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Monitoring Ship Emissions Using Sentinel-5P and AIS Data

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ABSTRACT

Ship pollution has become a growing concern due to its environmental impact. Various policies have been introduced to tackle this issue, such as the International Convention for the Prevention of Pollution from Ships (MARPOL) implemented by the International Maritime Organization (IMO) in 1973. The MARPOL limits the number of pollutants that ships can release into the environment and requires ships to reduce their sulfur emissions. For instance, the IMO introduced a sulfur cap of 0.5% in marine fuel that came into effect on January 1, 2020. The European Commission estimates an eventual reduction in sulfur air pollutants by 80% in the Mediterranean. The effectiveness of these policies is analyzed using data from Sentinel-5P and Automatic Identification System (AIS) messages. Data analysis shows a correlation between ship routes and pollution levels over the oceans using data from the past six years. Five-year averages and time lapses of yearly averages from Sentinel-5P are analyzed to further understand temporal correlations between pollution levels and ship tracks. Furthermore, the impact of coastal areas and cities on pollution levels is investigated by studying larger areas. It is found that the assessment of ship pollution using Sentinel-5P has some limitations: while nitrogen dioxide can be monitored effectively offshore, sulfur emissions from ships cannot be detected offshore or distinguished from coastal emissions using Sentinel-5P. This presents a significant challenge in monitoring and enforcing regulations aimed at reducing sulfur emissions from ships, especially in areas such as the Mediterranean Sea, which are highly influenced by coastal regions.

Keywords: Ship Emissions, Sentinel-5P, MARPOL, Sulphur, Nitrogen Dioxide

1. INTRODUCTION

Ship pollution has become a pressing environmental concern due to its detrimental impact on ecosystems and human health. The emissions from ships, including sulfur dioxide (SO_2), nitrogen oxides (NOx), particulate matter (PM), and greenhouse gases (GHGs), contribute significantly to air pollution, climate change, and ecological degradation.[1,2] In response to this issue, international efforts have been made to establish policies and regulations to mitigate ship pollution and promote sustainable maritime practices.

The International Convention for the Prevention of Pollution from Ships (MARPOL) is a crucial international treaty developed by the International Maritime Organization (IMO) to address various forms of marine pollution caused by ships. MARPOL was adopted in 1973 and has been periodically updated to incorporate new regulations and requirements.

One significant aspect of MARPOL is the regulation of sulfur emissions from ships. Sulfur dioxide (SO_2) emissions contribute to air pollution and adversely affect human health and the environment. To mitigate this impact, MARPOL Annex VI specifically targets the reduction of sulfur emissions from ships.

In October 2008, the IMO adopted amendments to MARPOL Annex VI[3] to introduce stricter sulfur emission standards. These amendments mandated the implementation of a sulfur cap on marine fuel used by ships. The sulfur cap limits marine fuel's maximum allowable sulfur content to 0.5% by mass. This regulation represents a significant reduction compared to the previous limit of 3.5% and aims to reduce sulfur emissions from ships substantially.

Implementing the sulfur cap was a crucial milestone in reducing air pollution from the shipping industry. It

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came into effect on January 1, 2020, and applies to all ships operating globally, regardless of their flag state. The regulation requires ships to either use low-sulfur marine fuels that comply with the sulfur cap or adopt alternative methods, such as exhaust gas cleaning systems (scrubbers), which can reduce the sulfur content of emissions.

The introduction of the sulfur cap on marine fuel has had a significant impact on the shipping industry and related sectors.[4] It has spurred changes in fuel procurement, fuel production, and technological advancements to comply with the new regulations. The transition to low-sulfur fuels or the installation of scrubbers has been a major undertaking for ship operators, requiring careful planning and investments.

The sulfur cap has played a vital role in reducing sulfur emissions from ships, improving air quality and environmental conditions. It has contributed to reducing sulfur-related health issues, such as respiratory problems, and has helped mitigate the adverse effects of acid rain and eutrophication in coastal areas.[5]

Compliance with the sulfur cap is monitored and enforced by port state control authorities, which conduct inspections and verify that ships are using compliant fuels or have appropriate scrubber systems installed. Non-compliance can result in penalties, detentions, or other enforcement measures. This method, while important, has limitations in terms of coverage and scope. It relies on periodic inspections and cannot monitor every ship consistently, leaving room for potential non-compliance or the under-reporting of emissions.

In recent years, there has been a growing recognition of the potential of satellite data for monitoring ship pollution.[6–10] Satellites provide a unique vantage point from which every ship can be observed, regardless of its location or whether it is within the jurisdiction of port state authorities. This capability offers a more comprehensive and continuous monitoring approach that can complement and enhance the existing inspection-based methods.

