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International maritime regulation decreases sulfur dioxide but increases nitrogen oxide emissions in the North and Baltic Sea

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Sulfur dioxide and nitrogen oxide emissions from shipping have been regulated internationally for more than fifteen years. Emissions reduction from shipping provides benefits for human health and the environment, but the effectiveness of regulations in reducing ship emissions is less well understood. Here, we examine how the establishment of European Emission Control Areas and other international maritime regulations in the North and Baltic Seas affect sulfur dioxide and nitrogen oxide emissions in the region. We combine and analyze more than 110,000 ship plume measurements, inspection results, and satellite data from 2018 to 2022. We find that compliance rates for sulfur emissions are higher near ports than in open waters. However, the regulations did not affect the concentration of nitrogen oxide emissions, which increased in the past three years. These findings highlight the need for enhanced emission regulations that improve air quality.

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With a death toll of up to 8.8 million premature deaths per year, anthropogenic air pollution has been identified as the global leading cause of death[1,2]. Air pollution from ocean-going vessels (OGVs) is one of the main sources of air pollution. Sofiev et al. have calculated that up to 800,000 of these premature deaths can be attributed to OGVs[3]. These are mainly caused by fine particulate matter known as $PM_{2.5}$.This $PM_{2.5}$ can be generated during the combustion process; however, a substantial amount of secondary $PM_{2.5}$ is also formed from other pollutants like sulfur oxides (SO_x), nitrogen oxides (NO_x) and Volatile Organic Compounds (VOCs)[3–7]. Air pollutants from OGVs—SO_x, NO_x, Ozone (O_3) and VOCs—also have direct adverse effects on human health and the environment. In 2014, OGVs were responsible for 13% and 14% of global anthropogenic emissions of SO_2 and NO_x, respectively[8–13].

The regulations put in place to reduce emissions from OGVs fall under the MARPOL Convention of the IMO[14]. Annex VI of the revised MARPOL Convention aims for a gradual decrease of global air pollution by SO_x and NO_x from OGVs[15] (Supplementary Notes 1). In addition, MARPOL Annex VI introduced ECAs with tighter emissions standards (Supplementary Fig. 1A–C) and is ratified by 105 countries representing 96.81% of the gross tonnage of the world merchant fleet[16–20].

According to the International Maritime Organization (IMO), thanks to the establishment of Emission Control Areas (ECAs) and the stricter SO_2 emission limits in 2015, SO_2 emissions fell by 28.6% between 2014 and 2017, while NO_x reported a 1.2% increase over the same period[12]. Sofiev et al. have estimated that before the strengthening of the global sulfur emission regulations for OGVs in 2020, SO_2 and sulfur-related particles in OGV emissions were responsible for up to 403,300 premature deaths a year and 14 million cases of childhood asthma[3]. With the introduction of global emission regulations for OGVs, it was estimated that 263,300 premature deaths (−33%) and 7.6 million cases of childhood asthma (−54%) could be avoided[3,4]. When concerning NO_x, the health benefits of introducing NO_x emission regulations are not immediately observed as new emission abatement technology needs to be introduced to be compliant with the defined emission limits of the regulations. The compliance rate is therefore linked to the scrapping rate, i.e., the rate at which old OGVs are scrapped and replaced by new OGVs as well as the engine overhaul rate, i.e., the rate at which old engines are replaced by new engines with lower emission limits[9]. Zhang et al. have estimated that the application of the latest introduced Tier III NO_x emission standards is the most advantageous approach to further reduce the detrimental impact of shipping on human health, as it would reduce up to 36,400 premature deaths per year[4]. The recently completed EU-funded Shipping Contributions to Inland Pollution Push for the Enforcement of Regulations (SCIPPER) project also recommended the establishment of further NO_x Emission Control Areas (NECAs)[21]. It should be highlighted that in order to attain the afore-mentioned health benefits a high compliance rate of international emission standards for OGVs needs to be reached.

Despite the fact that the abovementioned publications projected important health benefits from the implementation of international maritime emission regulations and that emissions models predict a decrease in air pollution from shipping[22,23], there still remains a research gap regarding the effectiveness of the established international regulations in reducing real-world emissions from OGVs in the wider ECAs. At the national level, Van Roy et al. showed varying results of the success of international regulations to improve air quality in Belgium[24].

The main objective of this article is therefore to examine the effects of the implementation of the European ECAs and other international maritime regulations in the wider North Sea and the Baltic Sea on OGVs' emissions. This is accomplished in a three-step approach. As a first step, the effects of international emissions regulations in the Bonn Agreement (BA) area (North Sea and North-East Atlantic area) (Supplementary Fig. 2) are examined. This was done by analyzing compliance rates based on more than 100,000 remote OGV emission measurements (Supplementary Table 2) collected by the BA Contracting Parties (CPs) using in-situ air quality (sniffer) sensors (Supplementary Methods 1). In the second step, data on (1) emission violations and penalties for the BA; and (2) overall port inspection results for the entire EU were examined. In the third step, satellite data for the years 2018–2022 was used to assess any changes in the atmospheric concentrations of SO_2 and NO_2 in the European ECAs. The presented work reveals that international regulations on fuel sulfur content (FSC) are well enforced by the BA Parties and by extension by the entire EU. Compliance rates are well under control and the results of this study show that SO_2 non-compliance has reduced substantially since the introduction of the global sulfur cap. The number of recorded infringements in BA and EU ports follows a similar trend. Based on satellite data it was found that atmospheric SO_2 concentrations inside the ECA have decreased since the introduction of the global sulfur cap. In contrast, this article demonstrates that NO_x emission regulations are less successful, with NO_x emissions from OGVs even increasing.

Results

Regionwide analysis of the remote monitoring data. Non-compliance data from all remote measurement stations and deployments was collected based on three different cutoff levels. This allows the assessment of the severity of the non-compliance behavior in addition to a temporal and spatial non-compliance trend analysis. For the main results, the 0.15% FSC cutoff level was used.

Temporal sulfur compliance trends. A decreasing trend in FSC non-compliance rates was observed across all measurement locations within the European Sulfur Emission Control Area (SECA) regions. The non-compliance rate decreased from 7.1 to 0.7%, with an average non-compliance rate of 1.5% when a 0.15% FSC cutoff level is used (Fig. 1). The pattern is similar for the other cutoff levels (Supplementary Fig. 3A, B). Following the implementation of the global sulfur cap in 2020, the non-compliance rates reached their lowest point, with an average non-compliance rate of 0.6%. It is important to acknowledge that the implementation of the sulfur cap in 2020 coincided with the global COVID-19 pandemic, which led to reduced fuel prices[25,26]. Additionally, several monitoring operations observed a slight increase in non-compliance, starting in 2022. This increase can be attributed to the rise in marine fuel prices resulting from the Russian invasion of Ukraine and the subsequent global price inflation[26].

Among the different remote measurement operations applied by the SECA countries, the French measurements with the remote piloted airborne systems (RPAS) exhibited the highest non-compliance rates. The average non-compliance rate was 9.4% and therefore substantially higher than the non-compliance observed by the other remote measurement operations, which varied between 0.1 and 3.7% for the same period. When considering the remote monitoring locations that conducted measurements throughout the entire 2015–2022 period, the Belgian airborne measurements recorded the highest non-compliance rate for the 0.15% FSC cutoff level (5.2%). However, the Danish helicopter measurements displayed the highest non-compliance rate for the 0.13% FSC cutoff level (8.5%). This

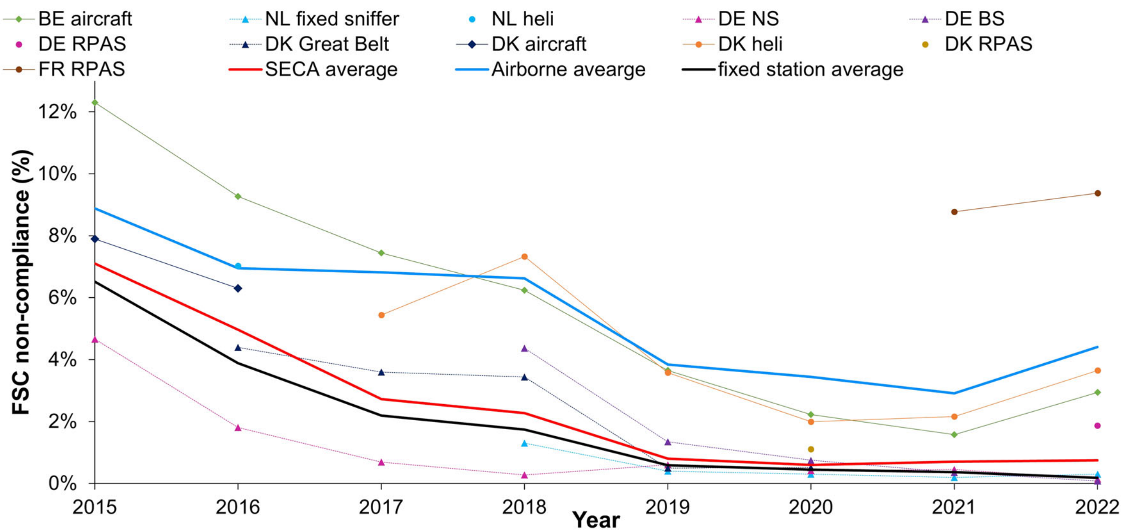

Fig. 1 FSC non-compliance for remote monitoring locations in the SECA. Non-compliance rates for the different monitoring locations for the 0.15% FSC cutoff level. Measurements with fixed wing aircraft are displayed with full lines and diamond icons, measurements using RPAS and helicopters have full lines and circle icons, fixed sniffer measurements are displayed with dotted line and triangular icons.

distinction is noteworthy as it illustrates that while the OGVs in Danish water exhibited higher absolute non-compliance rates, the level of the FSC exceedances was higher for the OGVs in Belgian waters.

Spatial sulfur compliance trends. The temporal analyses reveal notable disparities in non-compliance rates between fixed stations (1.0%), typically situated near ports, and airborne measurements (5.3%), typically conducted in the territorial waters (12 nm) and the Exclusive Economic Zones (EEZ) (200 nm) (Fig. 1). Similar patterns were observed for the other cutoff levels (Supplementary Fig. 3A, B). These differences in non-compliance rates between airborne measurements and fixed stations were statistically significant for all cutoff levels ($P < 0.001$).

