\right) = \frac{\mathrm{M(NO2)}\frac{g}{mol} \times \int [NO_x]_{ppb} - [NO_{x,bgd}]_{ppb} dt}{\frac{\mathrm{M(C)}\frac{g}{mol}}{0.87} \times \int [CO_2]_{ppm} - [CO_{2,bgd}]_{ppm} dt} = 3.333 \times \frac{\int [NO_x]_{ppb} - [NO_{x,bgd}]_{ppb} dt}{\int [CO_2]_{ppm} - [CO_{2,bgd}]_{ppm} dt} \qquad \text{Eq. 3}$$

$$EF_{NOx}\left(\frac{\mathrm{g}}{\mathrm{kWh}}\right) = SFOC \cdot EF_{NOx}\left(\frac{g}{kg\ fuel}\right) \qquad \text{Eq.4}$$

It is relatively straightforward to automate the sniffer measurements for realtime evaluation of FSC and fuel specific emission of NO_x from Equation 2 and Equation 3, respectively. From AIS data (Automatic Identification System) and wind measurements it is also possible to identify the ships in realtime and send out alerts to a database. The data is usually sorted in quality classes (high, medium or poor). The measurement uncertainty for the sniffer measurements depends on the distance to the ships, size of ships and wind conditions (speed and direction). Measurements with medium sniffer by Chalmers at the Great Belt bridge shows a typical measurement precision of 0.04 % in FSC units, this hence corresponds to 0.08 % uncertainty at 95 % confidence level (Mellqvist et al., 2018). There also appears to be systematic uncertainties, typically 0.05 % in FSC units, but this can usually be compensated for by comparison to other measurements. Some groups report smaller uncertainties and there is a need to homogenize this. At present there is extensive on-going work on this topic in the EU Horizon 2020 project SCIPPER and in September 2020 there was an extensive validation measurement campaign in Hamburg with multiple operators and instruments and accompanied onboard fuel sampling and the results will be used to derive a common method for uncertainty reporting.

3 Platforms and actors

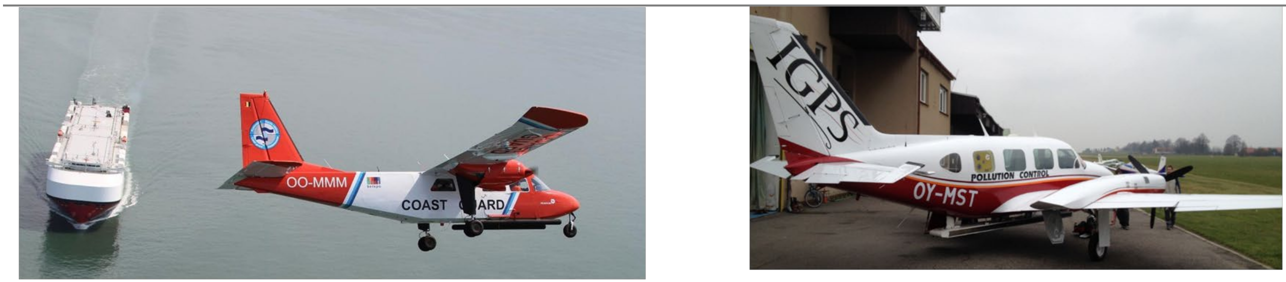
During the last 10 years fixed and mobile remote compliance measurements of FSC have been carried out at multiple sites/platforms in northern Europe by several operators. In Figure 4 the fixed sites in Europe are shown from which operational compliance measurements have been carried out. The sites from top left to bottom right corresponds to: Wedel in Germany operated by BSH (there are sites also in Kiel and Bremerhaven), Hoek van Holland in the Netherlands operated by TNO, Great Belt bridge in Denmark operated by Chalmers, Gothenburg ship channel in Sweden operated by Chalmers, Öresund bridge in Denmark/Sweden operated by Chalmers and Bay of Bothnia in Finland operated by Kine Robotics (there are 5 more sites along the coast of Finland). From all these sites measurements with realtime reporting are /have been conducted and with subsequent reporting to the EMSA data base Thetis-EU. In Figure 5 several airborne platforms are shown that have been used for ship compliance monitoring. The platforms from top left to bottom right, corresponds to Britten Norman with standard sniffer operated by the Royal Belgian Institute of Natural Sciences and equipped with Chalmers standard sniffer, Navajo Piper in Denmark with standard sniffer and optical system operated by Chalmers, Airbus H125 single-engine helicopter with mini-sniffer operated by Explicit, Schiebel drone equipped with mini-sniffer operated by EMSA and lastly smaller drones equipped with mini-sniffer operated by Explicit, Aeromon and Chalmers. In the following subsections the equipment employed at the fixed and mobile platforms is described in more detail.



Germany, Wedel Netherlands, Hoek van Holland Denmark, Great Belt

Sweden, Göteborg Sweden, Öresund Finland, Bay of Bothnia

Figure 5. Fixed platforms used for compliance monitoring.



Belgium, medium sniffer sensor

Denmark medium sniffer sensor

Denmark, mini sniffers

EMSA, larger drone with mini sniffer

Denmark, Finland and Sweden, small drones with mini sniffers

Figure 6. Airborne platforms used for compliance monitoring.

3.1 Standard sniffer systems

3.1.1 Sweden

Chalmers University of Technology has developed both an airborne and a fixed sniffer system in the Swedish project IGPS (Identification of Gross Polluting Ships) (Mellqvist, 2010; Berg et al., 2011) between 2006 and 2008 and the project IGPS-plius between 2009 and 2014 (Mellqvist, 2014; Beecken et al., 2014). These projects were funded by the Swedish innovation agency (Vinnova) and the Port of Gothenburg (Mellqvist et al., 2014). Chalmers has participated in several EU-funded projects, i.e. SIRENAS (Balzani-Lööv 2014: Alfoldy 2011; 2013), BSR-Innoship (Beecken et al., 2015), BSR-EnviSum (Repka et al., 2020a) and CompMon (Mellqvist, 2017a). In the projects, airborne and shipborne measurements have been carried out in the Baltic Sea, the English Channel, Neva Bay in Russia (2011, 2012 and 2018) and California (Mellqvist, 2017c). Chalmers operates sniffer stations at: (a) the inlet channel of Göteborg since 2009 (Mellqvist, 2010), (b) the Great Belt Bridge since 2015 on behalf of the Danish EPA (Mellqvist, 2018; 2019b; 2020a; 2020b) and (c) the Öresund Bridge since 2017 (Mellqvist 2017b) on behalf of the Swedish transport agency. Chalmers has carried out airborne monitoring for the Danish EPA in 2015 and 2016 (Mellqvist, 2018).

SO_2 is measured by UV fluorescence (Thermo 43i-TLE). For stationary measurements, a standard instrument is being used with response time of 40 s (t_{90}) while for airborne measurements a modified instrument without VOC-kicker is used to obtain a response time of 2 s (t_{90}). The applied sampling rate is 1 Hz. The SO_2 instrument has a known cross-sensitivity to NO of 1.5 %. NO_x is measured by chemiluminescence using a Thermo 42i-TL with a response time 1 s (t_{90}) and sampling rate of 1 Hz. CO_2 is measured either by NDIR analysis (Li-Cor LI-7000 and LI-7200) or cavity ring-down spectroscopy (CRDS) (Picarro G2301-m) with a response time of 1 s (t_{90}). The CRDS is very stable regarding drift and only requires infrequent calibration . The 1σ precision of the fuel sulphur content measurements corresponds to 0.04 % S m/m. The fixed systems are additionally equipped with ultrasonic anemometers for wind measurements as well as AIS receivers, processing units and mobile network communication equipment. The gas measurements are often complemented by particle measurements (PM, BC, PN).

Chalmers has developed a complete sniffer box for airborne measurement which includes the SO_2 and CO_2 sensors mentioned above, processing unit, AIS, power converter and interface for the aircraft's navigational data. Such a system has been built to the Royal Belgian Institute of Natural Sciences for aerial compliance monitoring.

The fixed and mobile gas measurements are calibrated using high purity reference gases ranging from 200 to 300 ppb ±5 % for SO_2 and NO_x span, and from 300 to 400 ppm ±1 % for CO_2 span. In the case of NO_x, NO is used as reference gas. The SO_2 and NO_x zero signal is retrieved by using the CO_2 calibration gas. Likewise, the CO_2 zero is retrieved by using the SO_2 calibration gas. At the fixed stations calibration are typically carried out every 10 days while for airborne, shipborne and campaign measurements calibration are carried out daily. The calibration procedures take into account the stabilization time, especially for the SO_2 instrument. The calibration gas is flushed during a period of 5 minutes for the SO_2 span calibration, while a period of 1 minute is normally enough for NO_x and CO_2 span calibration. Chalmers has developed a rapid monitoring system for gas and particle measurements that has been used on ships and vans during measurement campaigns. This includes measurements campaigns in Los Angeles and Long Beach in 2015, in Gdansk/Gdynia in 2017 and Saint Petersburg in 2011, 2012, and 2018 and Marseille in 2019.

3.1.2 Belgium

The Management Unit of the North Sea Mathematical Models (MUMM), which is part of the Royal Belgian Institute of Natural Sciences, conducts airborne measurements using a sniffer box developed by Chalmers and FluxSense AB (www.fluxsense.se), see above. MUMM conducts aerial measurements onboard an aircraft of type Britten Norman Islander. It has a range of about 3 hours for compliance monitoring flights, at a cruise speed of 110 kn and a stall speed of 35 kn. The standard approach for plume traverses is at altitudes of 150 ft (46 m). If necessary, samples near the vessels are also taken at lower altitudes depending on weather conditions and the particularities of the vessel. Since 2015, measurements have been conducted above Belgian and Dutch waters. Until end of November 2019, about 400 flight hours were conducted in total of which 85 flight hours for Dutch Human Environment and Transport Inspectorate (ILT) (Ward van Roy, 2020). The air is sampled with a probe at the bottom of the fuselage. The system contains a trace level UV-Fluorescence analyzer for SO_2, a NDIR analyzer for CO_2 and a processing unit. Furthermore, interfaces to ARINC 429, AIS and GPS as well as Ethernet for external user interface units, e.g. notebooks. It is fitted for 19'' racks. Its weight is 47 kg and it consumes 15 A at 28 VDC. The response time (t_{90}) of the SO_2 analyzer is about 2 s and less than 1 s for the CO_2 analyzer. The systems are regularly tested and calibrated with specified test gases. Since summer of 2020, the system is complemented with an Ecotech NO_x chemiluminescence instrument that has been implemented by Chalmers.