One key satellite data source for pollution assessment is the Sentinel-5P satellite. Part of the European Union's Copernicus program, Sentinel-5P is designed specifically for monitoring atmospheric composition and key pollutants, including NO_2 and SO_2. By analyzing data from Sentinel-5P, insights into the spatial distribution and concentration of these pollutants are gained, providing a valuable tool for evaluating the effectiveness of ship pollution policies.

This paper delves into utilizing satellite data to comprehensively assess ship pollution, emphasizing regions such as the Bay of Bengal, the Mediterranean, and the Gulf of Aden.

1. **Introduction to Data Sources**: This section introduces the data sources employed in the study, particularly the Sentinel-5P satellite and the Automatic Identification System (AIS) data set.
2. **Methodology**: The methodology utilized for the research is elaborated in this section.
3. **Use of Satellite Data for Ship Pollution Assessment**:
    - **Correlation Analysis**: Investigate the correlation between satellite-detected Nitrogen Dioxide (NO_2) and Sulphur Dioxide (SO_2) concentrations and the AIS messages to understand ship movements and activities.
    - **Ship Type Analysis**: Examine the distribution of different ship types across the studied regions based on the volume of AIS messages, understanding the primary contributors to pollution.
    - **Implications of Distinguishing Sulphur Emissions**: This subsection discusses the challenges and significance of distinguishing sulfur emissions from ships in offshore areas from those in coastal regions.
4. **Discussion**:
    - **Effectiveness of Ship Pollution Policies**: A critical examination of current policies, their successes, and areas of improvement.
    - **Future Research and Development**: Explore potential areas to bolster monitoring capabilities.
    - **Impact of Coastal Areas and Cities on Ship Pollution**: Delve into the complexities of ship pollution considering the influences of coastal emissions and proximity to urban areas. This section emphasizes the challenges of distinguishing ship-derived pollution from other sources in regions with high economic and tourism activities.

- **Analysis of Larger Geographic Regions**: Understand the intricacies associated with coastal emissions and urban centers in the broader context.

5. **Conclusion**: The paper concludes by summarizing the pivotal findings and insights acquired throughout the study.

This structured approach aids in offering a holistic view of the topic, ensuring the reader understands the challenges, current methodologies, and future potential in ship pollution assessment using satellite data.

2. DATA

This feasibility assessment was completed using existing data sources. For pollution, data from the Copernicus program was used. An existing composite of AIS message sources was used for vessel data that incorporates data from AAC Clyde Space satellites. The atmospheric trace gases analyzed in this study are limited to Nitrogen dioxide and sulfur dioxide:

1. Nitrogen oxides (NOx), which consist of nitrogen dioxide (NO_2) and nitrogen oxide (NO), are crucial trace gases found in the Earth's atmosphere. These gases are produced through natural processes such as microbiological processes in soils, wildfires, and lightning, as well as human activities like fossil fuel combustion and biomass burning. During the day, a photo-chemical cycle involving ozone (O_3) rapidly inter-converts NO and NO_2, so the concentration of NO_2F serves as a reliable indicator of the overall nitrogen oxide levels in the atmosphere.[11]

2. Both natural and anthropogenic processes contribute to the presence of sulfur dioxide (SO_2) in the Earth's atmosphere. SO_2 impacts both local and global chemistry and can result in short-term pollution and long-term effects on climate. Anthropogenic sources account for most SO_2 emissions, with only around 30% originating from natural sources. The release of SO_2 has detrimental effects on human health and air quality. Additionally, SO_2 plays a role in climate change by contributing to radiative forcing and the formation of sulfate aerosols. The emission of SO_2 from volcanic activity can also threaten aviation safety alongside volcanic ash.

2.1 Sentinel-5P satellite and its capabilities for monitoring atmospheric composition and key pollutants

Sentinel-5P is a satellite part of the European Union's Copernicus Earth Observation program. It was launched in 2017 to monitor the Earth's atmosphere to provide accurate and timely data on air quality and climate change. The satellite carries the Tropospheric Monitoring Instrument (TROPOMI), which can measure various atmospheric pollutants, including nitrogen dioxide, ozone, sulfur dioxide, carbon monoxide, and methane. The instrument has a spatial resolution of 7×3.5 km^2 over most spectral bands. It can produce daily global measurements, providing scientists and policymakers with valuable information to monitor and address environmental issues related to air quality and climate change.

