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Assessment of the Effect of International Maritime Regulations on Air Quality in the Southern North Sea

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Abstract: Air pollution is a leading cause of death worldwide, and it has a profound impact on the planet's climate and ecosystems. A substantial portion of air pollution is attributable to Ocean Going Vessels (OGVs). In light of this, international regulations have been put in place to mitigate air pollutant emissions from OGVs. While studies have indicated that these regulations can create significant health, environmental, and economic benefits, there remains a research gap regarding their specific impact on enhancing air quality. The aim of this study is to investigate how the implemented regulations have affected air quality in the Southern North Sea. The study found that the international regulations on ship emissions have successfully led to a decline in SO_2 emissions from OGVs in the Southern North Sea, which resulted in a reduction of ambient SO_2 concentrations inland, leading to positive effects on public health and the environment. However, the proportion of shipping's contribution to SO_2 emissions is projected to increase in the future. Moreover, the study revealed that the use of Exhaust Gas Cleaning Systems (EGCS) presents significant concerns. They were more frequently found to be non-compliant, and, more alarmingly, they emit higher mean levels of SO_2. It also emerged that international regulations in the southern North Sea have less of an impact on the reduction of NO_x emissions from OGVs than expected, which is all the more important given that NO_x emissions from OGVs are expected to account for 40% of the total domestic NO_x emissions for the northern region of Belgium by 2030.

Keywords: MARPOL Annex VI; emissions from ocean going vessels; remote emission monitoring; sulfur dioxide; nitrogen oxides; ECA; air quality measurements

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1. Introduction

Ninety-nine percent of the world's population is exposed to air containing high levels of pollutants that exceed the limits of World Health Organization (WHO) guidelines [1]. The negative health effects of air pollution are well-documented, with an estimated 9-million annual deaths worldwide attributed to exposure to ambient air pollution [2]. Despite significant reductions in emissions for many air pollutants over the past two decades, concentrations of air pollutants in the European Union remain too high. In 2020, the European Environment Agency (EEA) reported that 96% of city residents were exposed to harmful concentrations of particulate matter (PM) [3]. For the northern Belgian region of Flanders, it was estimated that PM is responsible for 300–600 premature deaths per year [4]. PM is not the only reason for concern, as despite a decrease of more than 50% in NO_x emissions in the EU since 1990, NO_x recorded values exceed the annual EU limits in several European countries, and all 35 EU member states (MS) have recorded values exceeding WHO guidelines for NO_x [3,5].

Ocean Going Vessels (OGVs) emit a range of air pollutants such as SO_x, NO_x, and PM [6–9], contributing to 10–15% of global anthropogenic SO_2 emissions and 15–20% of

NO_x emissions [10,11]. At the EU level, OGVs are estimated to be responsible for 24% of SO_2 and NO_x total emissions [12]. These emissions have severe health and environmental impacts [13–17]. While land-based sources of air pollution have been regulated for years, thus leading to a reduction in their contribution to air pollution [5,18], shipping was left unregulated for much longer. In 2008, regulations were introduced under the Marine Pollution Convention (MARPOL) of the International Maritime Organization (IMO) to decrease emissions from OGVs, in particular, SO_x and NO_x [19,20]. MARPOL Annex VI introduced Emission Control Areas (ECAs) with stricter emission limits [21–25].

As part of MARPOL Annex VI, Regulation 14 sets limits on SO_x emissions from OGVs. In 2008, the North Sea and Baltic Sea were declared Sulfur Emission Control Areas (SECAs) [22,26,27] (Figure S1A). In the SECA, OGVs are required to use compliant fuels or an exhaust gas cleaning system (EGCS) [28–31]. Outside the SECA, sulfur limits were tightened in 2020 by the so-called "Global Sulfur Cap" [32] (Figure S1B) and "Carriage Ban" [33]. SO_x emission regulations have been implemented in both EU and Belgian legislation [34–37]. The EU Sulfur Directive led to the implementation of mandatory inspection numbers and the creation of Thetis EU—the port inspection database managed by the European Maritime Safety Agency (EMSA) for the exchange of inspection and monitoring results [38].

Regulation 13 of MARPOL Annex VI introduces the NO_x emission limits [26,39,40]. In 2021, a NO_x Emission Control Area (NECAs) came into force in the North Sea and Baltic Sea [22,24] (Figure S1A). The NO_x emission limits are expressed as the weighted amount of NO_x emission (g), per Brake Horse Power (BHP), on the crankshaft (kWh). Based on the Keel Laying Date (KLD), the merchant fleet is divided into four tiers. The emission limit per tier is, furthermore, based on the Engine Rated Speed (ERS or n). Certification is done prior to and after the installation of the engines on board, based on test procedures described in the NO_x Technical Code [41]. These procedures are based on a weighted average of five different test cycles with four-to-five engine loads and corresponding weighting factors (Table S1) [41,42].

2. Methods

2.1. Belgian Coastguard Aircraft and Sniffer Sensor

The research was executed in the Southern North Sea, an area renowned for its high maritime traffic density [43,44]. The Scientific Service Management Unit of the Mathematical Model of the North Sea (MUMM) of the Royal Belgian Institute of Natural Sciences (RBINS) is one of the 17 Belgian coastguard partners [45]. MUMM is responsible for the monitoring and enforcement of MARPOL regulations in the Belgian North Sea area and neighboring waters, in the so-called Bonn Agreement (BA) Quadripartite Zone of Joint Responsibility (BAQPZJR) [45]. The Belgian coastguard aircraft, owned by RBINS, was used for this study. The aircraft is a Britten Norman Islander (BN2) equipped with modern avionics and a remote sensing system from Optimare (Bremerhaven, Germany). In 2015, the aircraft was equipped with a sniffer sensor system, developed by Chalmers University and built by FluxSense (Gothenburg, Sweden) [46].

2.1.1. Sniffer Sensor

The sniffer sensor consists of a set of different sensors and equipment mounted in a standard 19-inch rack (Figure S2). The most important units are (i) A Thermo Trace-Level Ultraviolet fluorescence sensor, used for the measurement of SO_2 in ppb; (ii) A Licor Bioscience nondispersive infrared (NDIR) sensor, used for the measurement of CO_2 in ppm; (iii) An Ecotech Serinus 40 chemiluminescence sensor for the measurement of NO_x; (iv) A custom-designed hydrocarbon kicker; (v) Three powerful vacuum pumps (one for the SO_2 and CO_2 sensor, one for the hydrocarbon kicker, and one for the NO_x sensor; (vi) Pressure and flow regulators; (vii) A log computer; (viii) A combined Automatic Identification System (AIS) and Global Positioning System (GPS) receiver; (ix) An Aeronautical Radio INC. (ARINC) module and; (x) A particle filter (1 µm) installed at the air-inlet of the sniffer sensor and on the other side connected to a stainless-steel sampling tube (3/8″) installed on the bottom of the aircraft [47].