Although based on the same methodology (Supplementary Methods 1), fixed and airborne measurements use different operational methods, which can partly explain the differing non-compliance rates. Airborne platforms try to avoid redundant measurements of the same OGVs, while fixed stations take a non-selective approach and measure all passing OGVs. This may therefore lead to a slight underestimation of the determined non-compliance rate by fixed stations if compliant OGVs like compliant ro-ro ferries are overrepresented in these datasets. Furthermore, aerial remote measurements may tend to focus on OGVs with a higher risk profile, and, to some extent, avoid OGVs operating only in the SECA, or smaller coasters, i.e., small to medium-sized cargo OGVs designed for transportation along coastlines or in relatively calm waters. This may overestimate the overall non-compliance rate by airborne measurements. Nevertheless, these findings indicate a clear pattern of adaptive non-compliant behavior among OGVs.

A comparison of non-compliance trends between the various measurement campaigns revealed a high consistency (Supplementary Tables 3 and 4). It was observed that locations in closer proximity to the SECA border have higher non-compliance rates. Measurements taken at the border by the MUMM and Chalmers University[27] demonstrated an average non-compliance rate of approximately 30%. When plotting the non-compliance data against the distance from the border, it followed an exponential decreasing curve, with a high goodness of fit (Fig. 2A). In order to mitigate the influence of the high compliance rate in ports, the combined airborne data from RPAS, helicopter, and aircraft was utilized (Fig. 2B). In this case, an excellent goodness of fit was also observed. Given the significant disparity between non-compliance rates observed in ports compared to those at sea, the relationship between compliance and the distance from port was determined (Fig. 2C). Similar patterns were observed for the other FSC cutoff levels (Supplementary Fig. 4A–C). The fitting constants and correlation factors (R^2) of the curve fittings for all cutoff levels are provided in Supplementary Tables 5 and 6.

This spatial analysis provided valuable insights into the distribution of non-compliance risks along the SECA border. Notably, the analysis revealed that the highest risk for non-compliance was observed within the first 300–450 km from the SECA border. The results indicate that compliance rates at sea, beyond a distance of 900 km, were 1.4% for the 0.15% FSC cutoff level. Furthermore, these findings indicate that non-compliance begins to notably increase at approximately 70–90 km from the port. At a distance of 180 km from the port, the proximity to the port stops influencing non-compliance behavior. It must be acknowledged that the number of points for these fittings was, in particular for the non-compliance in function of the distance from the port, very low. To obtain a better understanding of these relationships it is recommended that a dedicated more in-depth analysis based on the raw measurement data is conducted.

Upon comparing the Baltic Sea and the North Sea, noticeable differences in non-compliance rates were observed. In general, the Baltic Sea exhibited higher non-compliance rates, with an overall non-compliance rate of 2.2%, compared to 1.3% for the North Sea for the 0.15% FSC cutoff level (Fig. 2D). Similarly for the other cutoff levels the Baltic Sea demonstrated higher non-compliance rates. Importantly, for all cutoff levels, the differences were determined to be statistically significant ($P < 0.001$). When comparing the airborne results, for the North Sea a higher non-compliance rate is observed for the 0.15% FSC and the 0.20% FSC cutoff levels. However, the Baltic Sea showed a higher non-compliance rate for the 0.13% cutoff level. This indicates that non-compliant OGVs at sea in the North Sea tend to have higher absolute FSC levels compared to those in the Baltic Sea, whereas in the Baltic Sea, low FSC exceedances appear to occur more often.

NO_x emission control area. For this study, it was not feasible to compare the Belgian NO_x non-compliance data with other

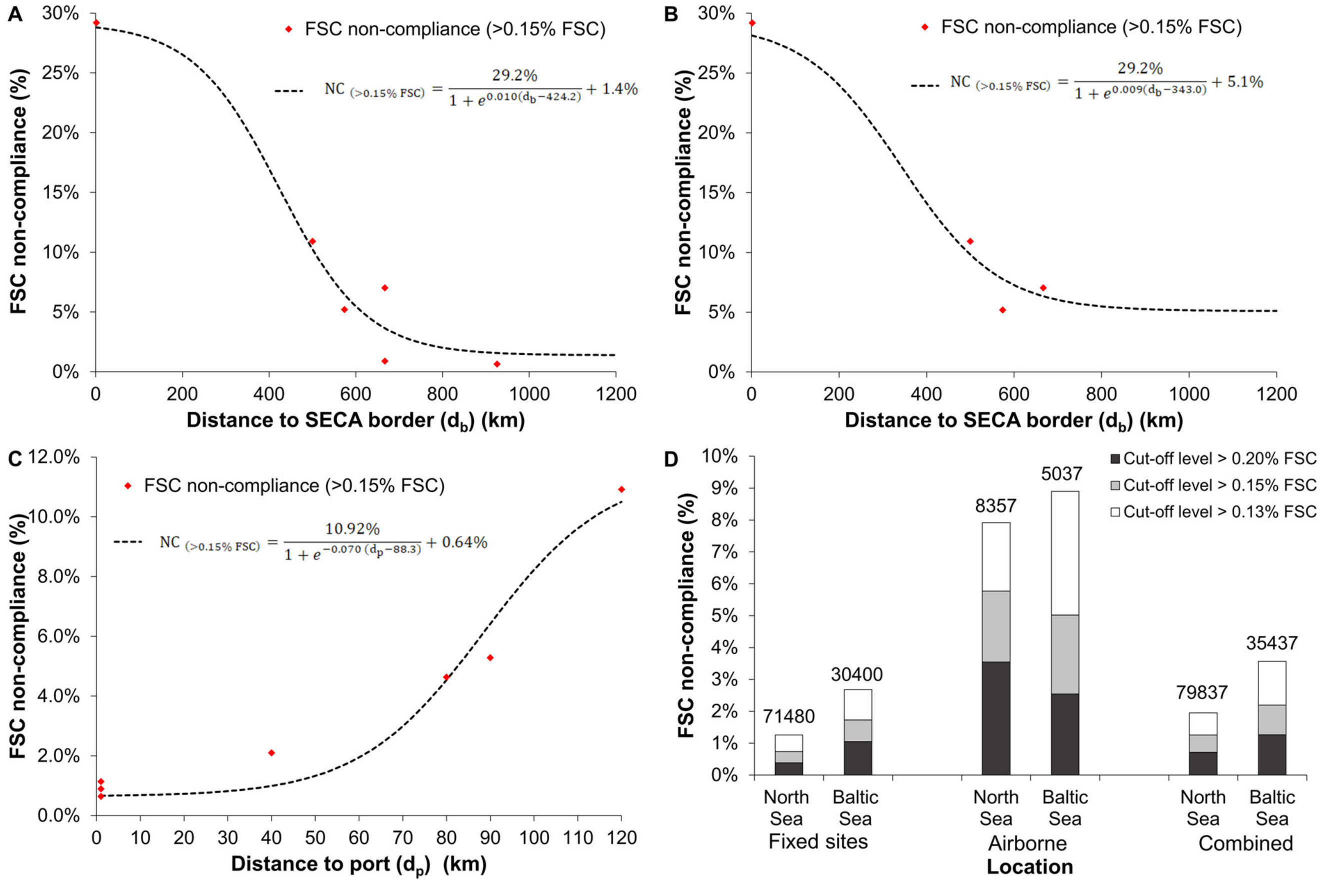

Fig. 2 Non-compliance function of distance to port/SECA border. Non-compliance fitting based on the mean non-compliance of the different remote measurement locations in function of the distance to the SECA border, for all remote measurements (**A**) and for when only the airborne measurements are considered (**B**). Non-compliance fitting in function of the distance to port (**C**). Difference in compliance rates between Baltic Sea and North Sea SECA, with the number of measurements per SECA (**D**).

locations since there are no other NECA countries reporting on NO_x non-compliance in an operational setup. However, it is worth noting that numerous other agencies conduct measurements of NO_x levels in addition to monitoring SO_2 concentrations in OGV exhaust plumes. While a direct comparison of NO_x non-compliance data may not be possible yet, these additional measurements provide valuable insights into the overall emissions profile and environmental impact of OGVs.

The examination of the Belgian data reveals that the mean NO_x emissions are not decreasing as anticipated with the implementation of stricter emission limits. On the contrary, the data indicates that average NO_x emissions are increasing[24,28]. Furthermore, non-compliance levels for NO_x emissions are also rising[24,28]. This trend can be attributed to the higher emission levels reported for Tier II OGVs compared to Tier I OGVs[24,28,29]. Based on the Belgian data, the observed increase in average NO_x emission coincides with an increase in the amount of measured Tier II vessels (Fig. 3). These findings have important implications for the parameterization of atmospheric emission models—such as the Steam Model[30,31]—which are fundamental sources for global emission inventories for shipping. By incorporating the correct NO_x emission factors based on the real-world emission factors per IMO tier, more accurate global assessments of NO_x emissions from OGVs can be achieved, thereby improving the understanding of their environmental and human health impact.