2.2 AIS Data set

AIS is a tracking technology used in the maritime industry to monitor and exchange navigational and other vessel-related information of vessels. AIS data is collected from AIS transponders installed on board vessels and transmitted via VHF radio signals. The data includes the vessel's identity, position, course, speed, and other information. AIS data is widely used for vessel traffic management, search and rescue operations, and marine environmental monitoring. The data is also used for research purposes, such as analyzing shipping patterns, estimating emissions, and assessing the impacts of shipping on marine ecosystems.
The WBG's (World Bank Group) International Monetary Funds' (IMF) World Seaborne Trade Monitoring System provided the data used in this study (Cerdeiro et al., 2020). The World Bank's Energy Sector Management Assistance Program and PROBLUE (Blue Economy Program) programs supported the data analysis. The data set includes six density layers, with vessel types grouped to meet the requirements of the WBG Offshore Wind Development Program, including:

1. commercial vessels,
2. fishing vessels,
3. oil and gas platforms, rigs, and floating production storage and offloading (FPSO),
4. passenger vessels,
5. leisure vessels, and
6. global vessel density layers encompassing all vessel categories.

The raster layers were generated by IMF's analysis of hourly AIS positions gathered between January 2015 and February 2021. Each grid cell has dimensions of 0.005° by 0.005°, corresponding to an approximate grid size of 500 m by 500 m at the Equator. The density in each cell represents the total number of AIS positions transmitted by stationary and moving vessels within that area, providing an overall measure of the intensity of shipping activity.[12] A map of the AIS messages distribution is shown in Fig. 1 revealing shipping lanes and the most traveled areas in Europe, the Mediterranean, the Arabian Sea, and the Bay of Bengal.

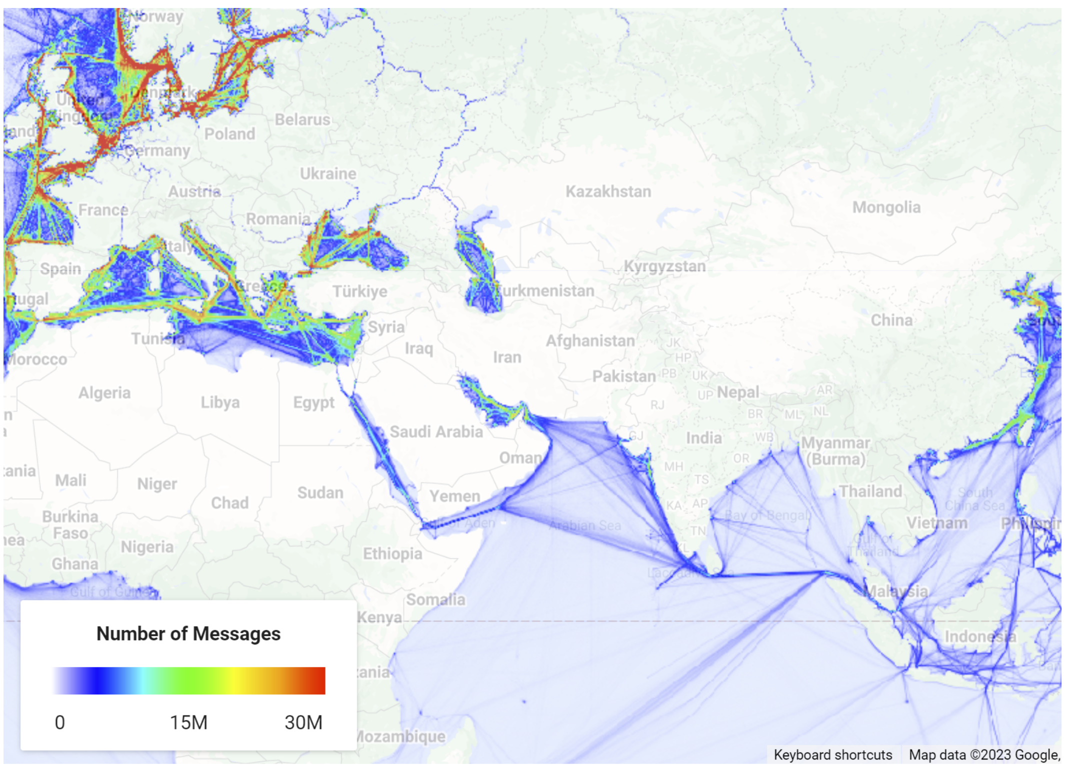


Figure 1: Total AIS messages distribution around Europe, the Mediterranean, Arabian Sea, and the Bay of Bengal.