2.1.2. FSC Measurements

The Fuel Sulfur Content (FSC) can be calculated based on the ambient and the exhaust plume's SO_2 and CO_2 concentrations [47–55]. To retrieve the amount of combusted fuel, the amount of C was multiplied with the carbon fuel content of 87% [49,51].

$$\mathrm{FSC} = 0.232 \times \frac{\int \left[\mathrm{SO_2} - \mathrm{SO_{2,bkg}}\right]_{\mathrm{ppb}} \mathrm{dt}}{\int \left[\mathrm{CO_2} - \mathrm{CO_{2,bkg}}\right]_{\mathrm{ppm}} \mathrm{dt}} [\%\mathrm{Sulphur}] \quad (1)$$

When the NO_x sensor was installed in 2020, this formula was modified to correct for the NO cross-sensitivity of the SO_2 sensor and was adapted by subtracting the measured SO_2 with the NO amount in the plume, multiplied by the cross-sensitivity factor (CS_{NO}).

$$\mathrm{FSC_{NO}} = 0.232 \times \frac{\int \left[\mathrm{SO_2} - \mathrm{SO_{2,bkg}}\right]_{\mathrm{ppb}} - CS_{NO} \times \left[\mathrm{NO} - \mathrm{NO_{bkg}}\right]_{\mathrm{ppb}} \mathrm{dt}}{\int \left[\mathrm{CO_2} - \mathrm{CO_{2,bkg}}\right]_{\mathrm{ppm}} \mathrm{dt}} [\%\mathrm{Sulphur}] \quad (2)$$

The general modus of the NO_x sensor during surveillance operations was set to NO_x. To estimate the NO concentration from the measured NO_x concentrations, a default NO/NO_x In-Stack Ratio (*ISR*) of 80% was used [47,55].

$$\mathrm{fsc_{no}} = 0.232 \times \frac{\int \left[\mathrm{so_2} - \mathrm{so_{2,bkg}}\right]_{\mathrm{ppb}} - cs_{no} \times isr \times \left[\mathrm{no_x} - \mathrm{no_{x,bkg}}\right]_{\mathrm{ppb}} \mathrm{dt}}{\int \left[\mathrm{co_2} - \mathrm{co_{2,bkg}}\right]_{\mathrm{ppm}} \mathrm{dt}} [\%\mathrm{sulphur}] \quad (3)$$

However, the NO/NO_x ratio is highly variable [56,57]. Therefore, by default, the NO_x mode was used. In case the initial FSC exceeded the operational threshold (T_{ops}), the sensor was set to NO mode and two new measurements were made.

The FSC measurement was found to have a negative bias that consisted of an absolute component or offset (*b*) and a relative component or slope (*a*) [50]. To determine these factors, three special gas mixtures containing SO_2 and CO_2 in different levels (Table S2) were used to imitate exhaust plume of different FSC levels (Figure 1).

$$\mathrm{FSC_{cor}} = \mathrm{FSC} \times a + b \quad (4)$$

subsubsectionNO_x Measurements

The NO_x emission factor (EF_{NOx}) in g NO_x/kg fuel is calculated similarly to the FSC using the background and plume NO_x and CO_2 concentrations [51,53,56,58].

$$\mathrm{EF_{NO_x}} = \frac{\mathrm{MNO_2}\frac{\mathrm{g}}{\mathrm{mol}}}{\frac{\mathrm{MC}\frac{\mathrm{g}}{\mathrm{mol}}}{0.87}} \times 1000 \times \frac{\int \left[\mathrm{NO_x} - \mathrm{NO_{x,bkg}}\right]_{\mathrm{ppm}} \mathrm{dt}}{\int \left[\mathrm{CO_2} - \mathrm{CO_{2,bkg}}\right]_{\mathrm{ppm}} \mathrm{dt}} \left[\frac{\mathrm{g}}{\mathrm{kgfuel}}\right] \quad (5)$$

$$\mathrm{EF_{NO_x}} = 3.33 \times \frac{\int \left[\mathrm{NO_x} - \mathrm{NO_{x,bkg}}\right]_{\mathrm{ppb}} \mathrm{dt}}{\int \left[\mathrm{CO_2} - \mathrm{CO_{2,bkg}}\right]_{\mathrm{ppm}} \mathrm{dt}} \left[\frac{\mathrm{g}}{\mathrm{kgfuel}}\right] \quad (6)$$

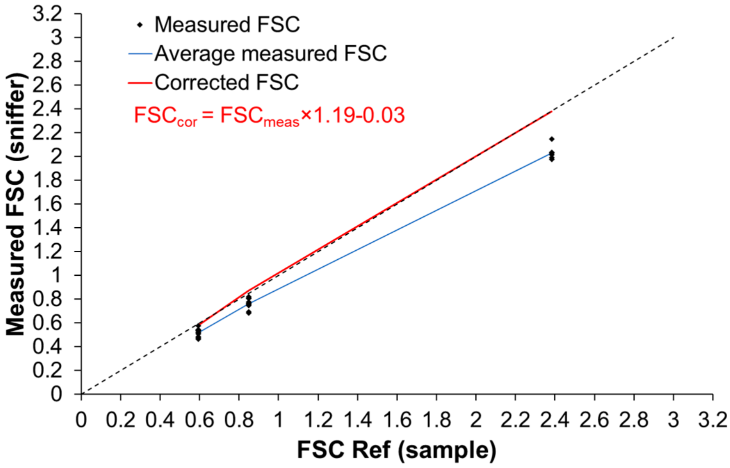

Figure 1. Correction using a linear regression (in red line) of FSC measurements of three special plume-simulation mixtures (black ⧫). The dashed line stands for a perfect match (x = y).

For the calculation of the NO_x emission in g NO_x/kWh, the NO_x emission factor (g NO_x/kg fuel) is then multiplied by the Specific Fuel Consumption (SFC), which is described by the amount of fuel consumed (in kg) per Break Horse Power (BHP) expressed in kilowatts per hour (kWh).

$$\text{SFC} = \frac{\text{kgfuel}}{\text{kWhBHP}} \quad (7)$$

$$\text{EF}_{\text{P,NO}_\text{x}} = \text{EF}_{\text{NO}_\text{x}} \times \left(\frac{\text{kgfuel}}{\text{kWhBHP}}\right) \quad (8)$$

Typically, the SFC ranges from 0.16 kg/kWh to 0.24 kg/kWh [11,48,59–67]. An average SFC of 0.2 kg/kWh is used by default. If the T_{OPS} is exceeded, radiocommunication with the OGV is established to obtain the fuel consumption and power data to improve the accuracy of the EF measurement.

2.1.3. Measurement Quality, Uncertainty, and Reporting Thresholds

Only high-quality measurements were retained based on following requirements: (i) Unquestionable linking of the plume to the OGV; (ii) Comparable response times of the SO_2, NO_x, and CO_2 gas sensors; (iii) Sufficient plume sampling time; (iv) High Signal-to-Noise Ratio (SNR); and (v) Absence of interference from other sources [50]. In addition, a Sniffer Quality Management System (SQMS) was composed describing the Standard Operational Procedures (SOPs) for the execution of the flights, the maintenance of the system, and the management of the data [47,50,56].