The Danish company Explicit took a different approach to the Belgian one by using modeling. They estimated main engine power and fuel consumption as input for the calculation of NO_x

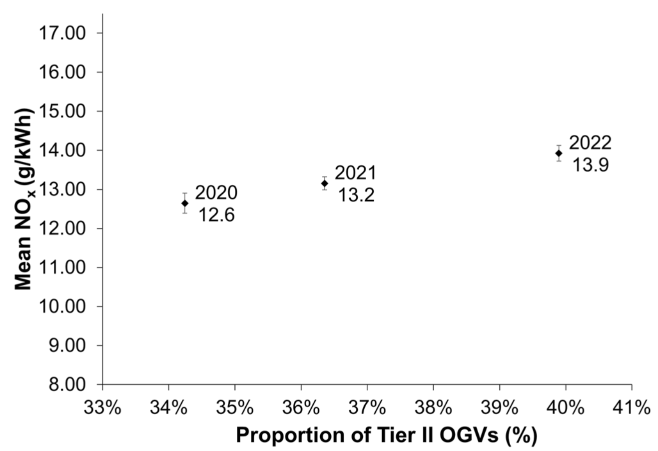

Fig. 3 Annual average NO_x emission factor in function of the proportion of Tier II OGVs. NO_x emission factors expressed in g/kWh in function of the proportion (%) of Tier II OGVs, error bars visualize standard error (based on the Belgian airborne dataset collected between 2020 and 2022)[24]. The *Y*-axis range shows the minimum and maximum emission limits for respectively Tier II and Tier I.

emission factors in grams of NO_x per kilowatt-hour (g NO_x/kWh)[29]. Explicit used this approach for reassessing the Danish historic NO_x measurement data. The findings of this study align with the results of the empirical approach of Belgium, revealing

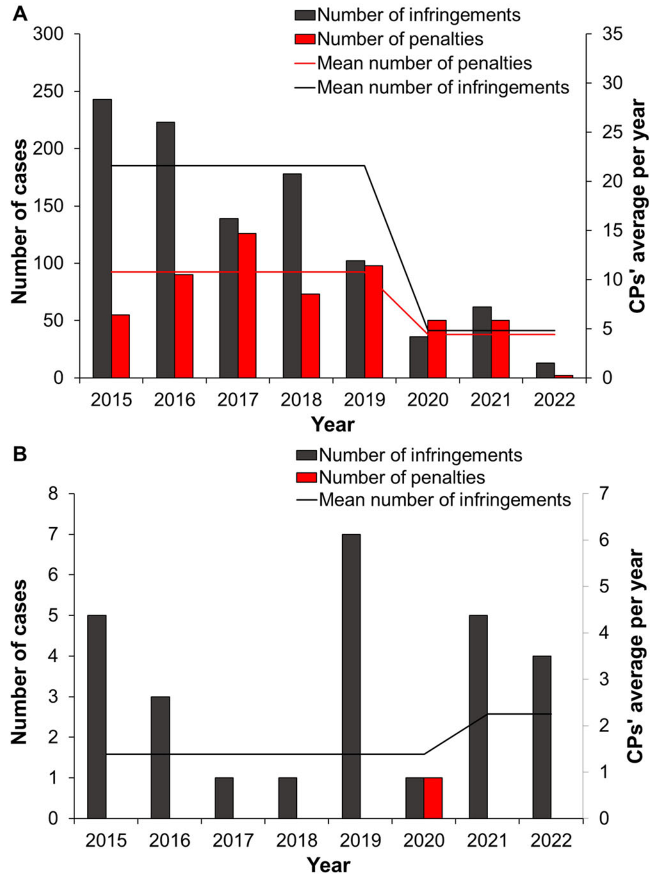

Fig. 4 Number of observed infringements and penalties in the Bonn Agreement. Infringements observed by port inspection authorities for SO_2 (**A**) and NO_x (**B**). Note that for 2022 not all BA CPs were yet able to provide data.

higher emission factors and a greater non-compliance rate for Tier II OGVs compared to Tier I OGVs. The Danish study also confirmed that OGVs emit more NO_x when operating at lower engine loads. Additionally, the results demonstrated that larger engines generate higher emission factors, which is in line with the Belgian measurements, albeit with a weak correlation. An increasing trend was observed across all Tier levels, excluding Tier III due to limited measurements (Supplementary Fig. 5).

Non-compliance with NO_x standards has also recently been investigated within the SCIPPER project. A particular emphasis was placed on Tier III OGVs. The advantage of the enforcement of Tier III OGVs is that a not-to-exceed limit is defined for all four engine load points, set at 50% of the applicable emission limit (Appendix II, MARPOL Annex VI)[15]. However, because the keel laying date (KLD) is defined in the MARPOL Annex VI regulations to determine Tier III classification, the large majority (73%) of the recently constructed OGVs are registered with a KLD prior to 2021. Consequently, they are subjected to the Tier II emission limits instead of the stricter Tier III emission limits[24].

In total 65 Tier III OGVs were monitored by the SCIPPER partners. The findings indicated that approximately half of the observed Tier III OGVs did not comply with the maximum NO_x emission limits for Tier III; ca 20% of the observed Tier III OGVs did not even meet Tier II emission limits[32]. This observation aligns with the limited Tier III non-compliance results reported by Belgium, where a non-compliance rate of 43% was observed. Various other studies have also highlighted concerns regarding elevated levels of NO_x emissions from Tier III OGVs[33,34].

Port inspections on sulfur and NO_x infringements

Results within the Bonn Agreement. The results of the sulfur infringements from most BA CPs follow an increasing trend between 2015 and 2020 (Supplementary Fig. 6A). The primary reason for this is that not all CPs immediately implemented inspection protocols; needed to gain experience; and had initially only limited information available to single out suspicious OGVs for inspection. As a result, not all CPs have inspection results for 2015. From 2016, all BA CPs were actively conducting inspections within their ports. During this time, remote monitoring operations and the exchange of alerts via Thetis-EU began to gain momentum, leading to the discovery of a higher number of infringements and deficiencies.

Due to a high number of observed sulfur infringements by one BA CP, the total observed number of infringements in the years 2015 and 2016 still provided the highest number of observed infringements (243 and 223) (Fig. 4A). The year 2018 provided the third highest number of recorded infringements (178). However, following that year, the number of identified infringements began to decline. It is important to note that the EU Sulphur Directive mandates Member States (MS) to provide port inspection data by June, as a result, at the time of publication, not all CPs were able to submit data for the year 2022.

The EU-Commission Implementing Decision played an important role in maintaining a consistent number of inspections conducted on OGVs throughout the entire time period. Although there was a decrease in inspections in 2020 due to the global pandemic, the majority of CPs were still able to fulfill the mandatory inspection requirements. It is worth noting that in this context, numerous CPs utilized the exemption outlined in the Implementing Decision to reduce the number of inspections by implementing remote monitoring (Art 3.3(a))[35].

Regarding the reported penalties on sulfur, an upward trend was observed between the years 2015 and 2017, reaching a peak of 126 cases in 2017 (Supplementary Fig. 6B). Subsequently, the number of penalties declined. It should be noted that there is a time lag in the reporting of penalties, as often the reported penalties correspond to infringements observed in the previous year. Therefore, the peak in penalties in 2019 aligns with the peak of infringements in 2018. To address this time lag, it is necessary to analyze the data from the original cases and assign them to the year of observation. However, this analysis was not feasible due to the sensitive nature of the legal cases involved.

When looking at the mean number of sulfur deficiencies and infringements observed by the BA CPs' port inspection authorities, a substantial decrease was observed after the global sulfur cap came into effect (Fig. 4A). Over the total period 2015–2022, 996 infringements were observed of which 544 were penalized. In the period 2015–2020, before the global sulfur cap came into effect, 885 infringements were observed by the port inspection authorities with a mean of 21.6 cases per year, 442 penalties were executed in the same period or on average 10.8 penalties per year, corresponding to 56% of the infringements. In the period 2020–2022, after the global sulfur cap came into force, a total of 111 infringements were observed. The mean annual number of observed deficiencies per BA CP decreased therefore significantly to 4.8 cases per year ($P < 0.001$). In total, 102 penalties were handed out after the global sulfur cap came into effect (91%). The mean number of penalties per BA CP per year therefore decreased significantly to 4.3 penalties ($P < 0.05$), which is just below the mean number of observed infringements, indicating that as of today there is a good legal follow-up of possible infringements within the BA.

There is a notable disparity between sulfur and NO_x. The result of the inquiry with the BA CPs provided proof of the successful enforcement and legal follow-up for sulfur infringements. In

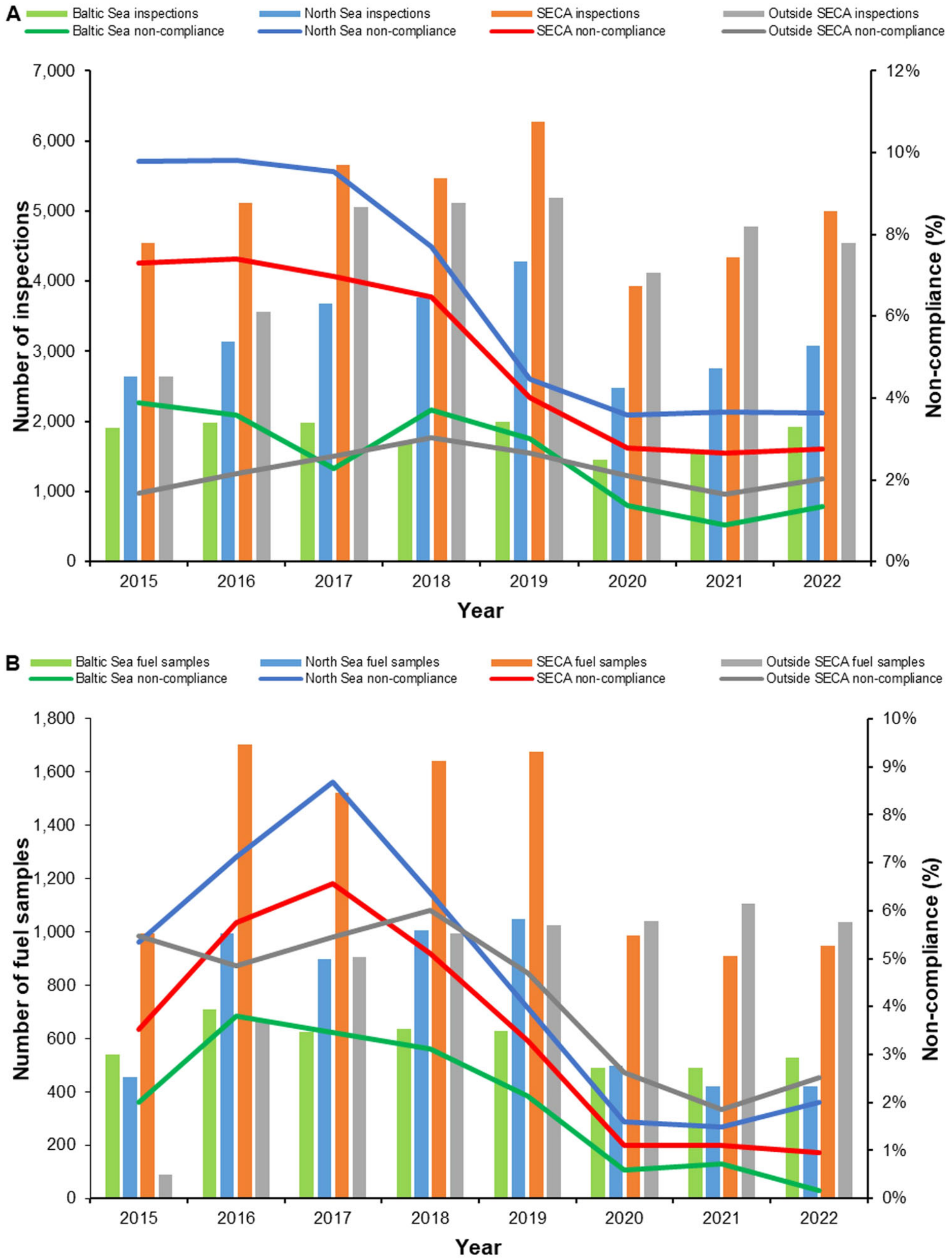

Fig. 5 Overall non-compliance results for the EU. Non-compliance for EU MS in the North Sea and Baltic Sea based on Thetis-EU data on documentary inspections (**A**) and fuel sample analysis (**B**).

contrast, the results of the inquiry on NO_x enforcement and legal follow-up within the BA were disappointing (Fig. 4B). Only two BA CPs have reported NO_x infringements and only one BA CP has imposed a penalty for a NO_x violation. Most of the other BA CPs are currently not enforcing NO_x regulations nor collecting data on the results of the NO_x inspections at the time of publication. This demonstrates that enforcement of NO_x regulations by BA CPs is currently lacking. Upon examining the limited available NO_x inspection data, it becomes evident there has not been a decrease in violations since the NECA was implemented, but rather, an increase. However, the scarcity of data does not allow statistical analysis or strong conclusions to be drawn about compliance rates within the BA.