3. METHODOLOGY

To find a correlation between the two data sets, we first chose three regions of interest (ROI) that showed a high intensity of traffic and were away from land to exclude influences from ports and larger cities. The chosen areas of interest include the Bay of Bengal (Fig. 2a, with coverage of 160492 km^2), an area of the Mediterranean North of the coast of Algeria and Egypt (Fig. 2b, with coverage of 77282 km^2), and the Gulf of Aden (Fig. 2c, coverage of 118217 km^2). Using Google Earth Engine (GEE), four years' worth of nitrogen dioxide (NO_2) and

(a) Bay of Bengal (b) Mediterranean (c) Gulf of Aden

Figure 2: Three ROIs which have been chosen according to their proximity to land and major cities.

sulfur dioxide (SO_2) data were collected from the Sentinel-5P satellite for the period between July 2018 and December 2022 (Sec. 2.1). For each ROI, we computed the time-averaged concentration for both NO_2 and SO_2 over each pixel.
In parallel, ship density layers were extracted from the AIS vessel data described in Sec. 2.2. This provided us with five different ship categories to study: commercial ships, fishing vessels, oil and gas platforms (along with rigs and FPSO vessels), passenger ships, and leisure vessels. Each category's ship density was given in terms of the total number of AIS messages received per pixel.
The data processing yielded three key collections per ROI, as follows:

1. Mean NO_2 Concentration [mol/m^2] (1km spatial resolution)
2. Mean SO_2 Concentration [mol/m^2] (1km spatial resolution)
3. Global Ship Density [Total Number of AIS messages/pixel] (1km spatial resolution)

The collections for each ROI were normalized to compare the correlation between NO_2 concentrations and ship density. The normalization was carried out by applying the following formula to each collection:

$$A_{norm} = \frac{A - A_{min}}{A_{max} - A_{min}} \tag{1}$$

where A_{norm} represents the normalized collection, A is the original collection, and A_{min} and A_{max} are the minimum and maximum values of the respective original collections. This normalization ensured that each collection's values ranged from 0 to 1, thereby allowing for effective comparison.
Finally, the correlation coefficient (r) between the NO_2 concentration and ship density was calculated for each ROI. The following formula defines the correlation coefficient:

$$r = \frac{\sum_{i=1}^{n}(NI_i - \overline{NI})(AIS_i - \overline{AIS})}{\sqrt{\sum_{i=1}^{n}(NI_i - \overline{NI})^2(AIS_i - \overline{AIS})^2}} \tag{2}$$

where NI_i and AIS_i are the individual values of the normalized NO_2 concentration and ship density collections, respectively, and $\overline{NI}$ and $\overline{AIS}$ are the means of those collections. This coefficient varies between -1 and 1, with values close to -1 indicating an inverse correlation, values near 0 indicating no correlation, and values close to 1 indicating a high correlation.

4. UTILIZING SATELLITE DATA FOR SHIP POLLUTION ASSESSMENT

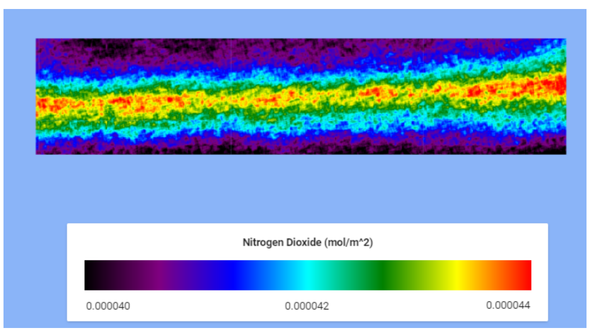
4.1 Correlation Analysis

The correlation analysis was performed for the three regions of interest. Temporally averaged NI_2 and SO_2 were spatially compared to the AIS message density, and the correlation coefficient was calculated. The results are presented for the Bay of Bengal in Fig. 3, the Mediterranean in Fig. 4, and finally, the Gulf of Aden in Fig. 5.

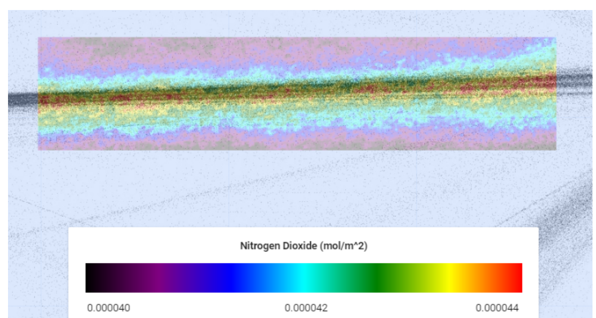
Each of these figures is organized in four plots, showing NO_2 and SO_2 density, a plot overlaying the location of AIS messages with the NO_2 and a 2D histogram, displaying the correlation between NO_2 density and AIS messages.