The uncertainty (U) for the FSC measurements was assessed based on three levels of FSC [50]. Improvements were made in the SO_2 measurement uncertainty from 2020 onwards, and the NO cross-sensitivity of the SO_2 sensor was eliminated. Furthermore, a custom-designed hydrocarbon kicker was introduced to remove the VOCs from the airflow, and the measurement bias was eliminated by using custom SO_2/CO_2 gas concentration mixtures to simulate exhaust plumes (Table S2) [47]. The uncertainty of the NO_x measurement was calculated based on three levels of NO_x per tier level for both OGVs with an ERS < 130 rpm and for OGVs with an ERS > 500 rpm (Table S3) [56].

The calculated uncertainties were then used for establishing operation threshold levels (T_{ops}) for reporting non-compliant OGVs. Three colors were assigned as flags to categorize the alert level. The yellow flag indicates the lowest alert level with a confidence interval (CI) of 68% (σ = 1). The orange flag has a higher alert level with a CI of 95% (σ = 1.96). The red color flag is reserved for the most severe pollution alerts and is based on a 99% CI (σ = 2.576) (Table 1). If a first measurement suggested possible non-compliance, a second measurement was taken, except in cases where it was not feasible for operational reasons [47,50,51].

Table 1. Alert flag thresholds for FSC (%) as from 2015–2022 and for NO_x (g/kWh) from 2020–2022.

		Color Flag	σ	U	**CI**	**Sulfur Limit**	T	T_{ops}
2015–2019		Yellow	1	30%	68%	0.10%	0.145%	0.15%
		Orange	1.96	35%	95%	0.11%	0.174%	0.20%
		Red	2.576	43%	99%	0.15%	0.275%	0.40%
2020–2022		Yellow	1	25%	68%	0.10%	0.13%	0.13%
		Orange	1.96	38%	95%	0.11%	0.18%	0.20%
		Red	2.576	48%	99%	0.15%	0.29%	0.30%
2020–2022 (with n = 2)		Yellow	1	18%	68%	0.10%	0.12%	0.12%
		Orange	1.96	27%	95%	0.11%	0.15%	0.15%
		Red	2.576	34%	99%	0.15%	0.23%	0.25%
Tier	NO_x **Limit**	**Color flag**	**NTE**	σ	U	T	$T_{ops\text{-}20}$	$T_{ops\text{-}22}$
Tier I	17	Yellow	15%	1	19.8%	21.2	25	25
		Orange	20%	1.96	44.5%	31.8	35	35
		Red	50%	2.576	58.5%	53.2	60	55
Tier II	14.4	Yellow	15%	1	19.8%	17.9	20	20
		Orange	20%	1.96	44.5%	26.9	30	30
		Red	50%	2.576	58.5%	45.0	50	45
Tier III	3.4	Yellow	50%	1	19.8%	5.4	7	6
		Orange	60%	1.96	44.5%	7.5	9	8
		Red	65%	2.576	58.5%	8.9	12	9

2.2. Thetis–EU

The EU Sulphur Directive led to the creation of Thetis–EU, an online database utilized for exchanging inspection results. The European Maritime Safety Agency (EMSA) manages and hosts the database. Thetis–EU is accessible to inspectors across all EU MS, including Norway and Iceland. However, due to Brexit, the UK no longer has access to the database [35,68].

2.2.1. Keel Laying Date

Information on the keel laying date (KLD) is crucial for determining the tier level in assessing NO_x compliance. This KLD data were acquired based on merging two database sources: (1) The Global Integrated Shipping Information System (GISIS) of the International Maritime Organization (IMO) [69]; and (2) Thetis–EU of the European Maritime Safety Agency (EMSA) [70]. The GISIS database was used to gather information on OGVs larger than 75 m with built year and IMO number, while EMSA provided accurate KLD and MMSI information of the OGVs that were constructed, as well as the planned vessels [56].

2.2.2. EGCS Data

Thetis–EU also includes information on EGCS. A list of 6048 EGCS–OGVs was obtained from EMSA after a formal request from the Belgian National Competent Authority (NCA). However, the data are based on the port inspections executed by the EU MS and is, therefore, non-exhaustive. There were several instances where OGVs have been observed to be equipped with EGCS that were not documented in the EMSA data [47,70]. In addition, EGCS information from the GISIS database from IMO was consulted [69]; this contained 1516 additional EGCS–OGVs.

2.3. Inland Air Quality Measurement Data

2.3.1. Inland Coastal Data and Non-Coastal Data

Air quality data from 41 inland measurement stations managed by the Flemish Environmental Agency (VMM) were collected to assess the impact of OGVS emissions on inland air quality [71]. The stations were classified into two categories: (1) Coastal or port stations; and (2) Non-coastal or non-port stations. Data were collected for the period from 2008–2022. The difference between the two categories stands in proportion to the air pollution contribution from the maritime transport sector. However, it should be noted that this difference also includes a significant contribution from industry and energy sources, as these facilities are largely located in port areas, which may be particularly true for SO_2.

2.3.2. Trend Analysis by Emission Source

To conduct a trend analysis by emission source, data from VMM were used [71]. These data consist of emission data categorized by source for the period spanning from 2000 to 2020. In addition, a short-term linear regression trend was created for each SO_2 and NO_x source based on past years' data, omitting 2020 because it was affected by the global COVID pandemic. For most sources, the period used for the linear regression was either from 2010–2019 or from 2015–2019.

Regarding shipping, the future projections for SO_2 and NO_x were established by combining several trends: (1) The trend of the difference between coastal and non-coastal stations between 2016 and 2022 (slope = *a*, intercept = *b*); and (2) The projected increase in shipping (2.1% annually) [72]. An additional correction factor for FSC noncompliance (*c*) was added for the SO_2 future projects. This factor was based on the correlation between the increase in SO_2 emissions from shipping and the FSC non-compliance rate. This factor was calculated for the period from 2021–2022 and was then between 1.06 and 1.08; therefore, a factor of 1.07 was used for the future projections (2023–2030).

$$NO_{x_i} = (a \times (2020 + i) + b) \times 1.021^i \quad (9)$$

$$SO_{2_i} = (a \times (2020 + i) + b) \times 1.021^i \times c \quad (10)$$

2.4. Statistical Analysis

The normality of the emission measurement data was evaluated using a Kolmogorov–Smirnov test, which showed that the data did not follow a normal distribution ($p < 0.05$). Consequently, non-parametric tests were utilized. A two-tailed Kolmogorov–Smirnov test was used to compare the distributions of measurements obtained between different groups (temporal periods, Tier levels, EGCS, etc.); statistical significance was determined at $p < 0.05$. To assess the difference in compliance rates between the two distributions, a two-sided chi-square test was used, with statistical significance defined as $p < 0.05$ [73,74]. When discussing Type I errors, they refer to false positives, while Type II errors refer to false negatives.

3. Results and Discussion

From 2015 onwards, the RBINS has been conducting airborne surveillance operations for the monitoring of Regulation 14 of MARPOL Annex VI concerning sulphur emissions from OGVs [47,50,75]. The RBINS expanded its monitoring efforts in 2020 to include Regulation 13 of MARPOL [47,56]. The collected dataset contains 6954 FSC measurements and 2353 NO_x measurements and, therefore, comprises the largest set of airborne OGV emission measurements to date.