3.1.3 The Netherlands

Netherlands Organization for Applied Scientific Research (TNO) has been operating a fixed station at the entrance of the ship channel to Rotterdam in Hoek van Holland since 2015. Before that a mobile system was used, starting with campaigns already in 2006. Recently, during autumn 2019, TNO moved their equipment to another position in the area. This site is closer to the sea and will allow monitoring of larger ships and with other wind directions.

TNO uses the Thermo 43A SO_2 analyzer which is running with a hydrocarbon kicker with a response time of about 40 s. NO_x is measured with an Ecophysics 600 CLD analyzer based upon the chemiluminescence reaction between NO and O_3. The response time is less than 1 s. The volume mixing ratio of CO_2 is determined with a Li-Cor NDIR instrument. This instrument has a response time less than 0.1 s. Meteorological parameters as wind direction and speed are measured using a Vaisala WxT530. The system also contains an AIS receiver to collect AIS information. Usually, all monitors are calibrated in the field once a month using secondary standards. When the monitoring results are suspect, the site is visited, and instruments are checked and calibrated. When needed they are brought back to TNO's laboratory where they can be compared with primary standards.

3.1.4 Germany

Since 2017, the Federal Maritime and Hydrographic Agency (BSH; www.bsh.de) is carrying out operational ship emission compliance monitoring at the pilot station in Wedel/Elbe, i.e. at the entrance to the port of Hamburg and this has been expanded to other measurement locations (Bremerhaven and Kiel). These measurements were preceded in Wedel by the University of Bremen already in 2014 within the BSH funded research project MeSMarT (www.mesmart.de). The chemical composition of ship plumes with respect to CO_2, SO_2, O_3 NO and NO_x is measured with monitors from HORIBA (APSA-370, APNA-370, and APOA-370), mlu-recordum (Airpointer) and Li-Cor (LI-840A). The SO_2 instruments have a known cross-sensitivity to NO of about 0.5 to 1.5 %, which needs to be corrected when measuring ship plumes. The SO_2 sensitivity and the detection limit is given to be < 1 ppb. NO is detected by chemiluminescence. To measure also the NO_x concentration, NO_2 is converted to NO in a deoxidation converter. Note that the same approach is used by all chemiluminescence systems on this report. The NO_2 concentration is calculated by the difference between NO_x and NO. The NO_x instrument in operation automatically switches between NO and NO_x measurement every 10 s, corresponding to the temporal resolution. The t_{90} response time is given to be below 60 s and 90 s for Airpointer and HORIBA, respectively. Again, for both instruments the sensitivity and detection limit is less than 1 ppb. For data interpretation the meteorological parameters temperature, pressure, wind vector, humidity, precipitation and global radiation are measured with a weather station (LUFT WS700-UMB). To allocate measured plumes to individual ships the shipping traffic at the measurement location is recorded with AIS-receivers (Watcheye R AIS). To ensure high quality measurements, every 25 hours an automated instruments self-check is performed by an instrument internal zero- and span check. Zero- and span-air is generated locally by pulling ambient air thru an activated charcoal filter and Purafil filter to remove all sulfur, O_3 and NO_x compounds. After the zero-check, the ambient air is again pulled through the zero-air filter followed by a permeation source for SO_2 and NO_2 or an O_3 generator to load the air with a known amount of SO_2, NO_2 or O_3. In total the zero- and span-check procedure last 35 minutes. Even though, the zero- and span check is not used to calibrate the instruments it indicates instrumental drift and malfunctioning. Unfortunately, so far automated zero and span-checks for CO_2 cannot be performed. Two times a year the gas monitors are calibrated on site with external calibration gas from certified gas cylinders.

3.1.5 Finland

A Finish ground-based monitoring network of 5 stations is operated by the KINE Robotic Solutions Oy's on behalf of the Finnish Transport and Communications Agency (Traficom). The monitors are based on a commercial Airpointer system by mlu-recordum (see 3.1.4) together with other equipment used for example for meteorology in the system setup.

3.2 Mini sniffer systems

This application corresponds to the use of light weight and low-cost sensors for sniffer measurements from drones and manned helicopters. The applied sensors are electrochemical sensors (EC) or infrared sensors (NDIR), depending on the gas to be measured. Generally, these sensors are not suitable to measure the low concentrations observed in the diluted plumes where the standard sniffers work. The response time of the EC sensors and NDIR sensor are 30 s and 1 s, respectively.

A challenge with these sensors is large cross sensitivities to other gaseous constituents, temperature, pressure and relative humidity. Forinstance, the ECC SO_2 sensor generally used has 100% negative cross sensitivity to both NO_2 and O_3, and drifts with humidity and temperature. The cross sensitivity is not linear with concentration. In addition, it is required that the concentration is stable around 30 s, to give time for SO_2 to diffuse through a membrane, and it is uncertain what happens when the concentration varies rapidly, which is the case in ship plumes. All in all, due to the sensor characteristics described above it is complicated to assess the uncertainty in the field for this type of sensor. In contrast to the standard sniffer techniques the mini sniffer systems needs to be applied much closer to the fluegas channels of the ships, typically 50 m, where the plumes are less diluted and the concentrations of the pollutants is sufficiently high, i.e. close to the ppm range. The companies Explicit ApS (Denmark) and Aeromon Oy (Finland) have developed their own small-sized sniffer systems, based on similar sensors.

Explicit calibrates the sensors at certified laboratory once in 6 months (or 100 h running time) while Aeromon carries out in field calibration prior to each mission. The Explicit system comprises low-cost micro sensors, electrochemical and infra-red, measuring SO_2 (EC), NO_2 (EC), NO (EC) and CO_2 (NDIR), temperature and humidity and is intended for use on any rotary-wing aircraft. The sensors are integrated into Mini Sniffer Units (MSU) housed inside a standalone snifferbox (ca. 5 kg) for mounting on a manned helicopter or into light-weight sniffer payload packages (ca. 500 g) for mounting on UAVs (short and long-range). In Denmark, regular helicopter surveillance of sulfur emissions has been carried out since 2017 on behalf of the Danish Environmental Protection Agency (Explicit, 2020; 2021). Chalmers has built a drone based mini-sniffer system based on low cost EC sensors (same as Explicit) and a medium expensive NDIR sensor.

3.3 Optical systems

Chalmers University of Technology conducts airborne measurements using passive DOAS which is looking downwards at a 30° slant angle with respect to horizon (Berg et al., 2011; 2012). Solar radiation which is scattered at the sea surface is used as background in this case. For the measurement of SO_2, an Andor Shamrock SR-303i imaging spectrometer is used together with an F/2 telescope. The grating used has 2400 lines mm^{-1}. The spectral resolution is 0.47 nm. The spectrograph is connected to an Andor Newton 920 BU UV enhanced CCD detector. For the measurements of NO_2, a second but similar system is used except that the spectrograph has been substituted by an Andor Shamrock SR-163. The 1-σ precision is in the order of 20 ppb for both SO_2 and NO_2, over an assumed plume width of 50 m. This system has been applied successfully in the English Channel during the Compmon project (Mellqvist, 2017a). Also the University of Bremen operates several DOAS systems to monitor ship emissions in Germany. (Seyler et al., 2017; 2019).

4 Results

Here we show compliance monitoring results obtained in the BSR interreg project EnviSum (Repka et al, 2019) and the EU-CEF project Compmon (Mellqvist 2017a). In addition, we show data from national monitoring in Belgium, Germany, the Netherlands and Sweden, se below. Detailed information about these measurements is given in section 3 and overview of available data until 2019 can be found in Appendix A.

4.1 Fuel Sulfur Content

In this section are shown examples of FSC compliance measurements carried out using standard sniffer equipment from fixed stations, aircraft and patrol vessels.

In Figure 7 airborne measurements by Chalmers is shown at the SECA border (5°W) in the English Channel. The measurements were carried out in 2016 as part of CompMon (Mellqvist, 2017a) by standard sniffer from a Navajo Piper, Figure 6. The noncompliance rate obtained with the standard sniffer was 13 % inside the SECA, corresponding to FSC above 0.2 % and this was considerably higher than measurements in other location in the SECA.

A similar measurement to the one above was carried out on the Baltic sea in Aug 2017, Figure 8, as part of EnviSum (Repka et al., 2020a). The noncompliance rate was 6 % and this was considerably higher than similar measurements at the Great Belt bridge on the same year, i.e. 1.7%.

In Figure 9 is shown shipborne measurements of 175 ships in the Neva Bay in Oct 2018, also carried out as part of EnviSum (Repka et al 2020). The ships were departing or arriving from/to Sankt Petersburg and the noncompliance rate was 5 %, hence similar to the Baltic sea airborne measurements. As a coincidence they are also similar to the noncompliance rates at the Great Belt bridge in 2018 (Mellqvist 2019b) but in the latter case this was caused by malfunctioning scrubber ships.

FSC measurements from the fixed site at the Great Belt bridge during 2020 are shown in Figure 10 (Mellqvist 2021). A FSC histogram is shown for 3910 ships measured during 2020. The noncompliance rate is 1.4 %, corresponding to FSC above 0.18 % (95 confidence limit). As a side comment it is estimated that the data had a systematic bias of -0.077 % in FSC unit during 2020. To compensate for this a bias compensated threshold is used instead corresponding to 0.11 %, as indicated in the figure.