4.2 Bay of Bengal

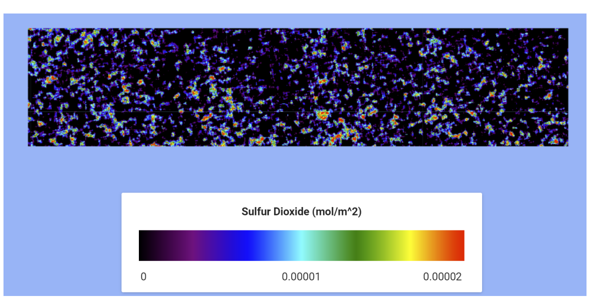
The analysis of NO_2 over the Bay of Bengal reveals a straight concentration line, with peak intensities located centrally. These peak intensities align perfectly with the regions of the highest AIS message densities. Notably, no discernible pattern was observed in the SO_2 distributions. The correlation coefficient between nitrogen dioxide concentrations and AIS message densities was 0.79. The Mediterranean region displayed a line of NO_2 intensities, with two distinct spots of increased concentration. The main line of intensities mirrors the primary shipping lane identified through AIS message densities. Additionally, some minor lanes are discernible. The intersections of shipping routes coincide with the highest NO_2 densities. Despite the lack of a clear pattern in SO_2 densities, the region exhibited the highest sulfur measurements in the study. The correlation coefficient between NO_2 and AIS message densities here was 0.46. In the Gulf of Aden, NO_2 concentrations formed a straight line with the most intense regions centrally located. However, the maximum concentration was skewed towards the city of Aden. This pattern in NO_2 concentrations mirrored the two primary shipping lanes highlighted by the AIS message densities. Again, no visible pattern was found in SO_2 densities. The correlation coefficient between NO_2 and AIS message densities in this region was 0.38. The correlation analysis of satellite-derived NO_2 concentrations and AIS message densities across the three studied regions suggests a noticeable relationship between shipping activities and NO_2 emissions. The Bay of Bengal displayed the strongest correlation, followed by the Mediterranean and the Gulf of Aden. SO_2 distributions, however, remained inconsistent across the regions, emphasizing the complexities in associating them directly with shipping activities based solely on the current data.



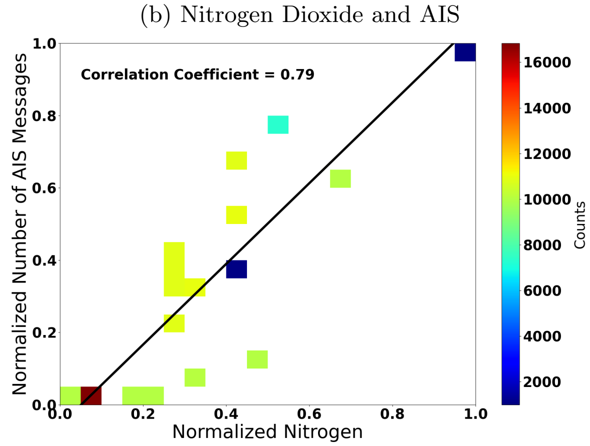
(a) Nitrogen Dioxide



(b) Nitrogen Dioxide and AIS

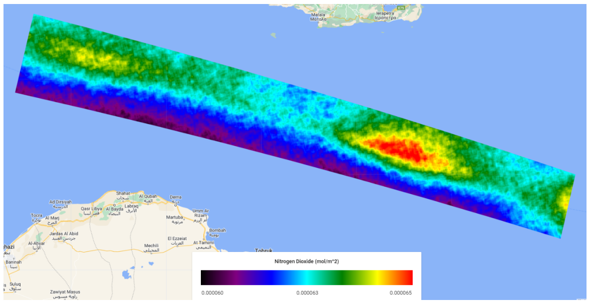


(c) Sulphur Dioxide

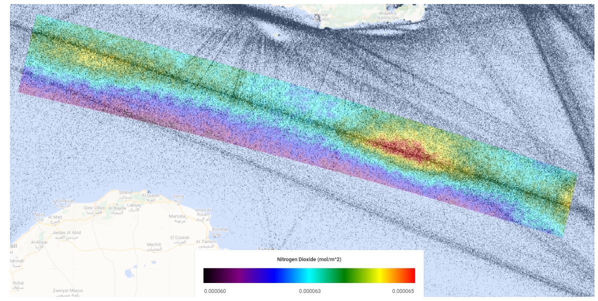


(d) Correlation between Nitrogen Dioxide and AIS Messages

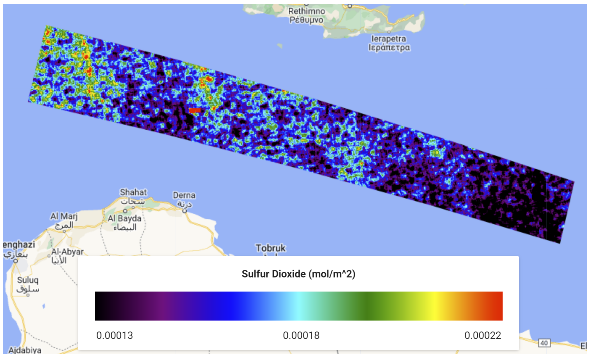
Figure 3: Correlation analysis for the Bay of Bengal.