3.1. Belgian Airborne Monitoring Dataset

During the monitoring period from July 2015 to November 2022, the RBINS conducted 414 flights and 645 operational flight hours, making approximately 10,446 low passes in the exhaust plumes of 7536 OGVs, measuring 6954 OGVs' FSC and 2353 OGVs' NO_x emission [47,50,56,75].

The predominant type of measured OGVs was container OGVs (31%), followed by tanker OGVs (29%), general cargo and bulk carrier OGVs (20%), and passenger and Roll On, Roll Off (RORO) OGVs (15%) (Figure S3). Regarding NO_x monitoring, the majority of monitored OGVs were Tier I OGVs (52.6%), followed by Tier II OGVs (37.5%), Tier 0 OGVs (9.6%), and Tier III OGVs (0.3%).

The standard operating procedures (SOPs) specified a minimum ship length of 100 m, although smaller OGVs were occasionally included. The average length of the monitored OGVs was 214 m (Figure S4), and only OGVs that were on-route were measured, with an average speed of 12.7 knots (Figure S5). The majority of the monitored OGVs had a port of destination in Belgium (30%), Netherlands (24%), the UK (10%), and Germany (7%), with the main ports being Antwerp (22%), Rotterdam (17%), and Zeebrugge (5%) (Figure S6). The most frequently observed flag states were Liberia (11%), Panama (13%), and the Marshall Islands (10%) (Figure S7A,B), which corresponds to the global fleet distribution [76].

For the data collected between 2015 and 2019, no correction for the NO cross-sensitivity was conducted. Therefore, the data between 2015 and 2019 were first corrected to allow for a long-term analysis. For this purpose, the FSC values without NO correction (FSC uncorrected) and the FSC values with NO correction (FSC corrected) for the period from 2020–2022 were used to conduct a linear regression (Figure 2). The regression values (a = 0.93; b = 0.02. and r = 0.98) were consequently used to correct the 2015–2019 FSC measurement data (FSC_{cor}) (Figure 2).

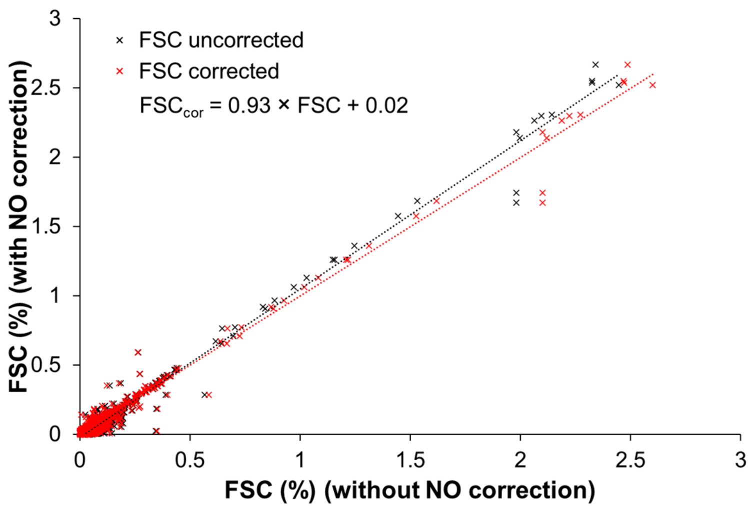

Figure 2. Linear regression between the FSC, including the NO cross-sensitivity and the FSC without NO cross-sensitivity. The dashed line represents the perfect match (x = y).

3.2. Mean FSC and Compliance Trends

The improved measurement quality and reduced measurement uncertainty in 2020 allowed for more accurate measurements of the FSC [47]. To enable long-term trend analysis, the measurements for the period from 2015–2019 were first corrected for their systematic bias. Based on the corrected FSC data, it was found that throughout the monitoring period from 2015–2022, the mean FSC of the measured OGVs remained relatively consistent (Figure 3A). However, when examining temporal trends, it was discovered that after the implementation of the Global Cap in 2020 ($p < 0.01$), the mean FSC significantly decreased from 0.083% to 0.068%. The improved accuracy in 2020 reduced the OGV compliance threshold from 0.15% FSC to 0.13% FSC. Therefore, the FSC measurements from 2015 to 2019 were recategorized according to the 2020 thresholds. While these thresholds are not suitable for individual OGV compliance reassessments from 2015–2019, they can be used for long-term compliance analysis. The overall compliance rate spanning from 2015 to 2022 was 92.8%, increasing from 83.3% in 2015 to over 95.1% in 2019 (Figure 3B). After the introduction of the Global Cap in 2020, compliance rates continued to rise, reaching a maximum of 98.0% in 2021, but they then decreased to 95.1% in 2022. Comparing the non-compliance rates from 2018–2019 (6.1%), the period from 2020–2022 (3.1%) showed a significant decrease ($p < 0.001$), indicating the effectiveness of the Global Cap.