Results within the EU. Upon examining the data on sulfur inspections and non-compliance rates within the EU, similar patterns were observed within the Baltic Sea and North Sea ECA as within the BA (Fig. 5A). In the wider SECA, in total 110,657 documentary inspections were conducted. The annual amount showed a slight increase since entering into force in 2015, with a relatively stable trend over the entire period, except for a small decline in 2020. This increase was mainly a result of the increased number of inspections by the North Sea ECA countries, while the Baltic Sea countries had a more stable number of conducted inspections throughout the entire period. The non-compliance rate based on documentary inspections followed a similar trend as the number of infringements in the BA. However, it is important to note that this pattern is largely influenced by a noteworthy reduction in non-compliance in the North Sea, while the reduction in the Baltic Sea is less pronounced. Also, when looking at the compliance results outside the SECA, the reduction was less pronounced. The overall non-compliance rate in the

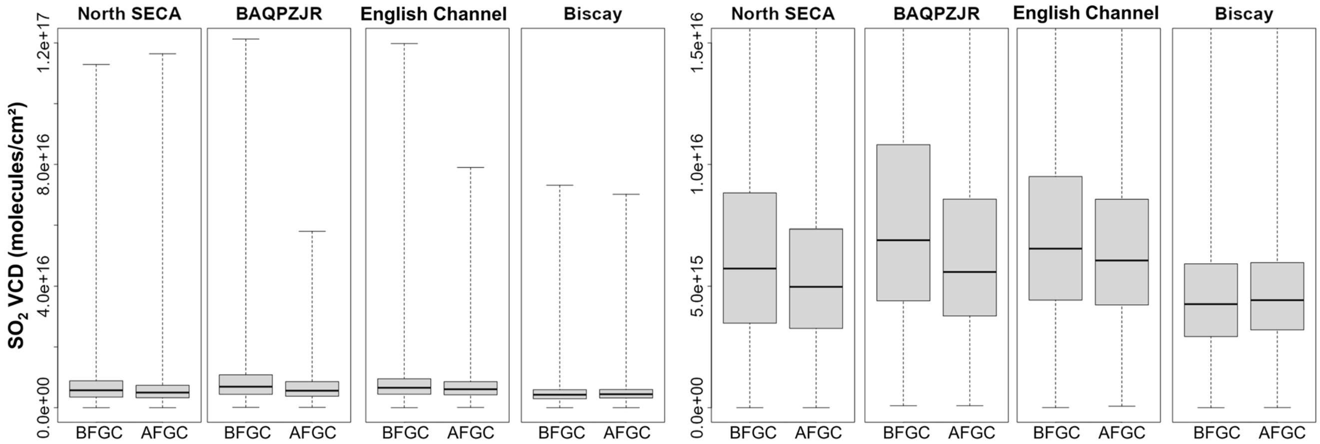

Fig. 6 Impact of global sulfur cap on SO_2. Box plot of annual SO_2 VCD levels between different areas before (BFGC) and after (AFGC) the global sulfur cap entered into force in 2020, with minimum, 25% percentile, median, 75% percentile and maximum. The left plots include the maximum values, while the right plots give the 25–75% percentile range.

North Sea (7%) was found to be significantly higher compared to the Baltic Sea (3%) ($P < 0.001$). The non-compliance rate within the SECA (5%) was markedly higher compared to the non-compliance rate outside the SECA (2%) ($P < 0.001$).

In addition to the documentary inspections, in accordance with EU regulations[35,36], fuel samples were collected by the EU MS (Fig. 5B). Besides a small reduction in the number of fuel samples collected in 2020 due to the global COVID-19 pandemic, the number of samples remained fairly consistent, with most EU MS providing a number above the mandatory requirement. When analyzing the inspection results from the fuel samples within the SECA, a significant increase in non-compliance was observed in 2016 and 2017, followed by a drastic reduction toward 2020, which then stabilized. This trend was observed for both the North Sea and the Baltic Sea. However, there was a slight increase in non-compliance observed in the North Sea in 2022, aligning with the findings from the remote monitoring operations in the BA. The North Sea non-compliance results of the fuel analysis (5%) were notably higher than the Baltic Sea (2%) ($P < 0.001$). The non-compliance trend of the fuel analysis outside the SECA also showed a substantial decrease by 2020, while the overall non-compliance rate (4%) was not found to be significantly different from the overall non-compliance rate of the fuel analysis within the SECA (4%) ($P = 0.9488$).

Spatiotemporal analysis of satellite data

Spatial analysis of atmospheric SO_2 data. Upon comparing the SO_2 vertical column density (VCD)—expressed in molecules/cm²—across the various regions (Fig. 6) for 2019 and 2021, notable findings emerged. Specifically, the BA Quadripartite Zone of Joint Responsibility (BAQPZJR) exhibited the highest concentrations of SO_2 pollution within the ECA. Meanwhile, the Bay of Biscay displayed a much lower pollution pressure of SO_2 (Supplementary Table 7). The implementation of the global sulfur cap is shown to have created a comparable reduction of SO_2 pollution levels across the SECA. The region outside the SECA did not seem to be impacted. When looking at the period 2018–2022, for some areas an increase was observed (Supplementary Fig. 7). However, due to the absence of certain months in 2018 and 2022, this was attributed to seasonal effects.

Temporal analysis of atmospheric SO_2 data. From the start point of the satellite data in 2018, the overall emission levels of SO_2 at sea were already relatively low, particularly in the SECA due to the implementation of the 0.1% FSC limit in 2015. Consequently, the SO_2 VCD maps for 2019 and 2021, the respective years before and after the global sulfur cap came into effect, visualize widely dispersed concentration levels, although areas with high shipping activities can be, to some extent, identified. (Supplementary Fig. 8). Accordingly, the proportional difference of SO_2 pollution levels before and after the implementation of the global sulfur cap does not exhibit a distinct pattern (Fig. 7).

When comparing the proportional difference in SO_2 VCD after the implementation of the global sulfur cap amongst the different areas (Supplementary Fig. 9), the most substantial decrease was observed for the BAQPZJR (−22.5%), the northern part of the SECA (−15.9%) and the English Channel (−9.5%). The Bay of Biscay was less impacted by the global sulfur cap and even showed a negligent increase (+3.0%), most probably because this area already had a lower SO_2 pollution pressure compared to the densely navigated waters of the SECA. However, there is also an indication that the sensitivity of the TROPOMI SO_2 data might be insufficient to conduct a thorough analysis of SO_2 pollution trends in areas with lower SO_2 pollution levels.

To conclude, the conducted spatiotemporal analysis indicated a positive influence of the global sulfur cap and other international and EU regulations on ambient SO_2 concentrations in the European SECAs. The findings are in line with the results obtained from the remote measurements and inspections conducted within the BA and the EU, therefore strengthening the validity and reliability of the findings. However, it should be noted that when utilizing satellite images to assess air quality improvement for SO_2 outside the ECAs, the analysis heavily relies on the shipping density and ambient SO_2 pollution levels.

Spatial analysis of atmospheric NO_2 data. When comparing absolute NO_2 VCD levels across different areas (Fig. 8), it was demonstrated that the NO_2 VCD within the North Sea NECA is overall considerably higher compared to the areas outside the NECA. Particularly in the BAQPZJR and the English Channel, NO_2 VCD levels are notably elevated, although there are some seasonal differences (Supplementary Fig. 10). However, it is important to acknowledge that the elevated NO_2 VCD levels in these areas are likely to be influenced, to some degree, by industrial activities and other densely populated areas in the southern parts of the UK, northern parts of France, Flanders, and the Netherlands. On the other hand, Riess et al. provided evidence that the TROPOMI data primarily captures emissions within the first 200 meters above sea[37]. In addition, despite possible other contributing factors, the monthly NO_2 VCD