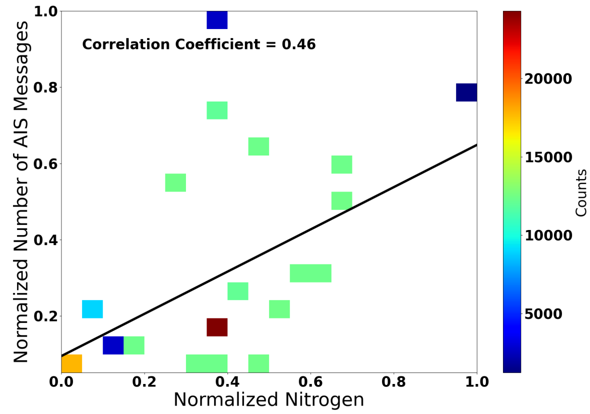
(a) Nitrogen Dioxide



(b) Nitrogen Dioxide and AIS



(c) Sulphur Dioxide

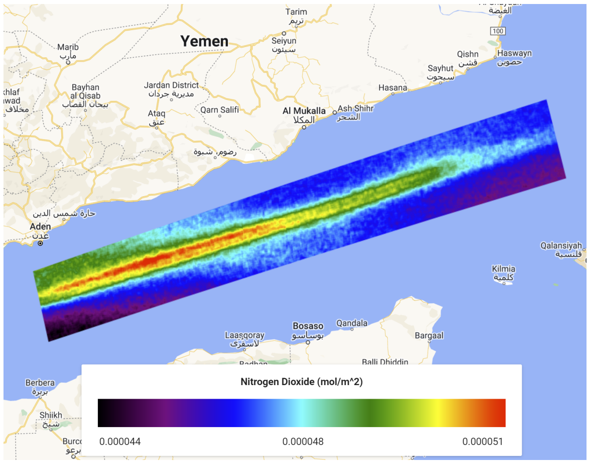


(d) Correlation between Nitrogen Dioxide and AIS Messages

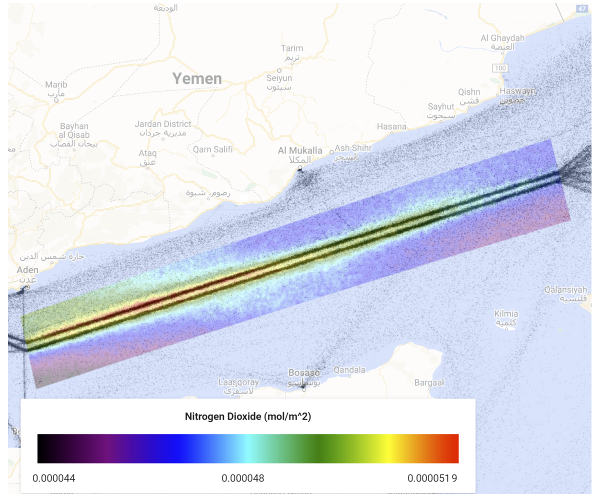
Figure 4: Correlation analysis for the Mediterranean.

4.3 Time Series Analysis

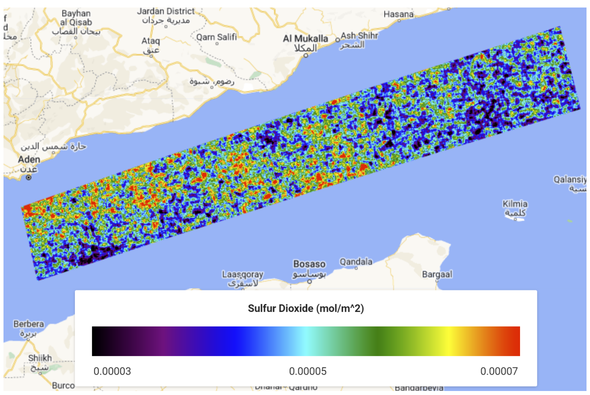
The time series analysis focused on the average monthly NO_2 concentrations over each ROI. Trend lines based on the averaged data reveal interesting patterns related to changes in economic activity and environmental factors (see Fig. 6). In the Gulf of Aden and the Bay of Bengal, there is a noticeable increase in NO_2 concentrations over time. This upward trend is likely a result of various factors, including increased economic activity after the pandemic,[13] heightened traffic congestion, and the escalating use of fossil fuels for power generation. These findings imply that air quality in these regions could deteriorate, with NO_2 levels trending upward. Contrarily, the trend line for the Mediterranean region remains relatively constant, indicating stable NO_2 levels over time. Seasonal changes in the Mediterranean are more prominent than in the other ROIs, as NO_2 concentrations tend to increase in summer and decrease in winter. We suspect that the other ROIs (the Gulf of Aden and the Bay of Bengal) do not show the same pronounced seasonal changes as they are situated in regions of tropical climates closer to the Equator. In contrast, the Mediterranean is more affected by temperate and continental climates.[14] The COVID-19 pandemic also had a noticeable effect on NO_2 levels, as evidenced by a temporary dip during the year 2020 in concentrations due to reduced economic activity and traffic congestion during the pandemic. This effect was most pronounced in the Mediterranean region, potentially due to its status as a major tourism hotspot and the presence of major cities around the Mediterranean Sea. In the Gulf of Aden and the Bay of Bengal, the impact of the pandemic was less severe, reflecting the lesser extent of tourism and proximity to major cities and, thus, the reduced influence of the pandemic on local economic activity. The temporary improvements in air quality during the pandemic offer a window into the potential benefits of reduced fossil fuel reliance and optimized transportation systems. However, as the world recovers from the pandemic and economic activity resumes, it is expected that NO_2 emissions will also rebound unless significant changes are made. The time series videos for two locations (the Mediterranean and the Bay of Aden) can be accessed from the links in Fig. 7 and Fig. 8. Both videos show the monthly mean over daily satellite measurements of NO_2. Whereas the