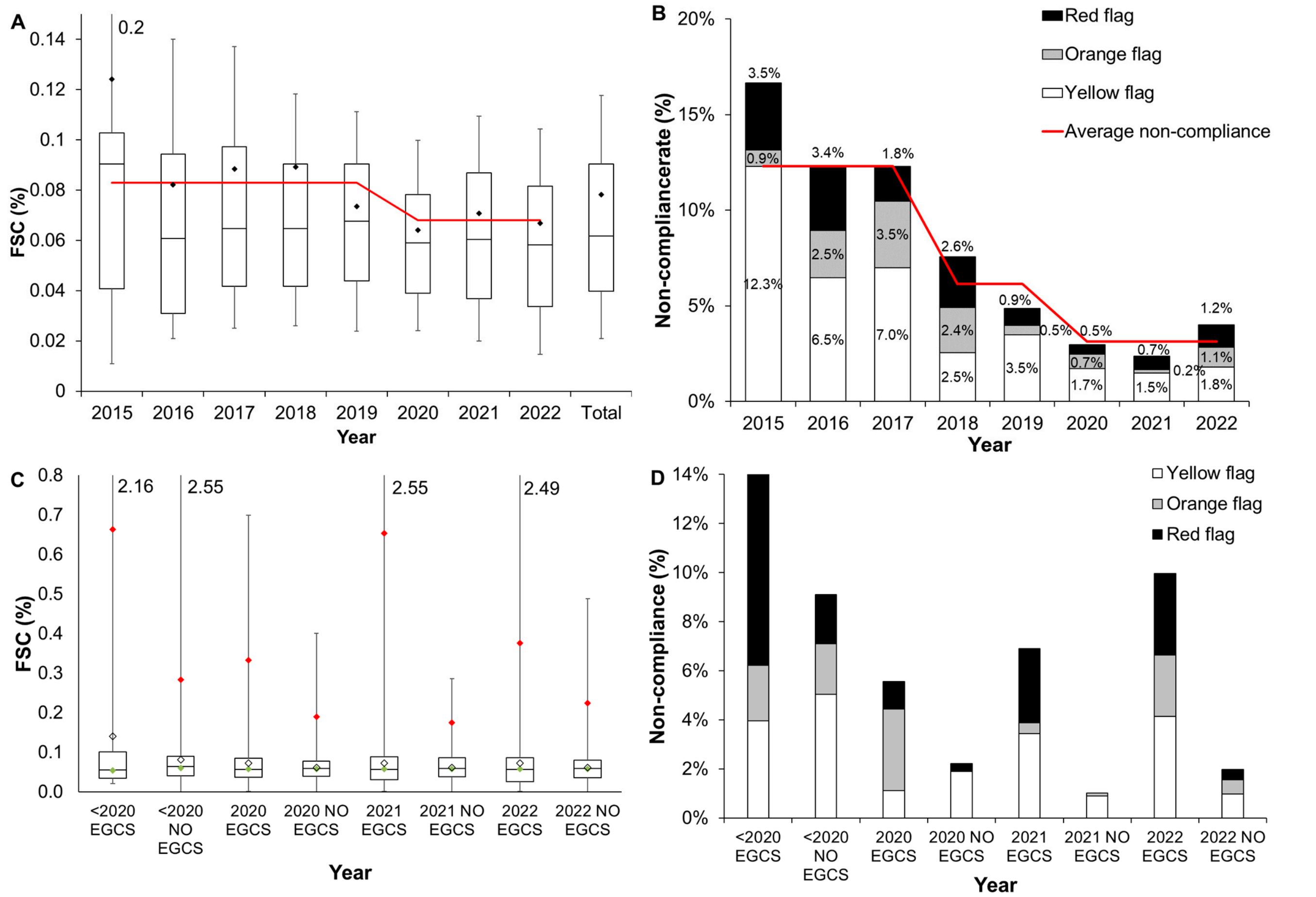

Figure 3. Evolution of the average corrected FSC concentration from 2015–2022 with median 10, 25, 75, and 90% percentiles and mean FSC per year (⧫), with mean FSC for the period before and after 2020 (red line). (**A**) Non-compliance evolution based on the corrected FSC data from 2015–2019. (**B**) Mean, median, 25, and 75 percentile boxplots for monitored FSC for EGCS OGVs and non-EGCS OGVs. The overall mean is provided in white diamonds (◇). The mean non-compliant FSC is provided in red diamonds (⧫); the mean compliant FSC is provided in green diamonds (⧫). (**C**) Compliance rate of EGCS OGVs compared to OGVs without EGCS. (**D**) When the upper whiskers exceeded the limits of the graphs, the value was noted on the graph.

The non-compliance rates per flag state (OGV's nationality) were generally proportionate to the number of observations per flag state (Figure S7A). The "flags of convenience," i.e., flags of convenience, are countries with favorable regulations and lower taxes, allowing OGV owners to avoid stricter regulations and labor standards in their home countries. However, they were not found to create higher non-compliance levels. The flag states of Germany (DE), Belgium (BE), and the UK had proportionate higher non-compliance rates. However, a closer examination of the OGVs involved showed that they were very often linked to the same shipping companies. For DE, 10 out of 11 possible non-compliant OGVs were from one company (seven different OGVs). For BE, nine out of 10 possible non-compliant OGVs were from one company (three different OGVs); all observations were in 2016. For the UK, nine out of 21 OGVs concerned one OGV that was equipped with an EGCS and was repeatedly observed non-compliant during the commencing phase of its EGCS from 2016–2017. Six other observations concerned one OGV, this OGV belonged to the same company of the nine non-compliant BE observations. Three other vessels belonged to another shipping company. This shows that some shipping companies have a higher risk profile for violations than others. However, since no general information related to ship owners was available, this could not be widely verified.

During the monitoring period from 2015 to 2022, there was a significant increase in the number of OGVs equipped with Exhaust Gas Cleaning Systems (EGCS). At the start of monitoring in 2015, less than 1% of OGVs had an EGCS. However, as a result of the implementation of the Global Cap, by the end of 2022, approximately 30% of the global fleet was equipped with an EGCS [77]. The effect of this trend was examined by comparing the mean FSC and non-compliance rates for EGCS and non-EGCS OGVs. It was found that EGCS OGVs had significantly higher FSC levels (0.100% FSC) compared to non-EGCS OGVs (0.075% FSC) ($p < 0.001$) (Figure 3C). In addition, the non-compliance rate was found to be significantly higher for EGCS OGVS (9.5%) compared to non-EGCS OGVs (6.9%) ($p = 0.0101$) (Figure 3D).

Furthermore, the analysis revealed both a very high relative contribution and very high absolute emission values for non-compliant EGCS OGVs. In the period from 2015–2019, 14 out of 102 red flags were related to EGCS OGVs (14%), whereas from 2020 onward, out of the 20 observed red flags, 16 were related to EGCS OGVs (80%). This indicates that EGCS OGVs not only result in higher amounts of non-compliance, but of equal concern, they were found to emit substantially higher levels of SO_2 once identified as non-compliant. The issues with EGCS OGVs can be attributed to certain international regulations, with MARPOL Annex VI Regulation 13 allowing the use of EGCS systems in the first place. Furthermore, the introduction of the Global Cap resulted in a decrease of mean FSC and non-compliance rates. However, the lower global limits have also led to a wider use of EGCS OGVs, especially outside ECAs. However, based on this analysis, this has resulted in higher SO_2 emissions and non-compliance rates. Finally, the EGCS guidelines do not allow for an effective monitoring mechanism for the port inspection authorities to verify the proper functioning of the Continuous Emission Monitoring System (CEMS) used by the EGCS [29]. It should be noted that this adverse effect on air quality is, in addition to other environmental concerns, arising from the discharge of washwater from EGCS [28,78–80].

3.3. Real World NO_x Emissions and Compliance Trends

The airborne monitoring of NO_x emissions from OGVs began a year before the implementation of the NECA in 2021. This allowed for the assessment of the impact of the new regulations on real-world NO_x emissions and compliance to regulation 13 of MARPOL Annex VI. It was found that neither the mean NO_x emission level nor the non-compliance rate was reduced after the NECA was introduced. On the contrary, there was an observed significant increase in the mean NO_x emissions from OGVs from 12.6 to 13.5 g NO_x/kWh ($p < 0.001$) (Figure 4A). The non-compliance rate also increased from 3.7% to 3.9%, though this difference was not found to be significant ($p = 0.8$).

The previously discovered trend that Tier II OGVs have a higher mean NO_x emission and non-compliance rate compared to Tier I [56] was reconfirmed by including the data from 2022 (Figure 4B,C). This is a result of the validation method for engine certification in the NO_x Technical Code, which defines two engine cycles for main engines based on four different engine states for the calculation of the weighted average (Table S1). This means that an engine is considered compliant as long as the weighted average is below the limit, even if emissions at certain engine states exceed the limit. Tier II engines were found to have higher NO_x emissions in the lower engine states due to fuel optimization, while Tier I engines have more constant emission levels with the engine load [56]. As lower engine states are often used in coastal shipping lanes with heavy traffic density, this results in Tier II OGVs emitting more NO_x in areas most vulnerable from an environmental and health perspective. Furthermore, currently for main engine states below 25%, there are no emission limits in place, and 23% of the observed non-compliant OGVs had an engine load below 25%. Therefore, they were not regulated (Figure 5).