A summary of the FSC results described above and measurements elsewhere by Chalmers is provided in Table 2 and furthermore plotted in Figure 11 in a time plot over the last 5 years. More information about data in the table can be found in the EnviSum report (Repka et al, 2019), the Compmon report (Mellqvist 2017a, Mellqvist 2017b) and several report to the Danish EPA (Mellqvist et al., 2018; 2019b; 2020a). Figure 11 also shows FSC data from other sites/platforms and operators in northern Europe, corresponding to national monitoring data from several of the operators in section 3, i.e. Mumm in Belgium (Van Roy, 2019), Explicit in Denmark (Explicit 2020; 2021), BSH in Germany (Weigelt, 2019) and TNO in the Netherlands (pers comm Jan Duyzer). It should be noted that the compliance levels from the different operators were individually derived and this has impact on the derived compliance levels. Nevertheless, from the graph it is obvious that the compliance level has improved significantly, with average noncompliance rate of 0.5 % in 2020 (red dotted line). The fixed site measurements in the ship channel to Hamburg (Andreas Wedel, 2019) shows improved compliance rates since 2015 with noncompliance rates less than 1 % in Wedel and Bremerhaven in 2019. Sniffer measurements at the Öresund bridge by Chalmers, on behalf of Swedish transport agency, shows a noncompliance rate of 0.3 % in 2020 with no ships above 0.3 %. In 2018 the corresponding noncompliance rate was 1 %.

In Figure 12 the FSC data from the site Great Belt (Mellqvist et al., 2020b) has been compared with airborne measurements on Belgian waters by Mumm (Van Roy, 2019) for ships in gross noncompliance, i.e. above FSC of 0.4%. The two data sets correlate well, although the noncompliance level in the airborne data is higher, probably due to the difference in location.

The FSC trends in Figure 12 are also in agreement with airborne mini-sniffer measurements of 600 ships around the coast of Denmark in 2019 and 2020 (Explicit, 2020; 2021) on behalf of the Danish

EPA. Between 2018 and 2019 the noncompliance dropped by 50 % with only 3 ships (0.5 %) above FSC of 0.3 % and only one in 2020 (0.14 %).

.

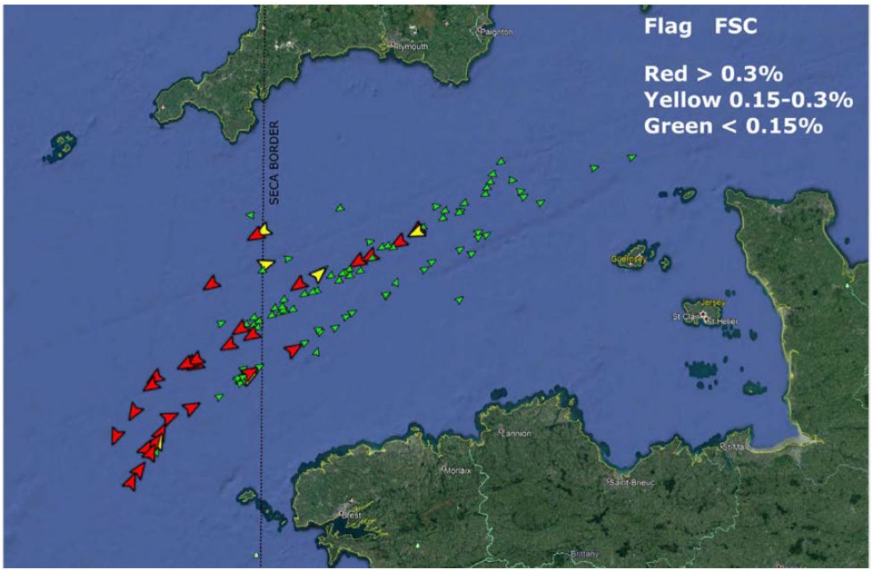


Figure 7. Airborne measurements as part of CompMon in 2016 by Chalmers (Mellqvist 2017a).

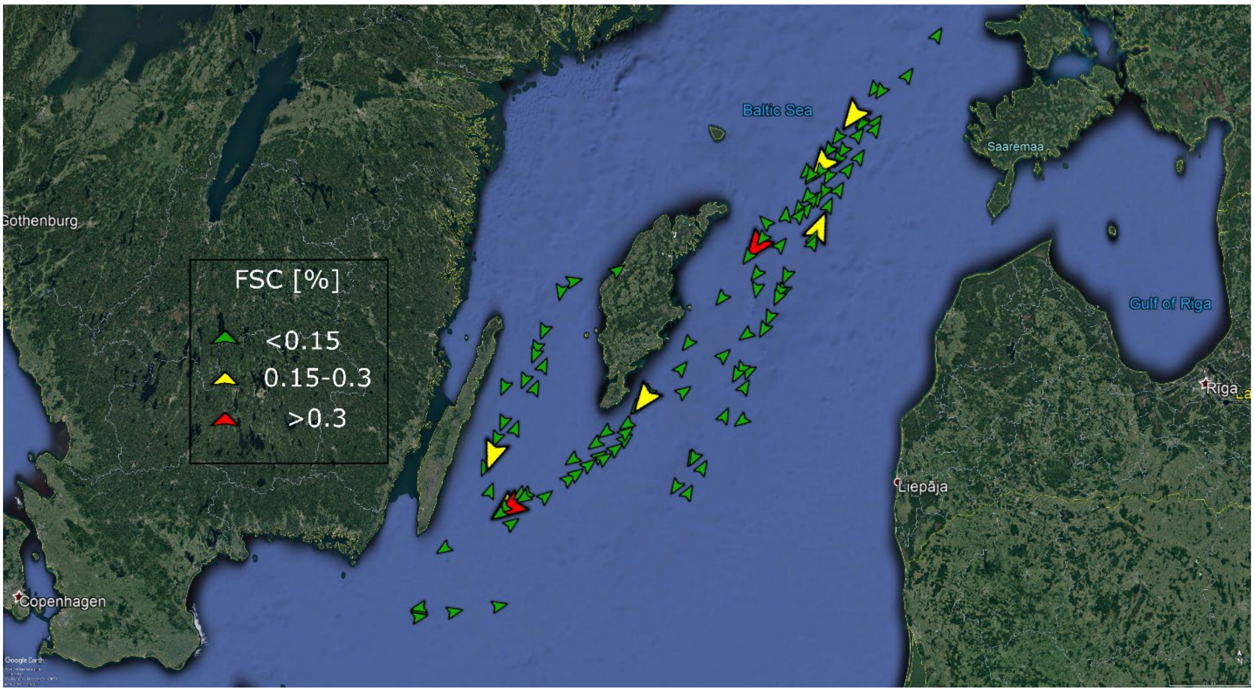


Figure 8. Airborne FSC measurements of individual ships in the middle of the Baltic Sea in Aug 2017 in the EnviSum project. The limit for detected non-compliance is here 0.15%, taking into account the measurement errors.

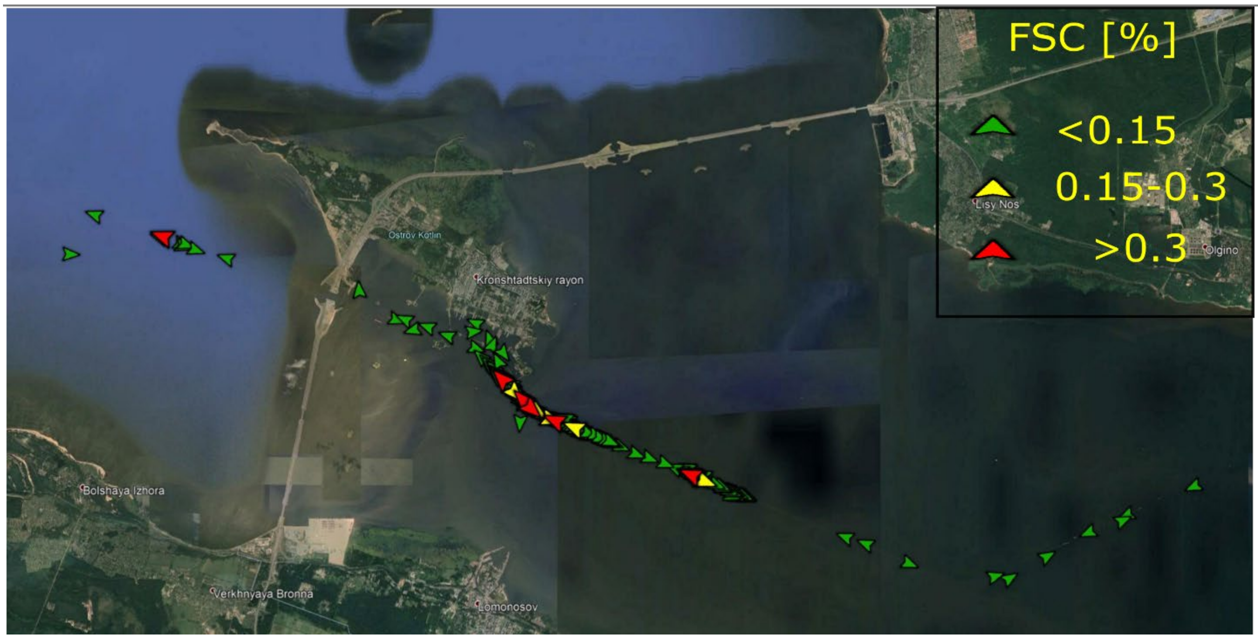


Figure 9. Shipborne FSC measurements of individual ships in Neva bay, St Petersburg in the EnviSum project. The FSC limit for detected non-compliance is here 0.15%, taking into account the measurements error.

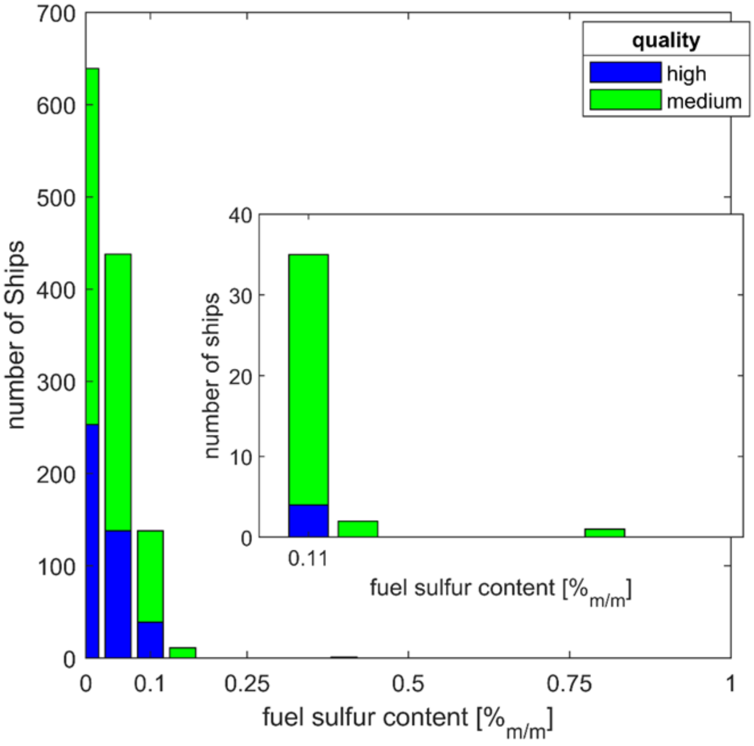


Figure 10. Statistical distribution, histogram, of the measured FSC with sniffer at the Great Belt Bridge Mellqvist, 2020b). The data corresponds to 3910 ship measurements with approved quality (medium and high). During the 2020 it is estimated that the data has i.e. systematic bias of -0.077 % and random of 0.047%, both in FSC unit. The threshold of 0.18% is therefore corrected for the systematic effects, and the threshold of 0.11% was therefore used here.