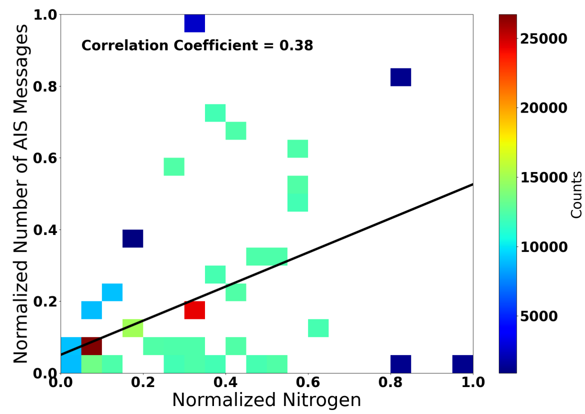
(a) Nitrogen Dioxide



(b) Nitrogen Dioxide and AIS



(c) Sulphur Dioxide



(d) Correlation between Nitrogen Dioxide and AIS Messages

Figure 5: Correlation analysis for the Gulf of Aden.

ship track is visible throughout most of the months in the Gulf of Aden, ship tracks are almost undetectable in the Mediterranean. Here, influences of high ship activity and the proximity of large cities disguise the presence of this one shipping lane. Depending on wind directions and intensities, large amounts of NO_2 are mixed and distributed over the region.

5. DISCUSSION

5.1 Distinguishing emissions from ships in offshore areas versus coastal regions

The spatial resolution of satellite data offers opportunities and challenges for monitoring and enforcing regulations on emissions in general. On the one hand, the broad coverage allows us to monitor emissions over vast areas that would otherwise be impossible to monitor with on-the-ground techniques. On the other hand, distinguishing between ship emissions and other sources can be a significant challenge, particularly in coastal regions. Our results from both the Bay of Bengal and Gulf of Aden regions demonstrate that monitoring NO_2 emissions in offshore areas is more straightforward. The dominance of ships in these regions provides an adequate emissions signal. As these regions are further away from significant land-based emissions sources, it is reasonable to attribute a significant portion of the observed NO_2 emissions to maritime activities, whereas SO_2 cannot be detected. However, coastal regions, such as the Mediterranean, are more complex. Here, the proximity to major urban areas

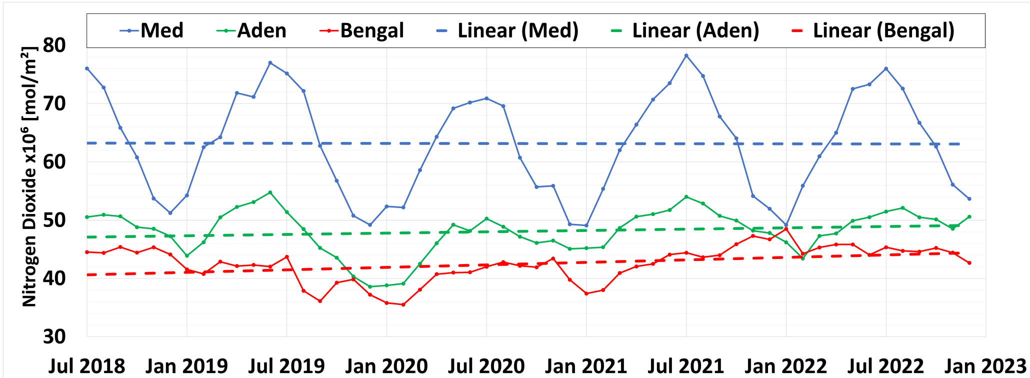


Figure 6: Time series of the monthly average NO_2 concentrations for the Gulf of Aden (green), Bay of Bengal (red), and the Mediterranean (blue). Linear trend lines are dotted in the same colors as the matching ROI time series.