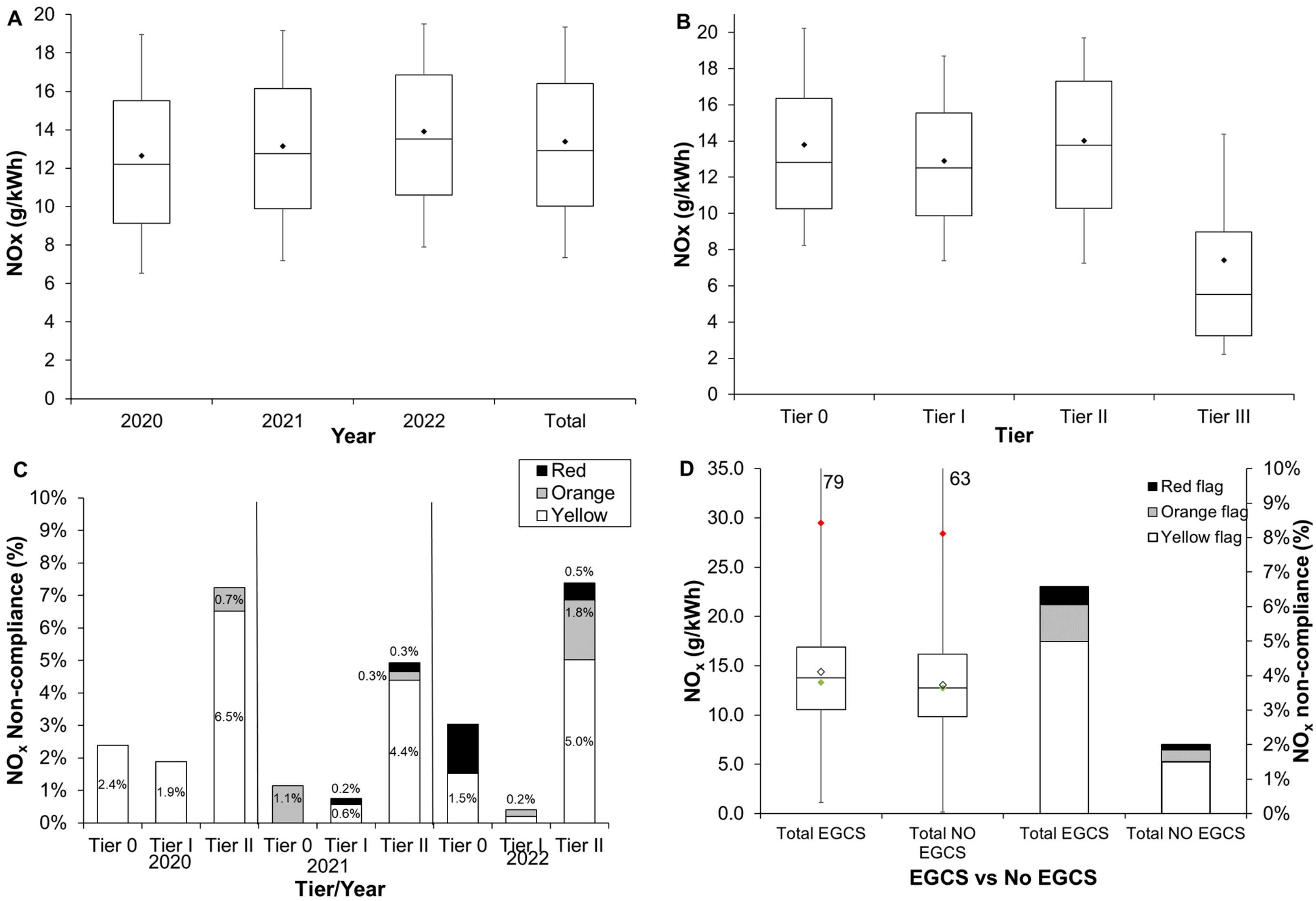

Figure 4. Boxplot with median 10, 25, 75, 90% percentiles, and mean NO_x emissions per year (**A**) and per tier level (**B**). NO_x non-compliance per tier and per year (Tier III is not represented due to the absence of Tier III data between 2020 and 2021) (**C**). Boxplot with median 10, 25, 75, 90% percentiles, and mean NO_x emissions between EGCS and non-EGCS OGVS. The overall mean is provided in white diamonds (◇). The mean non-compliant FSC is provided in red diamonds (⧫); the mean compliant FSC is provided in green diamonds (⧫). On the right side of this graph the NO_x non-compliance difference between EGCS and non-EGCS OGVs is provided (**D**).

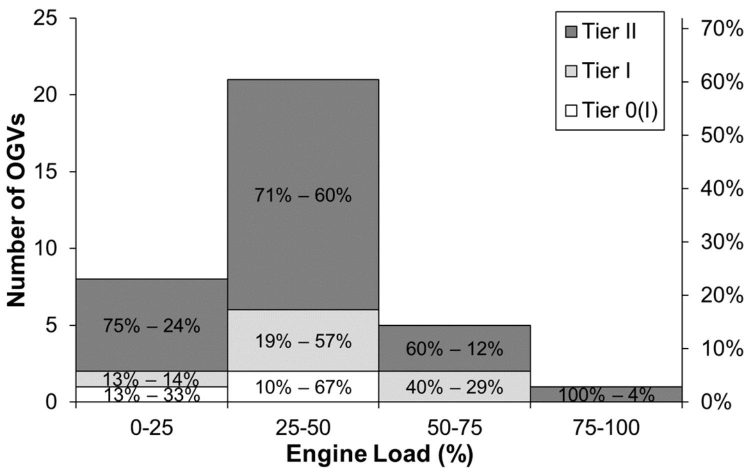

Figure 5. Distribution of the engine load of the observed non-compliant OGVs for NO_x.

Tier III engines have a not-to-exceed (NTE) limit for all engine states set at 150% of the emission limit, making it easier to assess compliance as it does not require an assessment of the weighted average. However, only seven Tier III OGVs (0.3%) have been monitored so far. This is concerning, as the majority of the OGVs that were built after 2021, when the Tier III limits came into force, still have a KLD before 2021. This means that they can still follow the Tier II limits. Based on the collected KLD information, it was discovered that only 21% of the merchant OGVs larger than 5000 GT, built in 2021 and 2022, had a KLD in or after 2021 and were certified as Tier III. The implementation of the NECA in the US in 2016 and Europe in 2021 can be clearly identified in the difference between the built year and KLD (Figure 6).

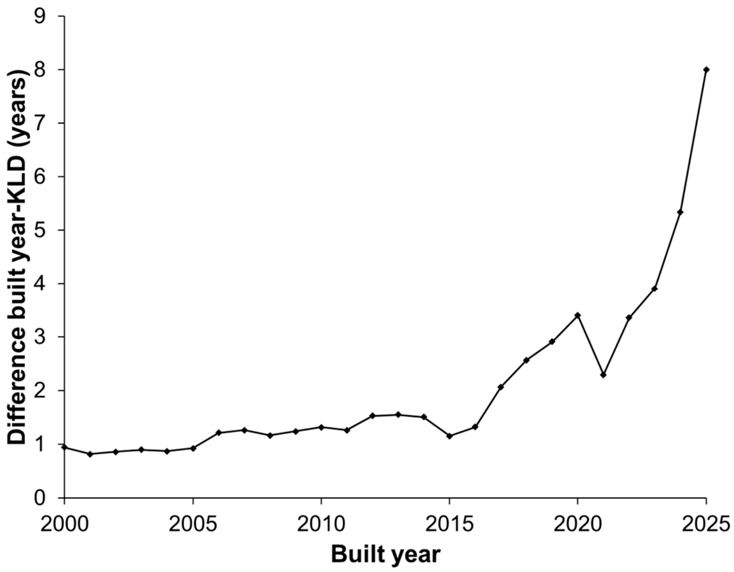

Figure 6. Difference between built year and KLD over time.