Table 2. Compliance measurements by Chalmers from fixed stations and mobile platforms in various campaigns. For more details: EnviSum (Repka et al, 2019) , Compmon (Mellqvist 2017a). Danish EPA (Mellqvist et al., 2018; 2019b; 2020a), Swedish Transport Agency (Mellqvist 2017b).

	Time period	Non compliance	Threshold	Ships	Project
Denmark, airborne	2015-2016	6-8 %	>0.2 %	820	Danish EPA
English Channel, Airborne	Sep 2016	13 %	>0.2 %	~75	CompMon
Middle Baltic Sea, airborne	Aug 2017	2 % 6 %	>0.3 % >0.18 %	~112	EnviSum
Tricity, PL, shipborne	Sep 2017	0 %	>0.18 %	134	EnviSum
St Petersburg, RU, shipborne	Oct 2018	5 % 3 %	>0.18 % >0.3 %	175	EnviSum
Göteborg harbor, SE	2016-2017	1-2 %	>0.18 %	~8000	CompMon, EnviSum
Öresundbridge SE Öresundbridge SE Pebbarholmen DK	2016-2017 2018 2019-2020	1-2 % 1 % 0.3 %/0 %	>0.18 % >0.18 % >0.20 %	~150 900 3300	CompMon Swed Trans Agency Swed Trans Agency
Great Belt bridge DK	2015-2016 2017 2018 2019-2020	5 % 1.4 % 5 % 1.4 %	>0.18 % >0.18 % >0.18 % >0.18 %	2511 4155 3580 9368	Danish EPA

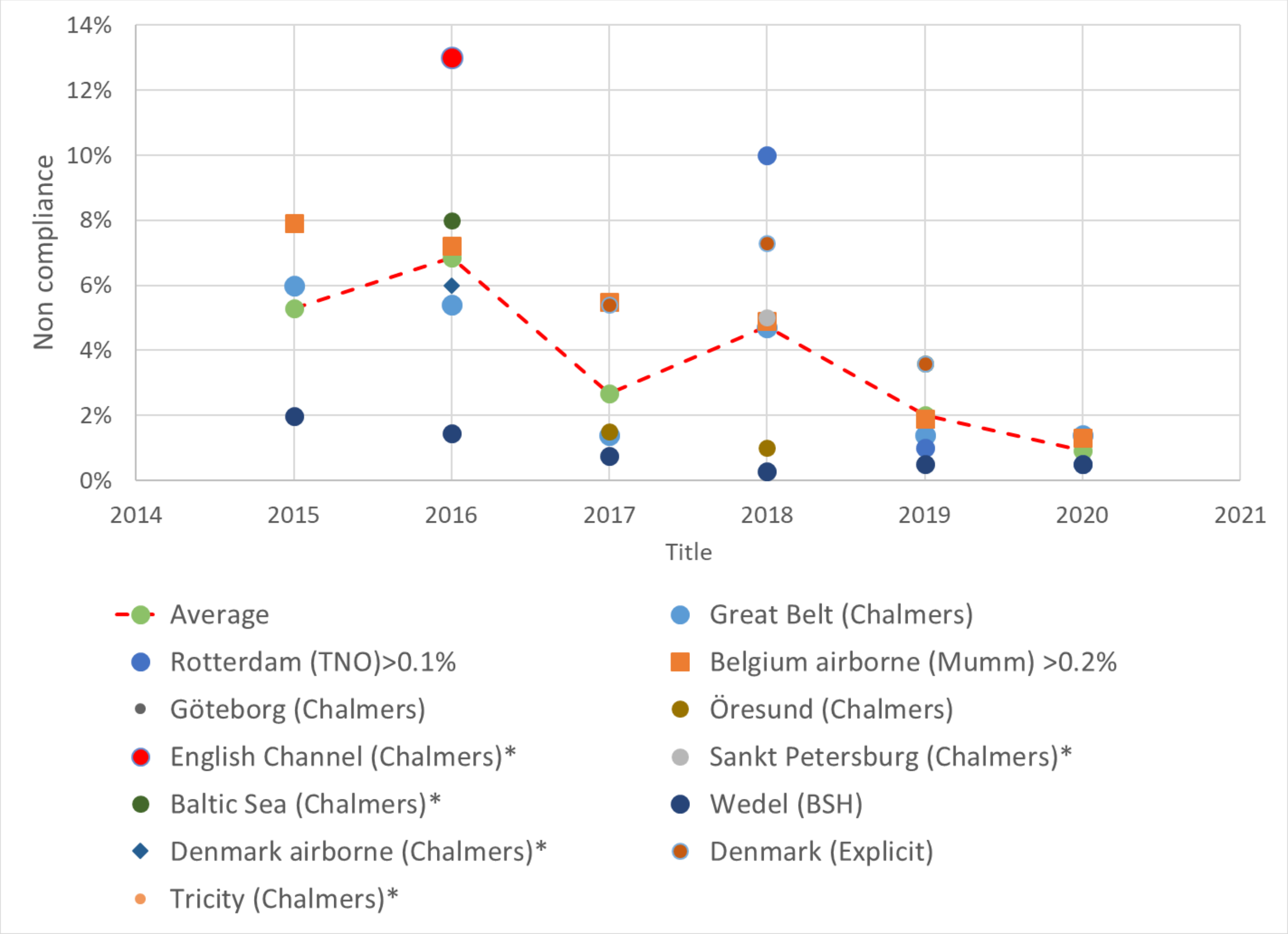


Figure 11. FSC compliance monitoring data in the SECA from different operators and platforms. The Chalmers data is explained in Table 2. In addition national data is included from: Mumm in Belgium (Van Roy, 2019), Explicit in Denmark (Explicit 2020; 2021), BSH in Germany (Weigelt, 2019) and TNO in the Netherlands (pers comm Jan Duyser).

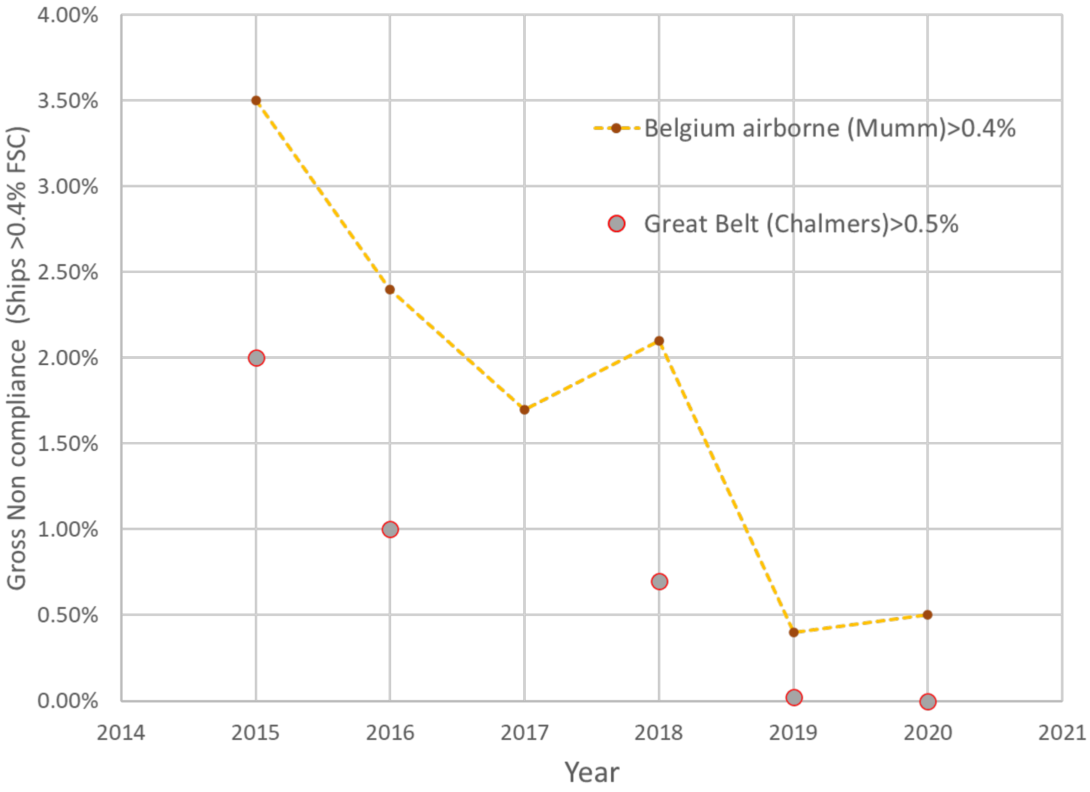


Figure 12. Fixed sniffer measurements at the Great Belt bridge (Mellqvist 2020a) and airborne sniffer measurements by Mumm on Belgian waters using a standard sniffer (Van Roy, 2019). The data corresponds to gross polluters with FSC levels above 0.4%.

4.2 Nitrogen oxides

For the FSC data in Table 2 there are corresponding measurements of fuel specific emissions for NO_x (g/kg_{fuel}). These emissions are converted to power specific emissions (g_{NOx}/kWh) assuming a fixed SFOC of 200 g_{fuel}/kWh. The power specific values have been compared to the tier levels for the respective ships. It should be noted that the remote measurement is a momentarily measure of the NO_x/CO_2 ratio at the specific load the ships is using at time of measurement, while the IMO regulation states that the limit should be obtained as a weighted average of 4 engine loads according to Equation 1. In addition, to decrease the uncertainty, the actual SFOC values of the ships are needed. We will discuss the above in the end of this section.