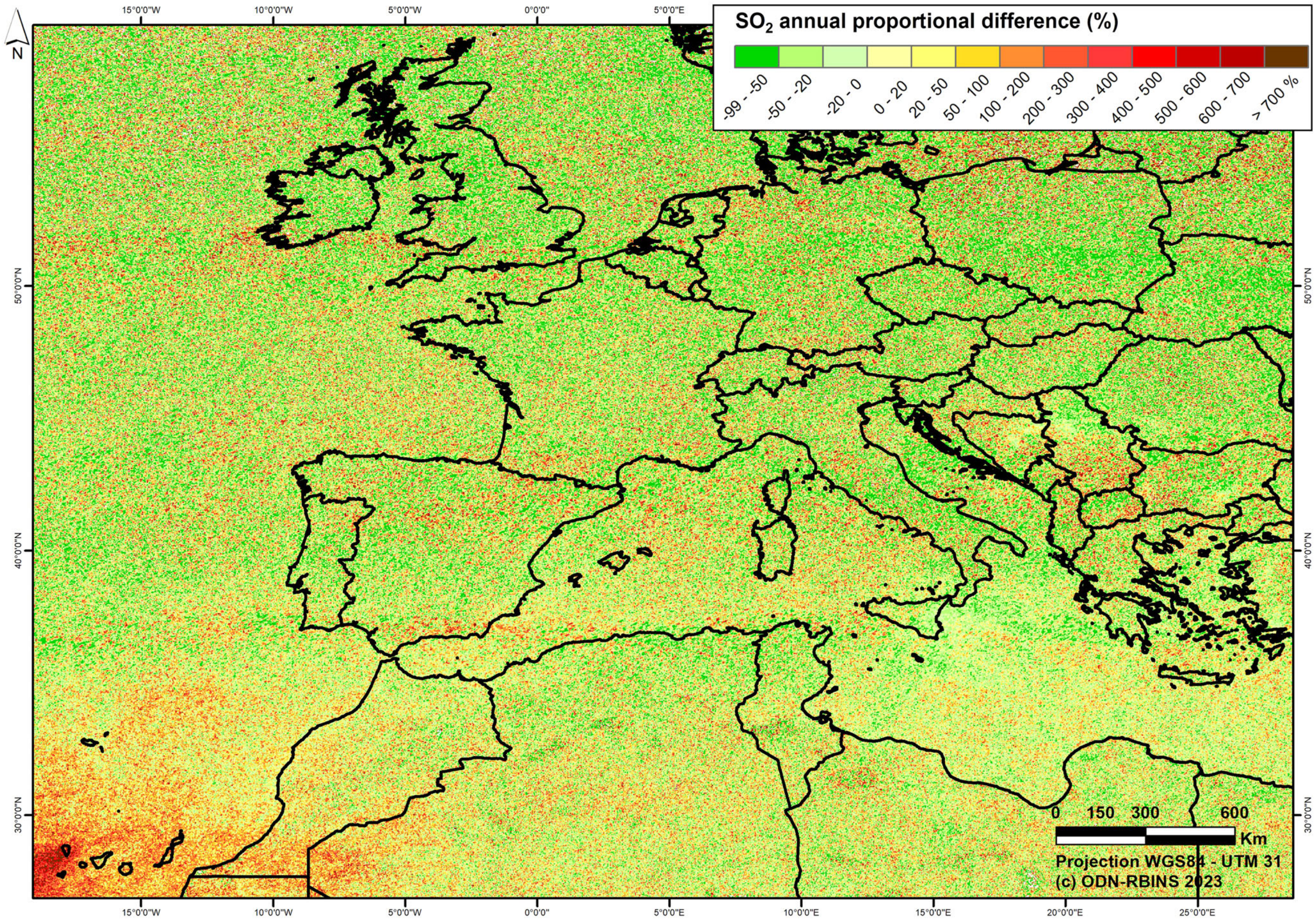

Fig. 7 Spatiotemporal analysis—impact global sulfur cap. Annual proportional difference of SO_2 VCD levels between 2019 and 2021.

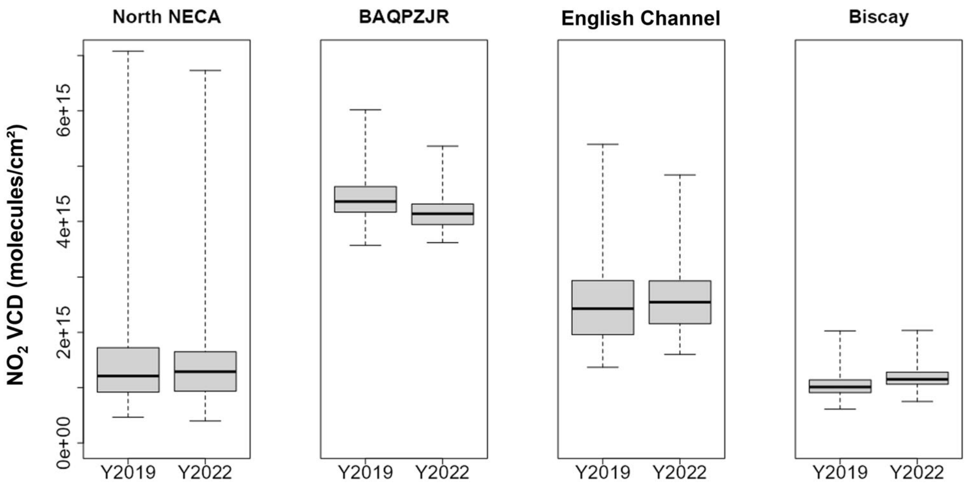

Fig. 8 Impact NECA on NO_x. Box plot of annual NO_2 VCD levels between different areas before (BFNC) and after (AFNC) the European NECA entered into force in 2021, with minimum, 25% percentile, median, 75% percentile and maximum.

satellite data clearly reveals visible shipping patterns (Supplementary Fig. 11). Consequently, it can be stated that emissions from OGVs provide the dominant factor in the observed NO_2 VCD data.

When looking at the average NO_2 levels before and after the implementation of the NECA for the different areas, it was demonstrated that NO_2 levels after the introduction of the NECA were impacted in different ways. The BAQPZJR area remained the most polluted area, with the English Channel following closely behind. However, since the implementation of the NECA, the Bay of Biscay became the third most polluted area, before the Northern NECA.

Temporal analysis of atmospheric NO_2 data. For the temporal analysis of NO_2, an annual and a monthly approach was used. For the annual approach, the proportional difference between 2019

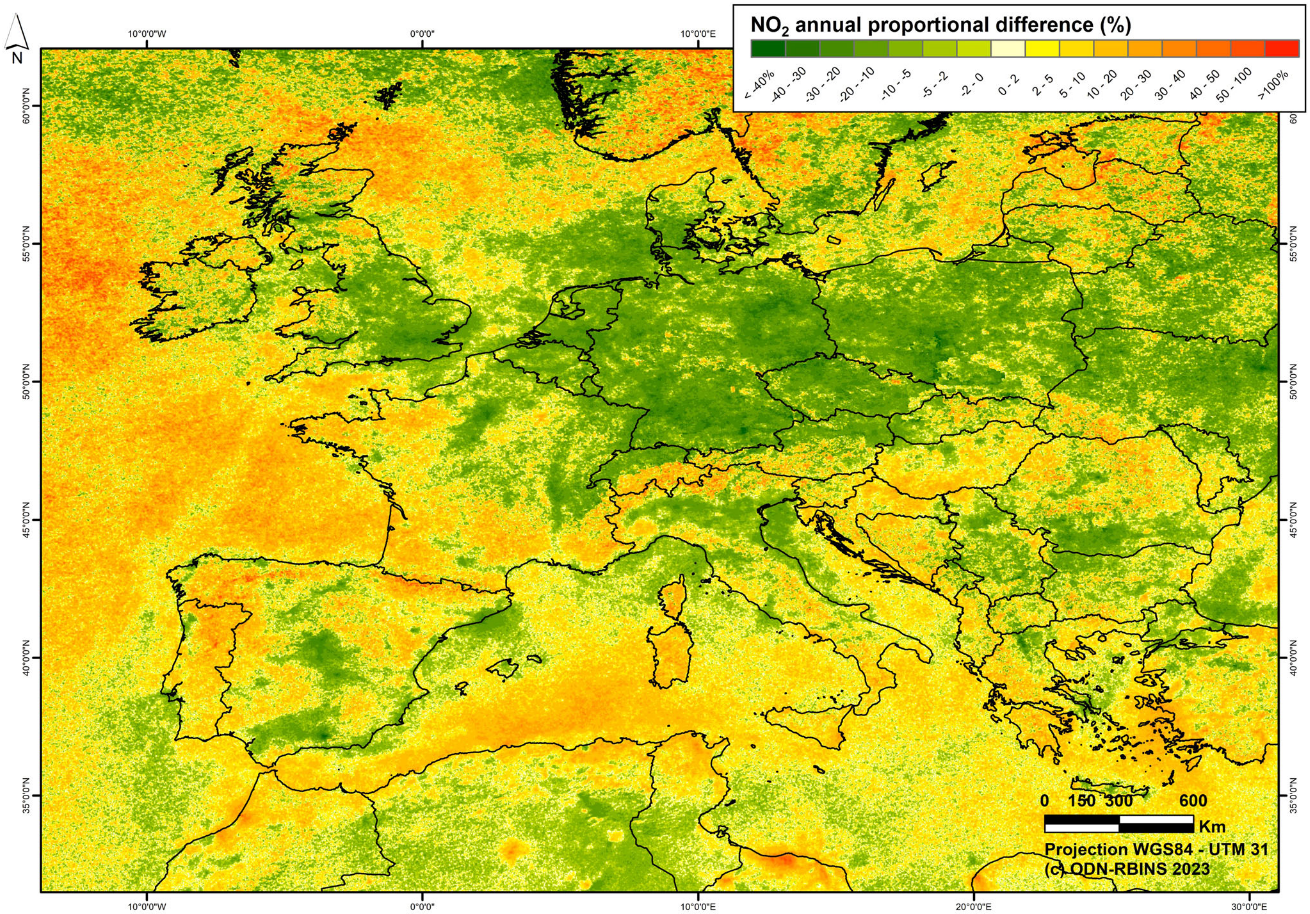

Fig. 9 Spatiotemporal analysis—impact NECA, annual approach. Annual proportional difference of NO_2 VCD levels between 2019 and 2022.

and 2022 was determined (Fig. 9). This map shows varying results on the proportional difference in NO_2 VCD levels throughout the North Sea NECA, with an annual proportional increase of +14.4% in the Bay of Biscay; +4.1% in the English Channel; and +1.0% in the Northern part and of the NECA. A decrease of −5.8% was observed in the highest polluted BAQPZJR area. This analysis does however not include seasonal differences, which could result in an over- or underestimation of the NO_2 pollution trends.