It cannot be overstated that this delay will have a substantial impact on the environment and public health [13,56]. Another remarkable discovery was that 43% of the limited number of observed Tier III OGVs were found to be non-compliant. This is in line with the observations made during the EU-funded Horizon 2020 project "Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations" (SCIPPER) [81]. The analysis provided clear evidence of the inefficacy and even counterproductive nature of the international maritime NO_x emission regulations in reducing actual NO_x emissions from OGVs in the ECA.

Looking at non-compliance by flag state, levels of non-compliance generally do not vary much by flag state (Figure S7B). However, it was observed that the Hong Kong- (HK) and Danish- (DK) flagged OGVs had a higher risk profile for non-compliance. For the DK flags, 10 out of 13 belonged to one company (nine different OGVs). For the Hong Kong-flagged OGVs, 10 out of 12 possible non-compliant OGVs belonged to the same shipping company (eight different OGVs). The two other observed OGVs belonged to another company (two different OGVs).

To evaluate how EGCS affects NO_x emissions, an analysis was conducted on the mean NO_x emission levels and compliance rate to NO_x emission standards between EGCS OGVs and non-EGCS OGVs. The findings revealed that EGCS-equipped OGVs had a mean NO_x emission level of 14.4 g NO_x/kWh, which was significantly higher than the 13.1 g NO_x/kWh for non-EGCS OGVs ($p < 0.001$). Furthermore, the non-compliance rate for EGCS OGVs was significantly higher at 7%, compared to 2% for non-EGCS OGVs ($p < 0.001$) (Figure 4D). These results were consistent across all monitoring years and for both Tier I and Tier II (Figure S8). These results confirm previous research that indicated the (minor) effect of EGCS on NO_x emission levels [78].

3.4. Impact Emissions from OGVs on BELGIAN Inland Air Quality

By analyzing the annual mean SO_2 and NO_x concentrations conducted in air quality monitoring stations located in coastal or port areas, compared to those not situated in such areas, the relative importance of air pollution from OGVs was elaborated. It was of no surprise that both SO_2 and NO_x concentrations were substantially higher in coastal/port areas, although declining concentrations were generally observed for both SO_2 and NO_x at all stations (Figure 7).

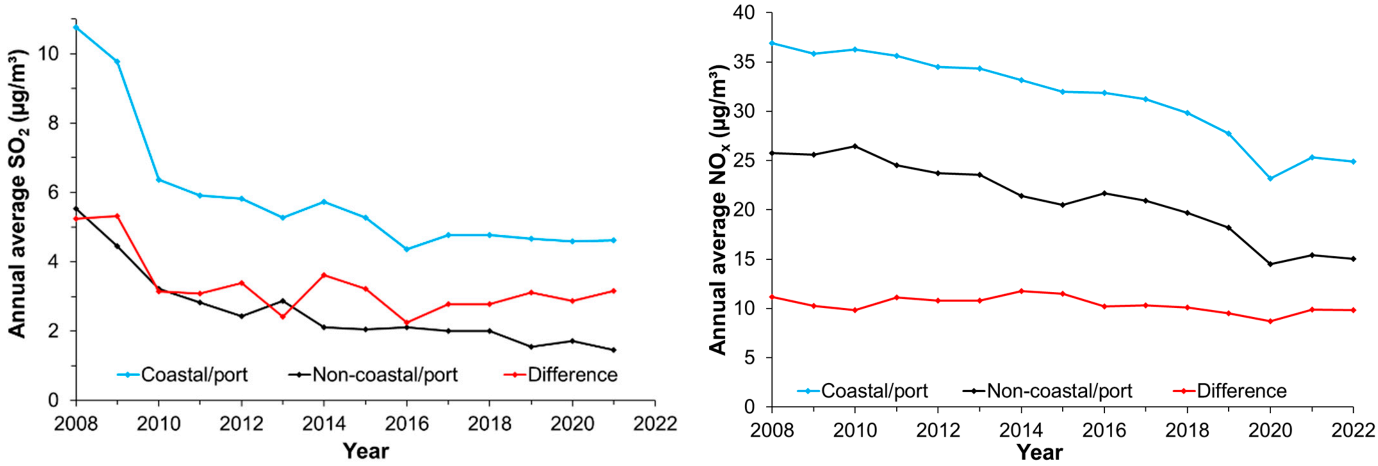

Figure 7. Evolution of measured SO_2 (**left**) and NO_x (**right**) concentrations for inland coastal and non-coastal air quality measurements stations in Flanders (data obtained from VMM) [71].

The difference in SO_2 concentration between coastal/port and non-coastal/port stations was found to slightly decrease between 2008 and 2016 but later started to reincrease slightly (Figure 7, left). Clear reductions were observed in 2010, 2013, 2015, and 2016, which can be attributed to the implementation of international SO_2 emission limits for OGVs. However, the reduction in 2013 can be neglected as it was linked to a short-term increase in pollution for non-coastal stations due to inland pollution sources [71].

Regarding the difference in NO_x concentration between coastal/port and non-coastal/port stations, a very stable trend was observed over the last decade (Figure 7, right). This indicates that emissions from OGVs have not decreased over time and were not substantially impacted by the introduction of the NECA in 2021. Consequently, emissions from OGVs are increasingly contributing to the total inland NO_x pollution.

The SO_2 analysis categorized by emission sources clearly indicates the impact of the introduction of the SECA and subsequent reductions in the maximum allowed FSC in 2010 and 2015 (Figure 8A). However, the future trend analysis also suggests that the contribution of SO_2 emissions from OGVs to the total SO_2 emissions in the Flemish region is expected to increase to approximately 7% by 2030.

Regarding NO_x emission sources, the impact of international shipping regulations was found to be less profound. The contribution of NO_x emissions from OGVs to inland NO_x in the Flemish region shows an upward trend. The establishment of the NECA in 2021 has had no significant impact on this trend; it is even projected that by 2025, the NO_x emission contribution from OGVs will surpass any other source and contribute to 40% of all NO_x emissions for the Flemish region by 2030 (Figure 8B). These results largely corroborate the findings of previous large-scale studies that modelled the shipping contribution to inland pollution [30,31,82–86].