In the graphs below, sniffer measurements of NO_x for individual ships are shown that have been carried out in the projects EnviSum (Repka et al., 2020) and CompMon (Mellqvist 2017a). Figure 13 shows the mass specific emissions of NO_x (g_{NOx}/kg_{fuel}) for individual ships in the Göteborg ship channel during 2017. The measurements were carried out from the Älvsborg site, Figure 5, which is marked with a yellow arrow in Figure 13. The ships are either accelerating or deaccelerating when passing the site (from 8 knots to full speed) and this should impact the NO_x emissions, although no obvious pattern can be seen in the data here.

Similar NO_x measurement data are shown for the Tricity area (Gdansk, Gdynia, Soput) measured in 2017 during EnviSum. Here the power specific emissions factors (g_{NOx}/kWh) of individual ships have been calculated and then compared to the corresponding IMO levels in Figure 2. This has been done by calculating the ratio of the measured emissions against the corresponding emissions levels in the IMO curves, taking into account the tier (build year) and rated engine speed of each measured ship. The ratios are color coded in the figure and red means 30 % above the limit. It can be seen that most ships are below their Tier 1 and Tier 2 limits and that the high ones are close to harbor and then running at low engine loads. As discussed below this is the case when the ships generally have higher emissions due to poorer combustion efficiency.

Figure 15 shows the mass specific emissions for ships at berth and in operation in Tricity (Gdansk, Gdynia and Sopot) in Poland. Note the distinct difference in NO_x emission between the auxiliary and main engines. The IMO annex VI legislation targets the main engine, but the remote measurements detect both the auxiliary and main one. When the ships move slowly, the auxiliary engine will be a distinct part of the total emission and since the mass specific NOx emissions of the two engines are rather different, as seen in Figure 15, this will cause a diluting effect of the main engine ship plume and resulting in an underestimation of the estimated power specific emission rate. See further discussion below.

Figure 16 shows NO_x emission results for individual ships on the Baltic sea in 2017, obtained using airborne measurements from a Navajo Piper with the Chalmers airborne sniffer system. The figure shows power specific NO_x emission rates (g/kWh) divided by the Tier I and Tier II limits for individual ships in the Baltic sea. Red means 30 % above the limit. At least 10 % ships out of 112 showed emissions above their tier levels. Since these ships were generally running at high loads this is likely significant, see discussion below.

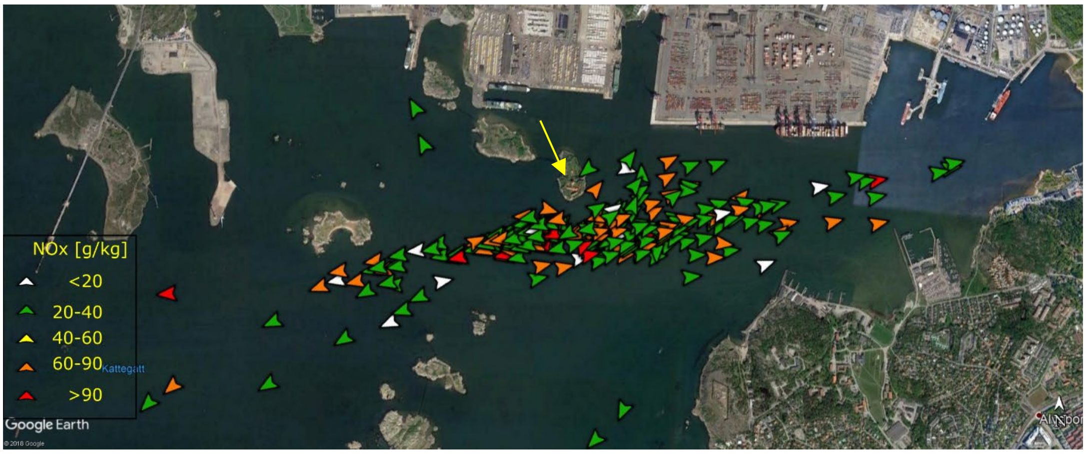


Figure 13. The mass specific emission of NO_x (g/kg_{fuel}) in individual ships upwind of the Älvsborg site (yellow arrow), close to the Göteborg ship channel.

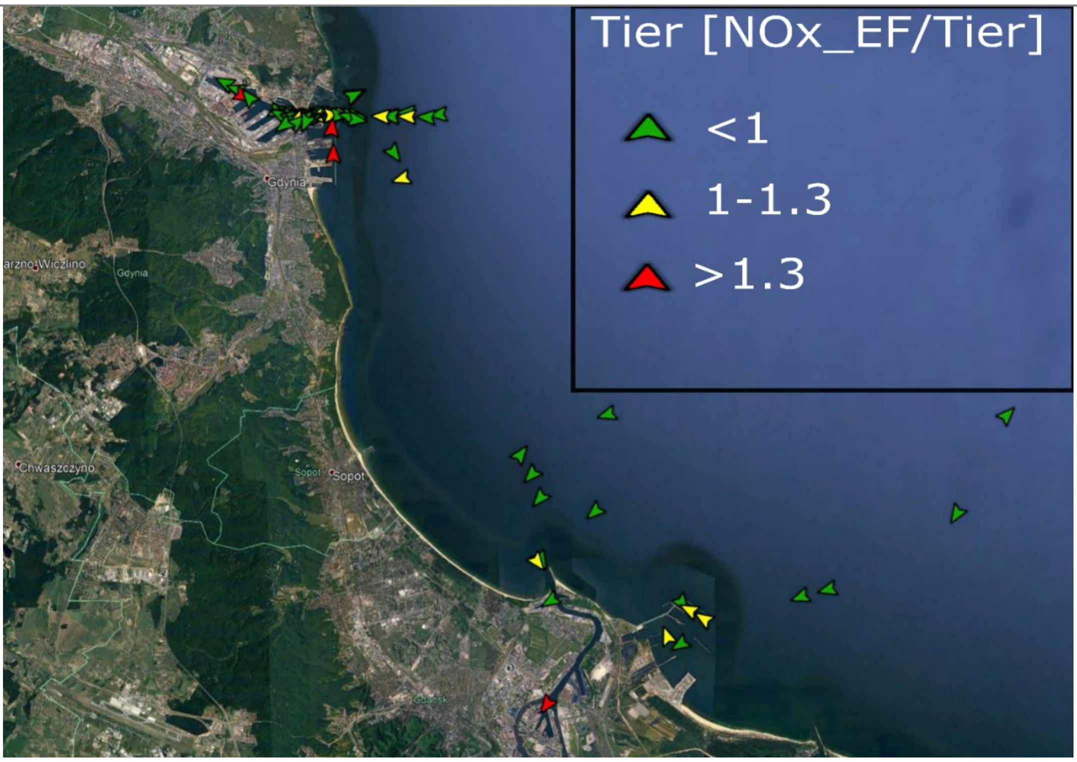


Figure 14. Power specific NOₓ emissions (g/kWh) for individual ships divided by the Tier I and Tier II limits for the individual ships in the Tricity area (Gdansk, Gdynia, Soput). Red means 30 % above the limit. The sniffer measurements were carried out from a measurement vessel.

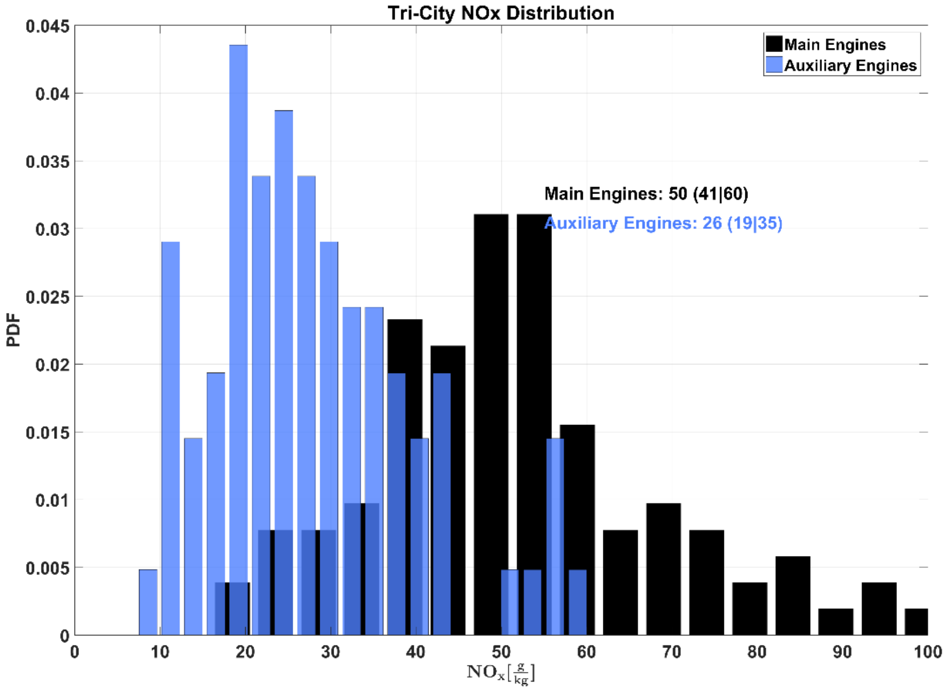


Figure 15. Shipborne mass specific NOx emission rates (g/kg) for individual ships in the Tricity area. Here is shown the probability density distribution for ships in operation (main engine) and ships at berth (auxiliary engine).