The comparison of the monthly NO_2 VCD levels did indeed reveal a seasonal effect in certain areas, particularly in the BAQPZJR. Consequently, to mitigate the potential for a seasonal bias and to get a better understanding of the ambient NO_2 VCD trends throughout the year, a monthly proportional difference analysis was conducted. For this monthly analysis, the proportional difference between the period before and after the implementation of the NECA was calculated for each month (Supplementary Fig. 12). This analysis yielded variable results. In the months of January, February, May, July, August, September, October, and December, there was a limited impact with localized variations with either an increase or decrease. On the other hand, March and June showed an overall increase, while April and November demonstrated an overall decrease in NO_2 VCD levels. Subsequently, the proportional difference maps per month were combined to create an average monthly proportional NO_2 difference map (Fig. 10A). This map demonstrates a slightly different picture compared to the annual proportional difference. Also here a NO_2 increase, albeit slightly lower, is observed for the Bay of Biscay (+10.3%) and the English Channel (+4.0%). However, a small decrease was observed for the Northern NECA (−1.4%). For the BAQPZJR, the monthly analyses demonstrate a similar reduction (−5.0%) as for the annual analysis. The differences with the annual analysis can be attributed to the influence of seasonal variability and the inclusion of the years 2020 and 2021, which were affected by the global COVID-19 pandemic. The evolution of the average NO_2 VCD over 2018–2022 clearly demonstrates the effect of the global COVID-19 pandemic. The impact was most substantial in the Northern NECA zone (−44%), the BAQPZJR (−19%), and the English Channel (−9%). The Bay of Biscay (+18%) was not impacted by the COVID-19 pandemic (Supplementary Fig. 13A).

Additionally, significant increases were observed in the Mediterranean Sea, and Atlantic Ocean, with increases in the average monthly NO_2 VCD levels of up to 20%. Due to a lack of data for the winter months in the north of the Baltic Sea, a full-year assessment could not be made. Nevertheless, the data that is available for the months of January–December indicates a slight reduction (Fig. 10B). In conclusion, these analyses confirm that the ambient NO_2 levels throughout the year either increased after the NECA implementation or where they decreased, the decrease was less substantial at sea compared to inland.

Discussion

Through the analysis of over 110,000 remote measurements of OGV emissions spanning a duration of seven years, valuable insights were obtained regarding the FSC compliance behavior of OGVs in the European ECAs. The results indicate a consistent decline in FSC non-compliance rates across the SECAs. However, it is important to remain vigilant as remote measurements suggest

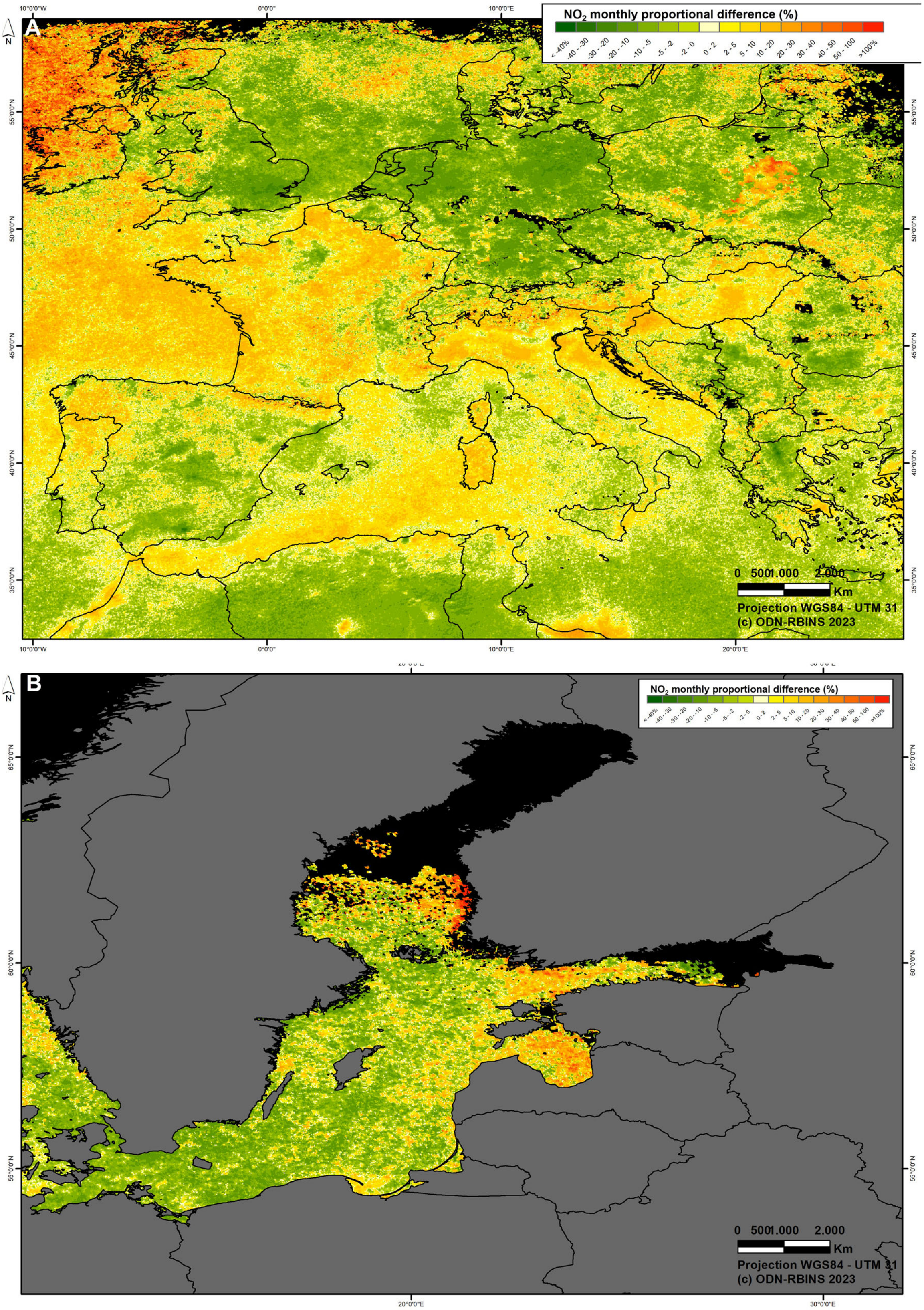

Fig. 10 Spatiotemporal analysis—impact NECA, monthly approach. Average monthly proportional difference of NO_2 VCD levels between the years before (2018–2020) and after (2021–2022) the NECA implementation for the North Sea ECA (**A**) and the Baltic Sea ECA (omitting December) (**B**).

a potential rise in non-compliance in recent years. Despite certain differences in measurement uncertainty and methodology, a strong correlation was observed between the results obtained from fixed sniffers, sniffer sensors utilized on fixed wing aircraft and mini-sniffers employed on RPAS and rotary wing aircraft. This indicates a considerable level of agreement between the different measurement methods and sensors, further supporting the reliability of the findings and suggesting a consistent pattern of compliance trends.

A spatiotemporal analysis conducted on the remote measurements revealed relatively high compliance within the SECA region, while also highlighting specific spatial compliance patterns in relation to the distance from ports, distance to the SECA border, and differences between the Baltic Sea and North Sea areas. It should be noted that this spatial analysis provides only an initial broad-scaled assessment. To obtain a more comprehensive understanding of the spatial distribution of non-compliance average FSC levels, it is necessary to conduct a thorough analysis of the raw measurement data. Conducting such an analysis would enable a deeper understanding of the specific factors influencing non-compliance risks within the SECA region. To compare average FSC levels, an intercomparison study first needs to be conducted. In light of this intercomparison, it should be noted that the Belgian monitoring data was adjusted for its measurement bias by utilizing plume simulation gas mixtures with specific concentrations of CO_2 and SO_2[26]. These plume simulation mixtures could be employed as a “round robin” mechanism to rectify measurement discrepancies between different sensors, enabling a comprehensive comparison of average FSC levels. This in turn would enable a more refined spatial analysis of compliance patterns, thus providing a higher resolution assessment. The insights gained from such an analysis can be used to identify areas with high risk of non-compliance, guiding the strategic deployment of remote monitoring operations. By focusing on these high-risk areas, enforcement efforts can be optimized to better address non-compliance and ensure better enforcement of international emission regulations.

In contrast to the relatively good FSC compliance following the global sulfur cap implementation, the introduction of the NECA in 2021 did not lead to any substantial impact on the remotely measured NO_x concentrations in European waters, nor did it result in an effective enforcement and sanctioning mechanism. On the contrary, it was found that NO_x emission factors and potential NO_x non-compliance are increasing. This outcome was somewhat expected, considering that the stricter emission regulations within the ECA primarily apply to Tier III vessels. Given the limited number of Tier III vessels currently in operation, the NECA implementation has not yet made a measurable impact in reducing average NO_x emission factors. Furthermore, previous studies already indicated increased NO_x emission factors for Tier II vessels compared to Tier I vessels[21,24,28,32,38,39]. Consequently, the outcomes of this study align closely with the conclusions drawn from other research studies.

The Parties of the BA, and by extension the EU MS, have successfully implemented a comprehensive and efficient system for conducting on-board port inspections of OGVs with regard to the sulfur content of marine fuels. Based on the results of more than 110,000 documentary inspections and more than 26,000 fuel samplings, the study indicates that non-compliance with FSC regulations in ports in both European SECAs exhibit a similar declining pattern. Nevertheless, by implementing remote monitoring to identify non-compliant OGVs and establishing an enforcement mechanism that considers the highest measured emission levels, the enforcement capacity can potentially be further improved. Conversely, the study revealed that the enforcement of the international NO_x emission regulations for OGVs in port is currently highly ineffective due to insufficient inspection and sanctioning procedures outlined in international regulations. The absence of a comprehensive EU regulatory framework specifically addressing NO_x emissions from shipping with inspection rules can be considered a critical factor in this context. In light of this, Canada recently submitted a document for the July 2023 meeting of the Marine Environment Protection Committee (MEPC80), a subsidiary body of the IMO, to address some of these Tier III-related issues[40]. It is worth noting that as early as 2007, the US already had submitted a document to the IMO Subcommittee on Bulk Liquid and Gases, foreseeing and addressing some of the very challenges that are currently being observed in the certification and testing processes of Tier III OGVs[41].

In order to evaluate the influence of international regulations on air quality within the European SECA, this study analyzed TROPOMI Sentinel 5 data from 2018 to 2022. The analysis of the spatiotemporal patterns in SO_2 satellite data demonstrates a limited decrease in SO_2 pollution levels in the North Sea SECA and a status quo or even a slight enhancement outside the SECA. The subsequent international and EU regulations on SO_2 have therefore had a substantial, positive impact on public health and the environment in the European SECAs. It is important to acknowledge that data for 2021 may have been affected by the global COVID-19 pandemic. Unfortunately, a complete annual dataset for 2022 could not be obtained. Future analysis will need to determine if the recent increase in FSC non-compliance, observed by the remote monitoring operations, and the recovery of economic activity after the global COVID-19 pandemic, will impact overall SO_2 pollution levels. Additionally, it should be noted that as shipping activities increase, an overall rise in SO_2 emissions is anticipated[24]. However, it should be acknowledged that the sensitivity of the TROPOMI data for SO_2 does not seem to be optimal for detailed analysis outside densely navigated areas.