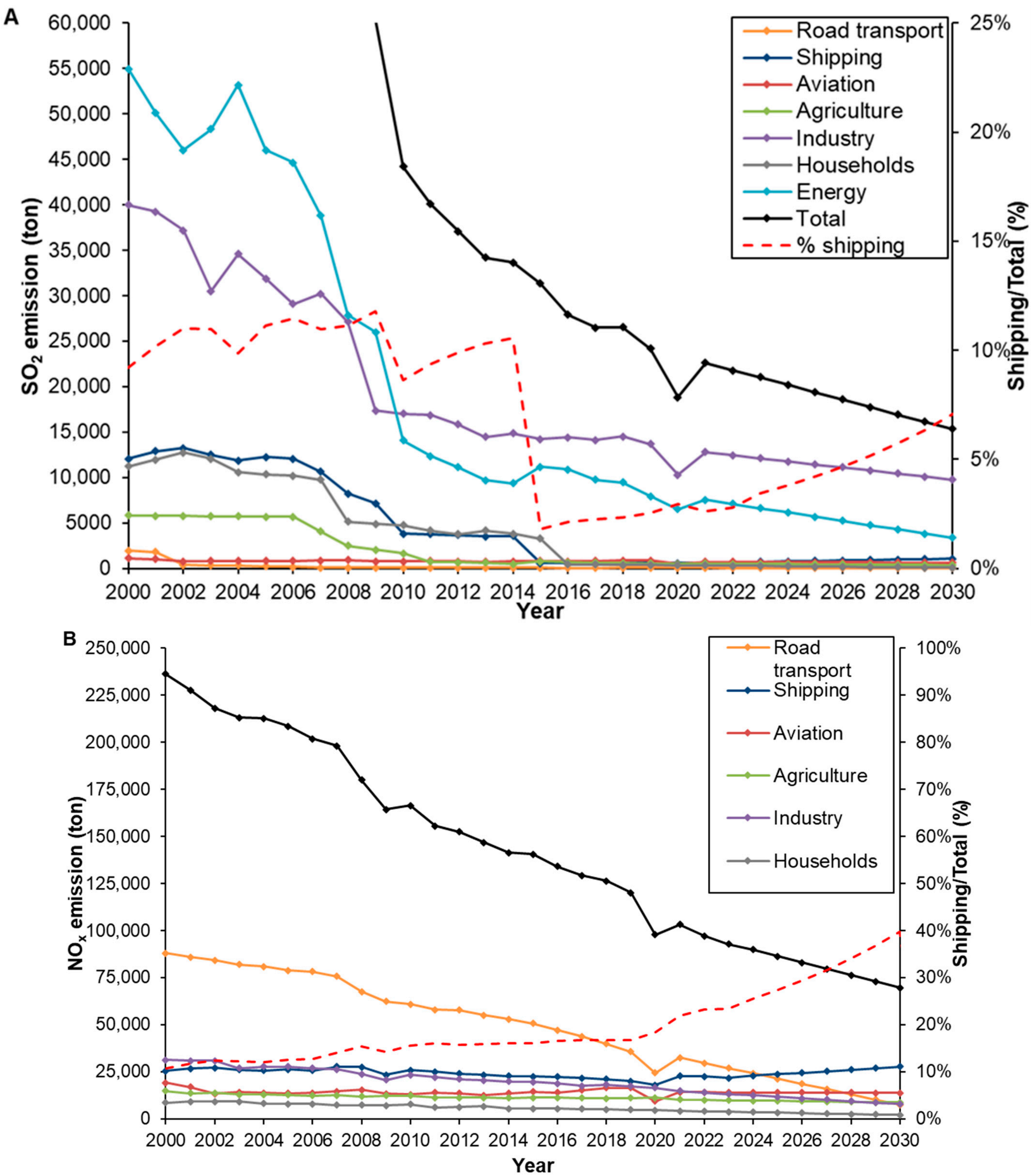

Figure 8. Evolution of SO_2 (**A**) and NO_x (**B**) emissions from different sources for the region of Flanders with future trends until 2030 and contribution of shipping (data from 2000–2020 obtained from VMM) [71].

4. Conclusions

This study showed that the implementation of Regulation 14 of MARPOL Annex VI and the assignment of the North Sea Emission Control Area have had a significant impact on the reduction of SO_2 emissions from OGVs. It also revealed that the introduction of the Global Sulphur Cap has further reduced SO_2 emissions, diminishing the contribution of shipping to domestic SO_2 pollution in Belgium from over 10% in the early 2000s to 3% in 2015. The implementation of the Global Sulphur Cap also coincided with an improvement in compliance levels, which can be partly attributed to the increased implementation of remote monitoring by North Sea coastal states. The effective implementation of clear regulations, monitoring, and enforcement practices at various policy levels (IMO, EU, Belgium) has proven to be successful in addressing SO_2 emissions from OGVs.

Yet the study shows that SO_2 emissions from OGVs are expected to rise to 7% by 2030. The Global Sulphur Cap has led to an increased use of EGCS, and SO_2 emissions from EGCS-equipped OGVs were found to be considerably higher than those OGVs without EGCS. Moreover, non-compliance is significantly more prevalent in EGCS-equipped OGVs, and FSC values appear to be particularly high when non-compliance is found in EGCS-equipped OGVs.

The study found that Regulation 13 of MARPOL Annex VI had no beneficial effect on the average reduction of NO_x emissions from OGVs. On the contrary, due to the way regulations are structured, the study demonstrated that real-world average NO_x emissions from OGVs are increasing. This trend, in combination with the expected growth in maritime transport, will make OGVs the largest contributor to NO_x emissions by 2025. By 2030, OGVs are estimated to be responsible for 40% of total domestic NO_x emissions in Belgium. Finally, this study showed that EGCS not only increased SO_2 emissions, but also resulted in higher mean NO_x emissions and increased non-compliance with NO_x regulations. These findings highlight that several aspects of the international NO_x regulations should be revised. In addition, this study shows that there are operational issues with EGCS OGVs that require attention.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/atmos14060969/s1, Figure S1. Emission Control Area (ECA) as defined by MARPOL Annex VI (A). Limits on the Fuel Sulfur Content of marine fuels according to the MARPOL Annex VI regulation 14 (B). NO_x emission limits according to MARPOL Annex VI Regulation 13 (C); Figure S2. Schematic overview of the updated sniffer sensor system, with NO_x sensor and HC kicker.; Figure S3. Distribution of the observed OGVs according to OGV type.; Figure S4. Distribution of the observed OGVs according to OGV length (m).; Figure S5. Distribution of the speed of the observed OGVs.; Figure S6. Distribution of 20-most observed countries (A) and ports of destination, based on the AIS information transmitted by the OGVs (B).; Figure S7. Non-compliance for FSC (A) and NO_x (B) according to flag state. The left non-compliance rate (%) is based on the non-compliance rate per flag state; the right percentage is the proportion of the number of non-compliant OGVs per flag state compared to the overall number of observed non-com.; Figure S8. Difference in compliance levels for EGCS OGVS versus non-EGCS OGVs for Tier I (left) and Tier II (right) OGVS.; Table S1. Test cycles and weighting factors according to the NO_x Technical code.; Table S2. SO_2 and CO_2 concentrations of the ordered plume simulation mixtures and effective FSC value.; Table S3. Intra-Assay Coefficient of Variability, freedom of degrees and total uncertainty for FSC and NO_x.

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