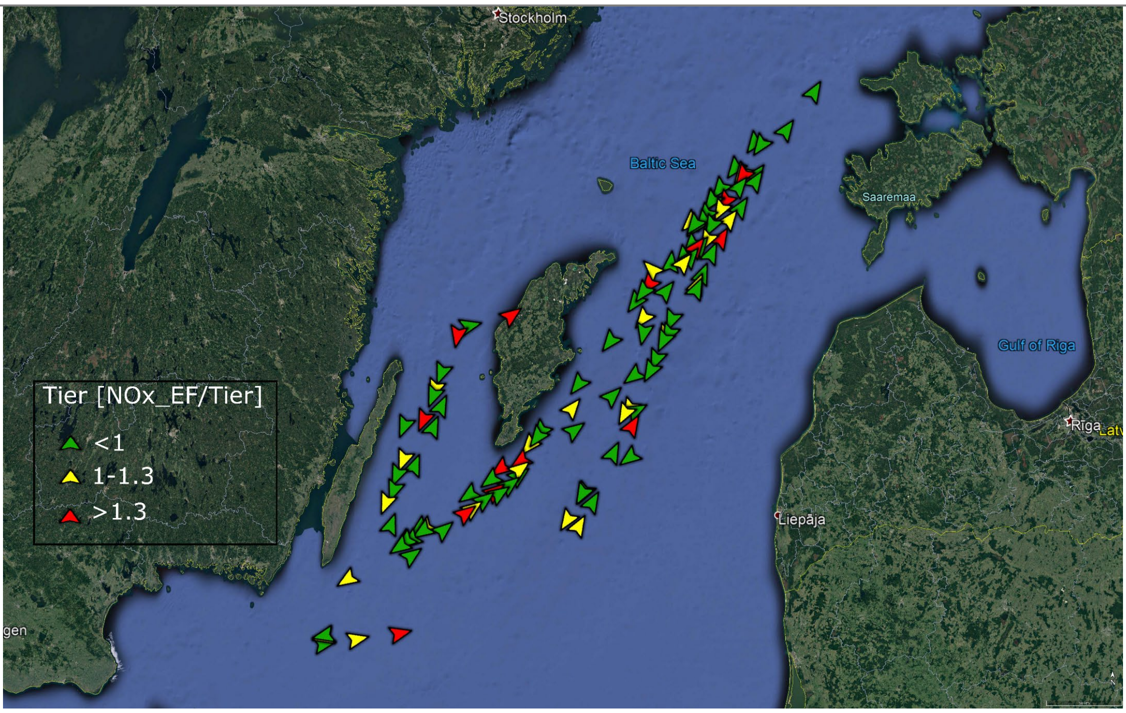


Figure 16. Airborne power specific NO_x emission rates (g/kWh) divided by the Tier I and Tier II limits for individual ships in the Baltic sea. Red means 30% above the limit.

In Figure 17 the mass specific emission rates (g/kg_{fuel}) of Black carbon (BC) particles measured in St Petersburg and Tricity are shown. The BC data have been measured using an Aethelometer (Magee 33). The data is divided into different ship types and are also shown as a function of ship speed. Here it can be seen that service ships, such as river barges, are dominant particle emitters and that the BC emission are reduced at higher speed on average. In general, the aethalometer has worked well in numerous ship measurement campaigns and we consider it a useful measurement tool to assess the BC emission from the ships. Nevertheless, at this stage there is no IMO rules or national legislation requiring such measurements to be carried out.

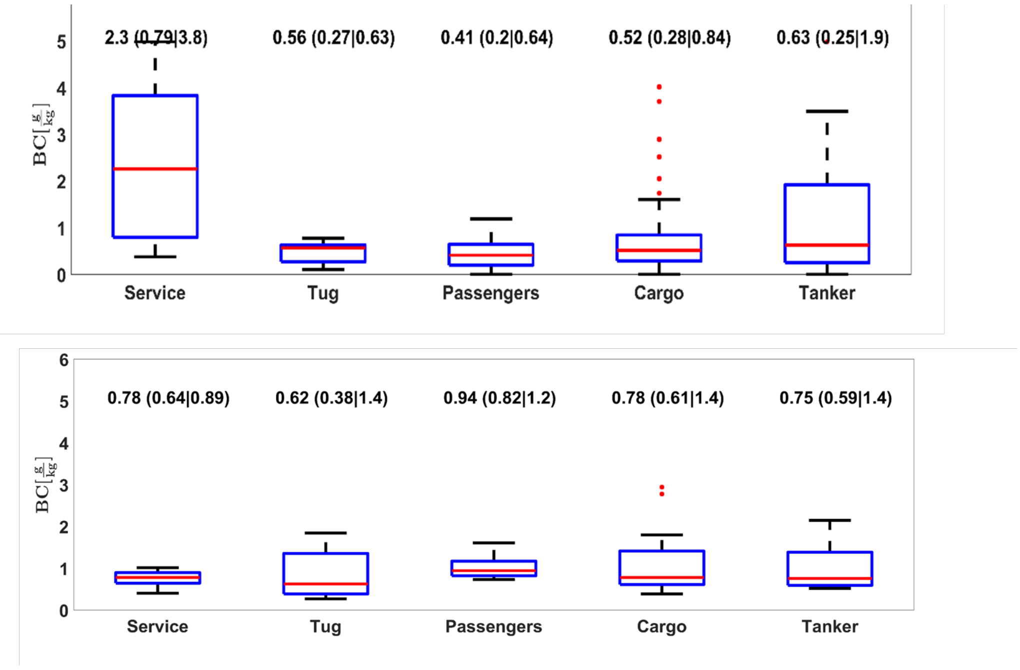


Figure 17. BC measurements in St Petersburg, Russia (upper panel) and Tricity, Poland (lower panel).

In Table 3 the fuel specific emission factors are shown for NO$_x$ and BC for several sites as part of measurements studies in EnviSum and CompMon. The main data correspond to mass specific emissions (g/kg$_{fuel}$), presented as median, 25th and 75th percentiles, respectively, for all measured individual ships. A comparison between measurement and the STEAM model (Jalkanen et al., 2009; 2012) from the Finnish Meteorological Institute (FMI) is also shown together with previous measurement results obtained with the same equipment in St Petersburg in 2012 as part of the Intereg BSR Innoship project (Beecken et al., 2015). It can be seen that the NO$_x$ emission factors measurements are rather similar in all studied areas, also when comparing 2012. The highest mass specific emissions are found on the open sea, when the ships operate on design speed while the lowest values are found for ships at berths. The median of the STEAM model generally agrees with the measurement median. This especially true for the measurements on the open sea while there is a considerable discrepancy for ships at berth. Also in the St Petersburg case there is a distinct difference in the statistical distribution and when comparing results for individual ships the scatter between model and measurements is rather high.

Table 3. Ship emission measurements of NOx and BC carried out from patrol vessels and aircraft during the projects Envisum (Repka et al., 2020a.) and CompMon (Mellqvist 2017a).

Ref	**NO$_x$** g/kg$_f$ **median 25th |75th percentile**	**NO$_x$** g/kWh	**BC** g/kg	**No Ships**	**Comment**	**Project**
Tri-city 2017	**50** 41|60	**10** 8.2|12	**0.81** 0.61|1.1	102	Main Eng	EnviSum
Tri-city *2017*	***55*** *49|63*	**11** 9.8|12.6			Steam Model Main Eng	EnviSum
Tricity 2017	**26** 19|35	**5.2** 3.8|7	**1.2** 0.78|1.6	78	At berth	EnviSum
Tricity 2017	***53*** *44|55*	**10.6** 8.8|11			STEAM Model at berth	EnviSum
GOT 2017	**55** 42|67	**11** 8.4|13.4	**0.52** 0.3|0.73	87		CompMon
GOT 2017	**64** 55|75	**12.8** 11|15			STEAM Model	CompMon
StPb 2018	**62** 51|79	**12.4** 10.2|15.8	**0.59** 0.29|0.88	175		EnviSum
StPb 2018	***64*** *55|73*	**12.8** 11|14.6			*STEAM Model*	EnviSum
Baltic Sea 2016	**69** 56|86	**13.8** 11.2|17.2		112	Airborne	EnviSum
Baltic Sea 2016	***78*** *65|90*	**15.6** 13|18			STEAM Model	EnviSum
StPb 2012	**57.7*** ±*20.9*	**11.5*** ±4.2		311	Beecken 2015 average	

As mentioned above, in the IMO NO$_x$ technical code it is required that the power specific emission rate is obtained as an average of 4 different loads (Equation 1). To convert the remote measurements to power specific emission the SFOC is also needed.

To assess this, and other uncertainty sources, the STEAM modelled data provided by FMI (Jalkanen, 2009; 2012) have been used which includes modelled average data for the SFOC for individual ships.

In Figure 18 a histogram of SFOC values (average load) are shown for 68000 ships, corresponding to 207 (190 | 230) g$_{fuel}$/kWh, where the first value is the median and the two others the 25th and 75th percentile values, respectively. Note that 200 g$_{fuel}$/kWh is used as a standard value. As seen in the figure the bulk of the ship have SFOC values between 180 and 240 g/kWh so if a value of 200 g/kWh is used this will cause a relative uncertainty in the SFOC value ranging between (-17% to +11%).

In Figure 19 is shown results from an uncertainty evaluation exercise using the STEAM model data. Here the power specific emission rates for different loads have been calculated for an oil tanker built in year 2000 using the STEAM propulsion and SFOC data and assuming that the mass specific NOx emission is load constant and the same as the IMO curve for high loads. This has been done firstly for only the main engine and secondly for the combined emission from the auxiliary and main engine, which is what the remote measurements actually detect. From these emission rates the weighted average power specific emission rate has been calculated for the main engine based on Equation 1.

In Figure 19 is shown the ratio between the apparent power specific emission rates for a given ship speed divided by the weighted IMO average. In the first case (main engine) only the main engine contribution is included, In the second case (Main and Aux) the power specific emission rate for the main and auxiliary together is divided with the weighted IMO average of the main engine. *The latter corresponds to the real measurement case and the inverse of this curve corresponds to the correction factor that should be applied for different speeds/loads*. Noteworthy is the large underestimation of the power specific emission rate at low ship speeds and even at 10 knots (37 % load) the underestimation is around 12 %. This example needs to be repeated for many ships but it indicates that a remote, short term, measurement for ships running below 40 % load (in this case 10 knots), may be associated with large uncertainties, while measurements at high loads should work reasonably well with uncertainties smaller than 10 %. The modelling shows that the auxiliary engines dilutes the signal from the main engine quite considerably at low loads and since the former are more fuel efficient (at low loads) the ship will appear to emit less NOx than it is actually doing when measured at low loads. Note that medium stroke ships (Ferries, Ropax) generally have shaft generators at speeds above 5 knots, wherefore this problem will not exist for such ships since the main and auxiliary will then be the same source.