In contrast, the TROPOMI NO_2 products proved substantially more useful for performing a meaningful analysis. The spatiotemporal analysis of the NO_2 satellite data reaffirmed the findings from the remote measurements and port inspections, indicating that the implementation of the NECA has not resulted in a substantial reduction of the NO_x pollution pressure from the shipping sector. On the contrary, it appears that NO_2 pollution levels only decreased substantially in the most polluted area (BAQPZJR), in other areas of the NECA, signs of an increase were observed. Strong decreases were observed over land, in particular above the cities of Paris, Brussels, Londen, etc. This also inevitably impacted the temporal analysis, particularly within the BAQPZJR region, explaining the observed NO_2 reduction in that area. Although this reduced input from land-based pollution was not accounted for in this study, it is safe to assume that if this land-based pollution were to be incorporated, an overall increase across all areas would be observed.

The findings derived from this study provide substantial evidence of the effectiveness of international regulations and the enforcement measures taken to address FSC non-compliance in the shipping sector. Notably, the implementation of inspection regimes in EU ports and the deployment of remote monitoring operations at sea have functioned as a considerable deterrent effect. These measures have proven instrumental in discouraging FSC non-compliant behavior within the shipping industry, emphasizing the pivotal role of well-defined and stringent regulations and effective enforcement measures. However, the results indicate that compliance is lower at sea compared to the port areas. In addition, the comprehensive analyses of the remote NO_x measurements and NO_2 pollution levels at sea solidify the conclusion that the international regulations on NO_x emissions from ships were ineffective in reducing NO_x pollution from the shipping sector. Therefore, this study strongly recommends the revision of current NO_x regulations, the implementation of additional NO_x emission regulations and decisive and effective enforcement measures in the North Sea and Baltic Sea.

Furthermore, the increased NO_2 VCD in the Bay of Biscay, the Mediterranean Sea and Iberian coast are highly notable. These findings strongly emphasize the importance of establishing a Mediterranean NECA in conjunction with the Mediterranean SECA, which is entering into force on May 1, 2024[42]. The introduction of a North Atlantic NECA encompassing the waters of France, Spain, and Portugal is also recommended. Based on the analysis conducted on the existing European NECAs, it should be emphasized that the introduction of additional NECAs without enhanced emission regulations would not result in the anticipated improvements in air quality.

The findings from this study emphasize the need to review the current air quality models that include ship emissions[31]. These models should accurately incorporate both the real-world emission factors reflecting actual ship emissions and the observed compliance levels at sea, accounting for spatial variations within the ECAs. By updating these models, valuable insights could be gained on the health impact of shipping, which could serve as a driving force for policymakers to reconsider and improve the prevailing international regulatory framework.

Methods

Research area

Bonn Agreement. The BA is a regional cooperation established in 1969 to prevent marine pollution from OGVs in the North Sea. Initially, this focused on oil pollution. The BA consists of 11 CPs including all North Sea coastal States, Spain, Ireland and the EU (represented by EMSA)[43]. Among others, through intensive cooperation, the BA recorded a significantly reduced amount of oil pollution over the last two decades[44–46]. Over the years, the BA was expanded to include other harmful substances besides oil. From 2015, several BA CPs petitioned the BA to extend the scope of the BA to include air pollution from shipping. In October 2019, the Ministerial Meeting of the BA formally approved the extension of the scope of the BA to include MARPOL Annex VI, recognizing the BA as the appropriate intergovernmental forum to roll out OGV emission monitoring activities[43,47].

North Sea and Baltic Sea emission control area. The establishment of the ECAs was included in the adoption of the MARPOL Annex VI regulations in 2008[15]. After several years of negotiations, the North and Baltic Sea SECAs were established in 2011, in addition to ECAs in North America and the Caribbean Sea[17]. The SECA covers the North Sea, the English Channel, and the Baltic Sea. The European NECAs were established in 2021[18]. The North and Baltic Sea NECAs cover the same area as the SECAs and are therefore both referred to as ECAs. The North and Baltic Sea ECAs cover a vast sea area, spanning from the English Channel to the Russian border, impacting air quality for over 280 million European citizens.

Remote measurement data in the Bonn Agreement

Remote monitoring locations. To obtain a comprehensive assessment of the impact of maritime SO_2 emission regulations in the European SECAs, annual compliance monitoring data from five fixed monitoring sites and nine airborne monitoring operations from six BA CPs in the SECA were analyzed (Supplementary Table 2), encompassing a total of 115,274 OGV measurements. Some deployments have been terminated, others are still ongoing, data from operations that are still ongoing were obtained from: (1) MUMM operates the Belgian coastguard aircraft equipped with a sniffer sensor from 2015; (2) BSH (Hamburg, Germany) is in charge of the German network of fixed sniffer stations from 2015, with stations in Hamburg, Kiel and Bremerhaven; (3) TNO (Delft, The Netherlands) operates a fixed sniffer station at the port of Rotterdam in The Netherlands on behalf of the Human Environment and Transport Inspectorate (ILT) from 2015; (4) Explicit executes RPAS measurements with dual mini-sniffers on behalf of EMSA in Denmark, France, Germany, Lithuania and the Spain[29,48–57] from 2019. Data from following terminated operations was used: (1) Chalmers University (Goteborg Sweden) operated an airborne sniffer and a fixed sniffer station at the Great Belt bridge in Denmark on behalf of the Danish Environmental Protection Agency (EPA) from 2015 to 2020; (2) Explicit (Virus, Denmark) conducted airborne measurements using helicopters equipped with dual mini-sniffers, and uses single mini-sniffers on RPAS, in Denmark on behalf of the Danish EPA from 2017 to 2022; (3) Explicit, conducted dual-sniffers measurement with a helicopter in the Netherlands in cooperation with ILT in 2016.

Out of the total measurements taken, the majority (101,464) were conducted using fixed stations along frequently navigated shipping lanes. This was followed by airborne measurements carried out by aircraft (8210), and subsequently by RPAS and helicopter measurements using mini-sniffers (4732). The Belgian airborne dataset contributed to more than half of the total number of airborne measurements (6961). However, the number of measurements conducted by any of the fixed sniffer sites greatly surpasses the number of measurements conducted by the airborne monitoring platforms. For determining average non-compliance rates within the SECA, a weighted average was calculated based on the number of measurements per station or deployment.

Compliance cutoff levels. Three different cutoff levels were used to assess possible violations: 0.20% FSC, 0.15% and 0.13% FSC. These three cutoff levels were used to facilitate the evaluation of variations in non-compliance levels across different scales, as a direct comparison of average FSC levels was not feasible due to the unavailability of raw measurement data. In addition, although remote monitoring stations and platforms employ similar techniques, slight differences in measurement methodologies and uncertainties exist among the different stations. Nonetheless, the data used in this study remains suitable for conducting a comparative analysis of general temporal and spatial compliance trends.

Selection of data for temporal analysis. Several stations or platforms only measured a low number of vessels for certain years. A minimum of 100 operational measured OGVs per year was applied for the temporal compliance analysis. As a result, in total seven annual compliance results were omitted from four different locations.

Spatial trend analysis. For the selection of the measurement sites for the spatial analysis, a minimum continued measurement period of two years and a total of 200 measured OGVs was applied. Locations that did not meet this requirement were either omitted or added to the location of the nearest other remote measurement location. The RPAS data from Lithuania (142 measurements in 2021) was therefore omitted. The data from the different airborne assets in Denmark were merged to one location. Furthermore, the airborne mini-sniffer measurements of the Netherlands in 2016 were added to the Belgian airborne measurements.

For the spatial analysis, in addition to the SECA measurements, measurements conducted at the southern ECA border were used.

These measurements were conducted by Chalmers University (114 in 2016) and the Belgian coastguard aircraft (23 in 2022). As sufficient data was not available for temporal analysis and as these measurements were conducted with the same sensor technology, the data at the SECA border was combined for the spatial analysis.

The emission data was fitted on an S-curve in function of the distance to the SECA border (d_b) and the distance to port (d_p).

$$\text{Non\_compliance}\,(\%) = \frac{(k-p)}{1+e^{-o(d_x-m)}} + p \tag{1}$$

with:

k = high Non_compliance rate (%)
p = low Non_compliance rate (%)
o = Non_compliance increase/decrease rate (%)
m = midpoint distance (km)
d_x = distance to SECA border/port

The weighted average non-compliance rates were used for the factors k and p, the least square method was applied for the determination of the factors o and m.

Inspection results of port inspection authorities in the Bonn Agreement. In accordance with the EU Sulphur Directive and the Commission Implementing Decision, the port state authorities of the EU MS conduct sulfur inspections[35,36]. These are done by either documentary inspection or by analyzing the fuel in accordance with the fuel inspection guidelines from IMO[58]. Within the scope of this research and the work conducted under the BA, inspection and sanctioning results from port State authorities from 9 out of 10 BA CPs were obtained. This data is part of the annual inspection results that are reported to the EC. The most CPs apply a 0.15% threshold for reporting infringements to the EC. Of all BA CPs, two are located outside the ECA (Spain and Ireland) and two are currently not reporting to the EC (Norway and the United Kingdom). In addition to the sulfur inspection results, NO_x inspection results were also collected. As NO_x is currently not regulated through an EU directive, inspection results are currently not being shared with the EC.

EU inspection results and Thetis-EU. The EU Sulphur Directive led to the creation of Thetis-EU, an online database used for exchanging inspection results. 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[36,59].

Keel laying date. Information on the KLD is required for the determination of the tier level when assessing NO_x compliance. For the Belgian NO_x remote monitoring assessment, this KLD data was acquired based on merging two database sources: (1) the Global Integrated Shipping Information System (GISIS) of the IMO[60] and; (2) Thetis-EU of EMSA. The GISIS database was first used to gather information on OGVs larger than 75 meters with construction year. In the second step, EMSA provided the accurate KLD[28]. For the Danish analysis, a ship database was acquired from IHS Markit.