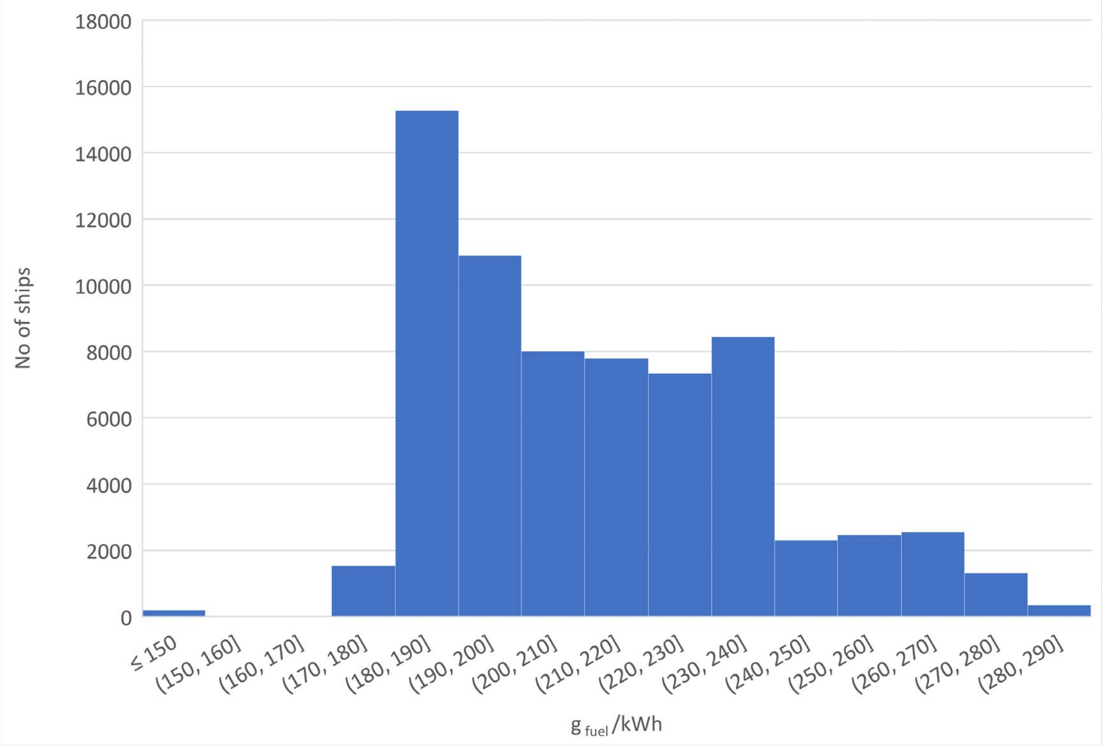


Figure 18. Histogram of average SFOC in g fuel/kWh of axial power for 68400 ships from STEAM model (Jalkanen, 2009). The median, 25th and 75th percentiles correspond to 207 (190 | 230) g/kWh. The corresponding numbers for auxiliary engines is 212 (189 | 232) g/kWh.

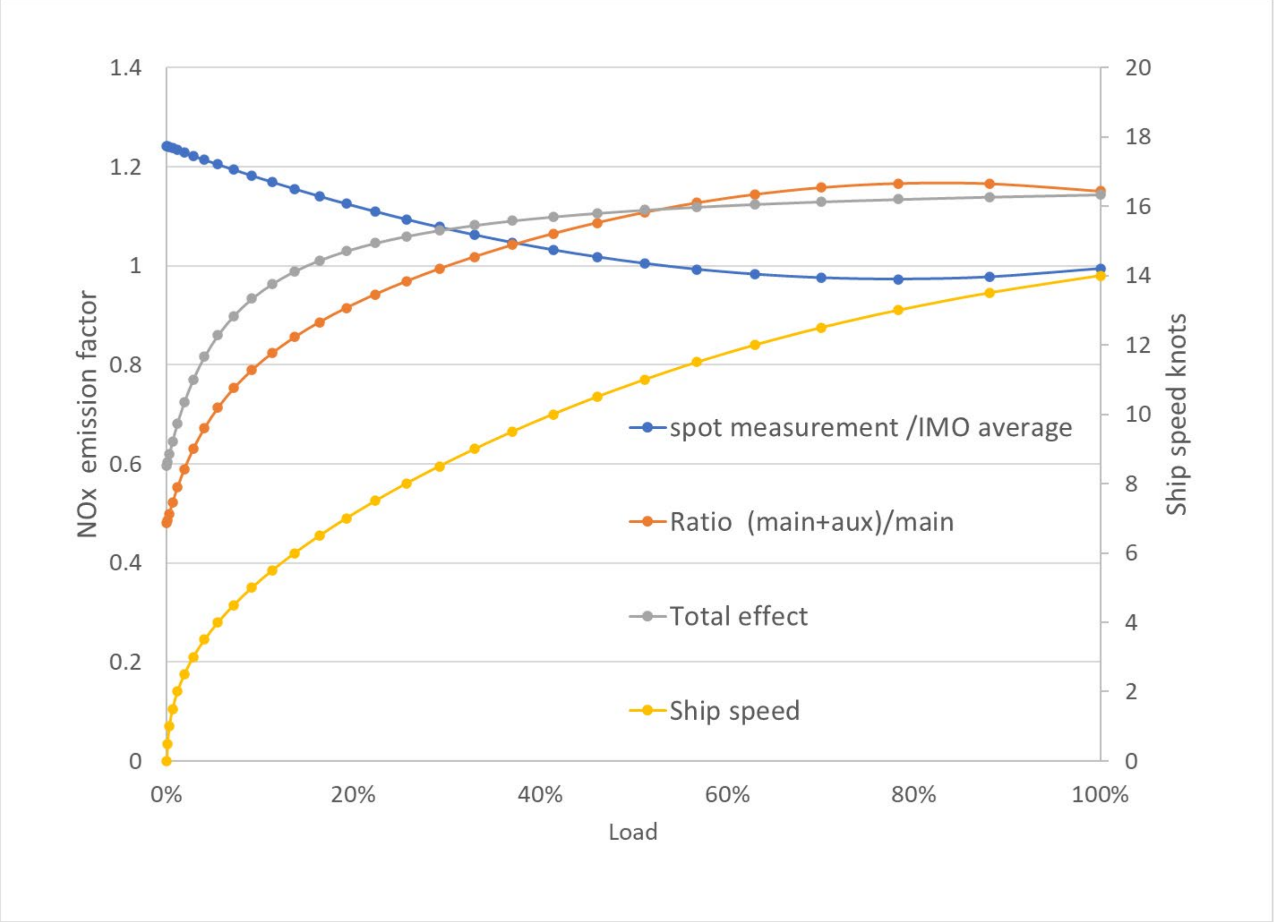


Figure 19. Modelled effect on apparent NO_x emissions. The STEAM model has been used to predict the ratio of power specific NO_x emission (g/kWh) against the IMO weighted average NO_x emission for a single Tier 1 ships. Two cases have been modelled, one with only main and the other with main and auxiliary.

5 Discussion

Remote measurements of FSC are efficient in controlling a large number of ships in a cost effective way. More than 4000 ships annually are forinstance controlled from the Great Belt site and the numbers is basically limited only by ship traffic density and prevailing wind direction.

Some challenges for FSC measurements include the following:

- Noncompliant ships are often below FSC 0.2 % in ports and it may therefore be necessary to improve the sensor sensitivity and accuracy. New laserbased ultrasensitive sensors is a good option for this.
- There are different techniques used for compliance monitoring and different operators. It is necessary to harmonize how the measurement uncertainties are reported by the different techniques to make it possible to put measurements from different techniques in the same database. A future standardization, including validation of measurements, is needed. Especially the mini-sensors needs quality routines with respect to calibration.

Challenges for NO_x includes:

.

- The specific fuel oil consumption (g_{fuel}/kWh) is required for each ship.
- The IMO technical code corresponds to an average of an engine cycle using different loads. The sniffer provides a snapshot and uncertainties with this needs to be modelled/assessed.
- At low ship traveling speeds the auxiliary engines will be a considerable fraction of the emission plume. Since auxiliary engines have better specific fuel oil consumption than the main ship engines at low load (and hence lower power specific NOx emission) this will dilute the total mixed plume measure by the sniffer system and cause a general underestimation of the NOx emission; this needs to be modelled/assessed further.
- The NO_x emissions from an example ship, corresponding to an oiltanker with built year 2000 was modelled at different loads using data from STEAM (Jalkanen 2012). This shows that a remote snapshot measurement for ships below 40 % load (in this case 10 knot), may be associated with large uncertainties, while measurements at high loads should work reasonably well.

Particles (BC):

- Measurement techniques can detect high emitting ships. However there are different definitions of BC and this needs to be agreed on before deciding what measurement technique to use. BC and PM exhibits transient emissions which makes it more difficult to carry out only short term measurements.

6 Acknowledgement

We acknowledge Belgian Mumm (Ward Van Roy), Danish EPA, Swedish Transport Agency, German BSH (Andreas Weigelt and Dutch TNO (Jan Duyzer) for providing measurements data. We also thank Jörg Beecken (BSH) for assembling information about the previous data from different groups (Appendix I). We thank Jukka-Pekka Jalkanen and Lasse Johansson (FMI) for providing STEAM data.

7 Reference

Alfoldy, B., J. Balzani, J. and F. Lagler.: FINAL REPORT ON REMOTE SENSING OF SHIPS' EMISSIONS OF SULFUR DIOXIDE, 21.06.2011, 2011, http://ec.europa.eu/environment/air/transport/pdf/ships/Final-report.pdf

Alfoldy, B., et al.: Measurements of air pollution emission factors for marine transportation, Atmos. Meas. Tech., 6, 1777-1791, 2013.

Balzani-Lööv, J. M., et al.: Field test of available methods to measure remotely SOx and NOx emissions from ships, Atmos. Meas. Tech., 7, 2597-2613, 2014, www.atmos-meas-tech.net/7/2597/2014/ doi:10.5194/amt-7-2597-2014, 2014.

Beecken, J., Mellqvist, J., Salo, K., Ekholm, J., and Jalkanen, J.-P.: Airborne emission measurements of SO2, NOx and particles from individual ships using sniffer technique, Atmos. Meas. Tech., 7, 1957–1968, 2014.