Inspection results. Under the EU Member States' obligations to report inspection outcomes to the EC as stipulated by the EU Sulphur Directive and Commission Implementing Decision[35,36], data on sulfur inspections conducted by the EU MS were obtained from EMSA[59]. As most, but not all, BA CPs are part of the EU, there is a certain overlap with the BA data. The EU data contains more States and includes all EU MS outside the SECAs. The EMSA data therefore gives a broader overview of the inspection results throughout the EU. However, the EU data does not contain results on penalties. Moreover, due to the lack of EU regulation regarding NO_x emissions from OGVs, the EMSA data does not contain NO_x inspection results.

The EMSA website publicly displays the amount of port inspections and compliance levels resulting from documentary inspections conducted by EU MS[59]. Its purpose is to enable EMSA to deliver thorough reports to the EC to assess the implementation of the EU Sulphur Directive by the EU MS[35,36]. Additionally, the EMSA website includes records of non-compliance detected through fuel sample analysis. However, the actual number of fuel samples themselves is not available on the website. A request for this information was made to EMSA to facilitate the analysis of temporal trends in fuel sample results.

Statistical analysis of remote monitoring data and port inspection results. Previous studies using the Belgian airborne data have already shown that emission measurements deviate from a normal distribution[24,26,28]. When the distribution of remote measurement data is compiled, they initially appear to follow a normal pattern, with the emission limit as the central point. However, although small negative values are occasionally observed, there are no highly negative values, while very high FSC values are possible. As a result, this inevitability renders the distribution non-normal. Pearson chi-square tests were used to assess the difference in compliance rate between two locations/deployments, with statistical significance defined as $P < 0.05$[61].

Satellite analysis. A spatiotemporal analysis was conducted using satellite data from the Tropospheric Monitoring Instrument (TROPOMI) Sentinel 5 to investigate the distribution and changes in SO_2 and NO_2 levels over European waters. The temporal analysis of SO_2 focused on the evaluation of the impact of the global sulfur cap, which entered into force in 2020[62], while the temporal analysis of NO_2 focused on the implementation of the European NECAs in 2021[18]. Additionally, a spatial analysis compared SO_2 and NO_2 pollution levels between different areas within the ECAs and differences between the ECAs and regions outside the ECA.

TROPOMI data. Data was gathered from TROPOMI on board the Copernicus Sentinel-5 Precursor satellite, which is operated by the European Space Agency (ESA). The satellite data contains measurements of the SO_2 and NO_2 VCD in the lower atmospheric layer (up to 80 km). For SO_2, the retrievals from the scientific COBRA V01 scheme processed by BIRA-IASB were used[63] for the period May 2018 until September 2022. For NO_2, the satellite operational data product (Level 2 data) was collected from the Copernicus Open Access Hub[64] for the period May 2018 until December 2022, using the PAL v2.3.1 retrieval algorithm. With the NO emissions converted to NO_2, factors such as ambient meteorological conditions, O_3, and solar radiation influence the conversion speed. However, conversion is considered to be in the time span of seconds to tens of minutes during daytime[65,66]. Therefore, the NO_2 satellite analysis gives a good representation of NO_x pollution levels.

TROPOMI retrievals for SO_2 and NO_2 have been filtered based on their quality assurance (QA) value. Only pixels with a QA value equal to or larger than 0.75 were selected, removing cloudy pixels (cloud radiance fraction > 0.5) and erroneous retrievals[64]. Subsequently, they were averaged to generate monthly VCD products. The monthly average VCD products were further compiled using ArcGIS and Qgis to generate VCD maps for spatial and temporal analysis.

Spatial analysis. For the spatial analysis, average SO_2 and NO_2 levels were compared between different areas. The North Sea ECA was divided into three zones: (1) the Northern part of the ECA; (2) the BAQPZJR and; (3) the English Channel. In addition, a fourth zone was added outside the SECA in the Bay of Biscay (Supplementary Fig. 14). The Baltic Sea was not included in the spatial satellite data analysis due to the substantial influence of land-based sources and the lack of satellite coverage for the winter months in the northern Baltic Sea.

Temporal analysis SO_2. Several studies provided scientific evidence of the impact of the global COVID-19 pandemic on ambient SO_2 levels, although this mainly concerned inland SO_2 pollution, pollution levels over sea were less impacted[63,67]. Additionally, the implementation of the global sulfur cap in 2020 marked a turning point for SO_2. Consequently, the temporal data analysis for SO_2 excluded the year 2020 to ensure unbiased comparability.

For the temporal analysis of SO_2, first the SO_2 VCD maps per month (*i*) for the period before (2018–2019) and after (2021–2022) the global sulfur cap came into effect were combined in a monthly mean SO_2 VCD map. As the year 2020 was omitted, the period before and the period after the global sulfur cap implementation composed the same amount of months (21).

$$\bar{SO}_{2\,\mathrm{Period}}(\mathrm{VCD}) = \frac{\sum_{i}^{21} SO_{2_i}}{21}(\mathrm{VCD}) \tag{2}$$

This data demonstrated substantial seasonal variability in pollution levels (Supplementary Fig. 7). The years 2018 and 2022 could not be used as they did not contain data for the full year. Therefore, the annual SO_2 VCD maps of 2019 and 2021 were calculated. In the second step, the proportional difference between these two maps was calculated to create the proportional difference between the annual SO_2 VCD.

$$\mathrm{Diff}_{SO_2}(\%) = \frac{\bar{SO}_{2\,2021} - \bar{SO}_{2\,2019}}{\bar{SO}_{2\,2019}} \tag{3}$$

Temporal analysis NO_2. In 2022, Ward Van Roy et al. used TROPOMI data to evaluate the impact of the implementation of the NECA[28]. That analysis was limited to the determination of the absolute difference in NO_2 VCD between 2020 and 2021. This indicated a potential decrease of NO_2 in the northern part of the North Sea SECA, but an increase in the southern part. However, by looking at the absolute difference, areas with high pollution levels are more prone to be highlighted. In addition, the analysis was limited to the years 2020 and 2021, which were impacted by the global COVID-19 pandemic[28,67,68]. Riess et al. reported a reduction of observed NO_2 concentrations in shipping lanes, between 10 and 20% as a result of the global COVID-19 pandemic[69]. For these reasons, a wider analysis was required that incorporated the relative impact of the NO_x regulations on the overall NO_2 pollution levels. The NO_x temporal analysis in this study focused on two analyses, an annual proportional difference and a monthly proportional difference. It must be acknowledged that, due to limited satellite coverage throughout the year the Baltic Sea ECA could not be fully assessed.

For the annual proportional difference, a similar analysis was conducted as what was performed for SO_2, while for NO_2, data for the complete 2022 was obtained. With 2021 being the turning point year, with the introduction of the NECA, the years 2019 and 2022 were compared.

$$\mathrm{Diff}_{NO_2}(\%) = \frac{\bar{NO}_{2\,2022} - \bar{NO}_{2\,2019}}{\bar{NO}_{2\,2019}} \tag{4}$$

As initially a potential seasonal effect was observed (Supplementary Fig. 10), an average monthly proportional difference was also calculated. First, monthly mean VCD maps were created for the period before (BFNC) and after (AFNC) the NECA came into effect. The BFNC period was composed of the months from May 2018 until December 2020 (32 months), and the AFNC period was composed of the months from January 2021 until December 2022 (24 months). Thus, for every month (i) two or three years (j) were available.

$$\bar{NO}_{2\,i\_\mathrm{period}}(\mathrm{VCD}) = \frac{\sum_{j}^{\mathrm{years}} NO_{2_j}}{\mathrm{years}}(\mathrm{VCD}) \tag{5}$$

This provided 12 NO_2 maps before (BFNC) and 12 NO_2 maps after (AFNC) the NECA came into force. In the second step, the proportional difference between these maps was calculated per month.

$$\mathrm{Diff}_{NO_{2_i}}(\%) = \frac{\bar{NO}_{2\,i\_\mathrm{AFNC}} - \bar{NO}_{2\,i\_\mathrm{BFNC}}}{\bar{NO}_{2\,i\_\mathrm{BFNC}}} \tag{6}$$

In the final step, the average monthly proportional difference was calculated

$$\mathrm{Diff}_{NO_2}(\%) = \frac{\sum_{i}^{12} \mathrm{Diff}_{NO_i}}{12}(\%) \tag{7}$$

To provide an analysis throughout the entire 2018–2022 period, the years 2020 and 2021 were not omitted. As NO_2 levels in 2021 were lower compared to 2020 (Supplementary Fig. 13), this almost certainly creates a negative bias for the period after the NECA came into force.

It must also be acknowledged that local concentrations of NO_2 are affected by the lifetime through background levels of NO_2 itself, O_3, and available sunlight[70]. As these vary in time, this will influence uncertainty in temporal comparisons. This dynamic is investigated in detail by Riess et al., showing that this will influence the calculated changes in emissions[69], not VCD levels used for this study. Meteorological conditions, driving dispersion, will also show temporal variability influencing the extent to which the study areas will be impacted by land-based sources or inversely drive ship emissions outside of the study areas. Such effects are not accounted for in this study but are expected to be minor given the year-to-year comparison.

Data availability

The anonymized full Belgian airborne monitoring dataset is available on the repository: https://doi.org/10.24417/bmdc.be:dataset:2687. The raw remote measurement data of the other Bonn Agreement countries is not provided as the data is legally owned by the authorities of the relevant countries and can therefore not be distributed. The port inspection results were provided by EMSA; however, the original data can not be made available due to legal concerns. The annual results of the remote monitoring efforts of the BA CPs, the inspection results of the EU MS and the sanctions and violations observed by the BA CPs are available on the repository: https://surv.naturalsciences.be/d/76719a8375fd409ebe5f/. The TROPOMI satellite data and geo-data are available on the repository: https://surv.naturalsciences.be/d/04c1441989684255b6ed/.

Code availability

The code used for the satellite analysis is available on the repository: https://surv.naturalsciences.be/d/3b8de56010584c39ac4b/.

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Author contributions
W.V.R. designed the research and wrote the paper; W.V.R., B.V.R., L.V., A.V.N., K.S. and J.-B.M. performed the analysis; A.W., J.M., J.v.V., D.v.D., J.B., F.T. and N.T. contributed data; A.V.N., K.S., J.-B.M., A.W., J.M., J.v.V. and F.M. read and commented on the paper.

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