Beecken J, Mellqvist J, Salo K, Ekholm J, Jalkanen JP, Johansson L, et al. Emission factors of SO2, NOx and particles from ships in Neva Bay from ground-based and helicopter-borne measurements and AIS-based modeling. Atmospheric Chemistry and Physics. 2015;15(9):5229–41

Beecken, J.: Remote Measurements of Gas and Particulate Matter Emissions from Individual Ships, PhD dissertation, Earth and Space Sciences, Chalmers University of technology, ISBN 978-91-7597-141-4, ISSN 0346-718X, 2015

Berg, N.: Remote Measurement of Ship Emissions, Technical report 43 L, Earth and Space Sciences, Chalmers University of Technology, 2011

Berg, N., Mellqvist, J. et al.: Ship emissions of SO2 and NO2: DOAS measurements from airborne platforms, Atmos. Meas. Tech., 5, 1–14, 2012.

EU: Council Directive 1999/32/EC of 26 April 1999 relating to a reduction in the sulphur content of certain liquid fuels and amending Directive 93/12/EEC, OJ L 121, 11.5.1999, p. 13–18 (EN), https://eur-lex.europa.eu/eli/dir/1999/32/oj, 1999.

EU: Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels, OJ L 327, 27.11.2012, p. 1–13 (EN), https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32012L0033, 2012.

Explicit, Airborne Monitoring of Sulphur Emissions from Ships in Danish Waters, Environmental Project No. 2121, The Danish Environmental Protection Agency, January 2020, 978-87-7038-157- https://mst.dk/service/publikationer/publikationsarkiv/2020/jan/airborne-monitoring-of-sulphur-emissions-from-ships-in-danish-waters/

Explicit, Airborne Monitoring of Sulphur Emissions from Ships in Danish Waters, Environmental Project No. 2154, The Danish Environmental Protection Agency, January 2021, 978-87-7038-256-4

Jalkanen, J.-P. et al., A modeling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area. Atmospheric Chemistry and Physics (9), 9209-9223, 2009

Jalkanen, J.-P. et al., Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxideAtmos. Chem. Phys., 12, 2641–2659, 2012, doi:10.5194/acp-12-2641-2012, www.atmos-chem-phys.net/12/2641/2012/

Mellqvist, J and Berg N., Final report to Vinnova: IDENTIFICATION OF GROSS POLLUTING SHIPS RG Report (Göteborg) No. 4, ISSN 1653 333X, Chalmers University of Technology, 2010 http://publications.lib.chalmers.se/publication/214636

Mellqvist, J., Ekholm, J., Salo K. and Beecken J., Final report to Vinnova: IDENTIFICATION OF GROSS POLLUTING SHIPS TO PROMOTE A LEVEL PLAYING FIELD WITHIN THE SHIPPING SECTOR, RG Report (Göteborg) No. 11, Chalmers University of Technology, 2014 http://publications.lib.chalmers.se/publication/214636

Mellqvist, J., Beecken, Conde, V, and J. Ekholm, CompMon report: Certification of an aircraft and airborne surveillance of fuel sulfur content in ships at the SECA border, Chalmers University of Technology, 2017a,, https://research.chalmers.se/publication/500250/file/500250_Fulltext.pdf

Mellqvist, J., Beecken, Conde, V, and J Ekholm, CompMon report: Fixed remote surveillance of fuel sulfur content in ships from fixed sites in the Göteborg ship channel and at Öresund bridge, Chalmers University of Technology, 2017b, https://compmon.eu/

Mellqvist, J., Beecken, and J Ekholm, Remote Quantification of Stack Emissions from Marine Vessels in the South Coast Air Basin, Report to South Coast Air Quality Management District, 2017c, http://www.aqmd.gov/fenceline-monitoring/project-3

Mellqvist et al., 2018, Surveillance of Sulfur Emissions from Ships in Danish Waters, final report to Danish Environmental Protection agency , DOI: 10.17196/DEPA.001,http://dx.doi.org/10.17196/DEPA.001

Repka et al., Envisum final report, 2019a, Clean Shipping: Exploring the impact of emission regulation, https://projects.interreg-baltic.eu/fileadmin/user_upload/Library/Outputs/EnViSuM_FinalReport.pdf, https://blogit.utu.fi/envisum/

Mellqvist et al., 2019b, Surveillance of Sulfur Emissions From Ships at the Great Belt Bridge 2018, Environmental Project No. 2107 October 2019 The Danish Environmental Protection Agency, ISBN: 978-87-7038-123-9, https://mst.dk/service/publikationer/publikationsarkiv/2019/okt/surveillance-of-sulfur-emissions-from-ships-at-the-great-belt-bridge-2018/

Mellqvist et al., 2020a, Surveillance of Sulfur Emissions From Ships at the Great Belt Bridge 2019, Environmental Project No. 2142 June 2020 The Danish Environmental Protection Agency, ISBN: 978-87-7038-203-8, (https://mst.dk/service/publikationer/publikationsarkiv/2020/jul/surveillance-of-sulfur-fuel-content-in-ships-at-the-great-belt-bridge-2019/)

Mellqvist et al., 2020b, Surveillance of Sulfur Fuel Content in Ships at the Great Belt Bridge 2020, Environmental Project No 2153, December 2020, The Danish Environmental Protection Agency, ISBN: 978-87-7038-250-2 , https://www2.mst.dk/Udgiv/publications/2020/12/978-87-7038-250-2.pdf

Mellqvist et al., 2020a, Airborne Marpol Annex VI Monitoring in Belgium Presentation at CSHIPP webinar on Clean Shipping International Policies, Nov 27

Van Roy, W., Airborne Marpol Annex VI Monitoring in Belgium, Presentation at Shipping & the Environment II, From Regional to Global Perspectives, Gothenburg, Sweden, 4-6 September 2019. https://s-and-e-2019.ivl.se/presentations.4.57581b9b167ee95ab99c3e.html

Seyler, A., Wittrock, F., Kattner, L., Mathieu-Üffing, B., Peters, E., Richter, A., Schmolke, S., and Burrows, J. P.: Monitoring shipping emissions in the German Bight using MAX-DOAS measurements, Atmos. Chem. Phys., 17, 10997–11023, https://doi.org/10.5194/acp-17-10997-2017, 2017.

Seyler, A., Meier, A. C., Wittrock, F., Kattner, L., Mathieu-Üffing, B., Peters, E., Richter, A., Ruhtz, T., Schönhardt, A., Schmolke, S., and Burrows, J. P.: Studies of the horizontal inhomogeneities in NO2 concentrations above a shipping lane using ground-based multi-axis differential optical absorption spectroscopy (MAX-DOAS) measurements and validation with airborne imaging DOAS measurements, Atmos. Meas. Tech., 12, 5959–5977, https://doi.org/10.5194/amt-12-5959-2019, 2019.

Weigelt, A., , Airborne Marpol Annex VI Monitoring in Belgium, Presentation at Shipping & the Environment II, From Regional to Global Perspectives, Gothenburg, Sweden, 4-6 September 2019. https://s-and-e-2019.ivl.se/presentations.4.57581b9b167ee95ab99c3e.html

Appendix A Description of European FSC measurement data until 2019

Table App. A-1: Example of measurement data (courtesy of Jörg Beecken BSH).

Country	Monitored Region	Measurement Period	Number of Measured Plumes until end of 2018	Method	Measured Species	Deployment
DE	Elbe River / Harbour entrance Hamburg (Wedel)	since 09/2014	16672	sniffer	SO_2, CO_2, NO, NO_2, O_3	ground-based (fixed site)
DE	North Sea Port Bremerhaven	since 08/2017	3661	sniffer	SO_2, CO_2, NO, NO_2, O_3	ground-based (fixed site)
DE	Harbour entrance Kiel / Kiel Kanal	since 04/2018	1557	sniffer	SO_2, CO_2, NO, NO_2, O_3	ground-based (fixed site)
DK	Danish waters	Since 07/2017	1018	sniffer	SO_2, CO_2, NO, NO_2	Airborne platform
NL	Dutch waters	one week: 09/2016	327	sniffer	SO_2, CO_2, NO, NO_2	Airborne platform
NL	Rotterdam	2006 to 2007	150	sniffer	PM, SO_2, NO_x	ground-based (mobile site also used to monitor inland shipping)
NL	Rotterdam	2015 to 2019	With some periods not available maximum 5000 reported per year(many rejected because of several reasons)	sniffer	SO_2, NO_x	ground-based (fixed site)
NL	Dutch inland waters	2006-2007	150	sniffer	PM, SO_2, NO_x	ground-based (mobile site also used to monitor inland shipping)
BE		Since 2015	3463	airborne sniffer	SO_2, CO_2	Fixed-wing aircraft
FI	Finnish waters	2015-2018	200	sniffer	CO_2, SO_2, NO_2, NO	Unmanned aerial system (multicopter)
GR	Greek waters	2017-2018	50	sniffer	CO_2, SO_2, NO_2, NO	Unmanned aerial system (fixed-wing)

DK	Danish Waters	2015 - 2019	1712	airborne sniffer /optical	CO_2, SO_2, NO_x,NO_2	Airborne
DK	Great Belt Bridge	2015 - 2019	23820	sniffer	CO_2, SO_2, NO_x	ground-based (fixed site)
DK	Great Belt Bridge	2017/07	312	sniffer	PM, PN and Black Carbon	ground-based (fixed site)
SE	Älvsborg/Entrance Port of Göteborg	2015 - 2019	14715	sniffer	CO_2, SO_2, NO_x	ground-based (fixed site)
SE	Älvsborg/Entrance Port of Göteborg	2016/08	391	sniffer	PM, PN and Black Carbon	ground-based (fixed site)
SE	Gotland / Baltic Sea	2017/08	136	airborne sniffer / optical	CO_2, SO_2, NO_x, NO_2	Airborne
SE/DK	Öresund Bridge	2018/06 - 2019	2473	sniffer	CO_2 ,SO_2, NO_x	ground-based (fixed site)
PL	Gdnya-Gdansk port	2017/10	527	sniffer	CO_2, SO_2, NO_x, PM, PN and Black Carbon	boat/in situ
RU	Saint Petersburg	2018/10	279	sniffer	CO_2,SO_2, NO_x, PM, PN and Black Carbon	boat/in situ
FR	English channel	2016/09	277	airborne sniffer /optical	CO_2, SO_2, NO_x, NO_2	Airborne