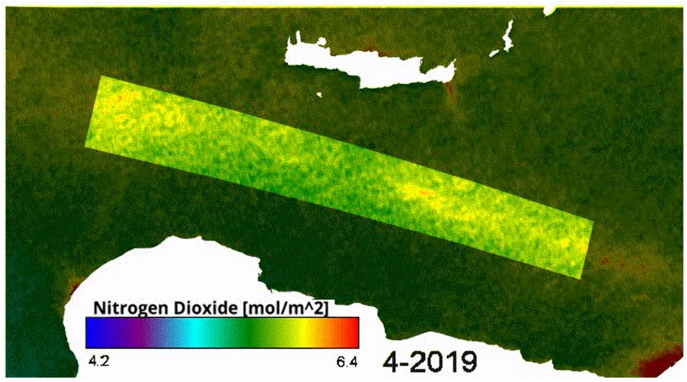


Figure 7: Video showing the monthly averaged NO_2 concentration over the Mediterranean Sea between January 2018 and December 2022. "Mediterranean_Timeseries.mpeg": http://dx.doi.org/10.1117/12.2678424.1

and industrial complexes, as well as more complex distributions of shipping lanes, can significantly contribute to the observed NO_2 concentrations. Although we observed many AIS messages from commercial ships in the Mediterranean, the high background NO_2 levels from terrestrial sources make it difficult to attribute observed emissions to only shipping unequivocally. These findings have important implications for the enforcement of regulations on emissions. In offshore areas where the signal from ships is clear, satellite data could serve as a reliable monitoring tool. Conversely, additional data sources or more complex modeling approaches may be required in coastal regions to differentiate shipping emissions from other sources. It is also worth noting that our AIS-based analysis does not account for the type of fuel used by the ships, which can substantially affect SO_2 emissions. Future studies could integrate additional data on ship fuel types to provide a more detailed assessment of the contribution of different types of vessels to NO_2 and SO_2 emissions. Moreover, it is crucial to remember that enforcing regulations is about monitoring and taking action. While satellite data can play a significant role in identifying potential violators, ground-based inspections and sanctions are essential for effective enforcement. Satellite data can guide these activities but cannot replace them. To summarize, while satellite data provide an invaluable tool for monitoring emissions, we need to be aware of its limitations and combine it with other data and methods to get a comprehensive view of nitrogen and sulphur emissions in offshore and coastal regions.

5.2 Effectiveness of ship pollution policies

Our findings reveal the complex nature of ship pollution and highlight the need for effective policy measures to curb emissions. As indicated by the increasing NO_2 concentrations in the Gulf of Aden and the Bay of Bengal, ship pollution remains a critical issue, despite ongoing efforts to mitigate the impact of maritime activities

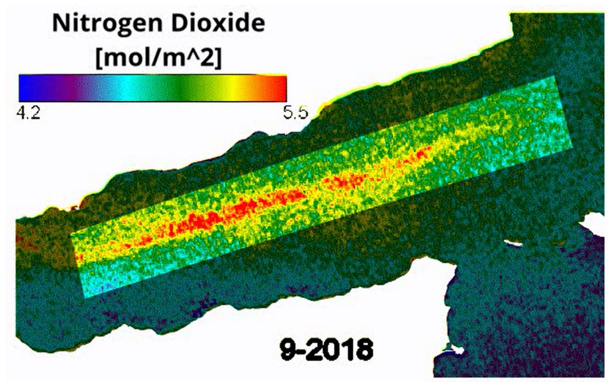


Figure 8: Video showing the monthly averaged NO_2 concentration over the Gulf of Aden between January 2018 and December 2022. "Bay_of_Aden_Timeseries.mpeg": http://dx.doi.org/10.1117/12.2678424.2

on air quality. The International Maritime Organization's (IMO) regulations, particularly those stipulated in the MARPOL Annex VI, have laid out strict standards for reducing harmful emissions from ships. However, enforcing these regulations poses a significant challenge, especially in international waters. Compliance with these regulations largely depends on the ships' flag states, which, in practice, can vary widely in their monitoring and enforcement capabilities. Satellite data can play a crucial role in monitoring the global compliance of these regulations. However, our analysis also highlights the need for more granular data, such as fuel types and operational modes of ships, for a more accurate assessment of the effectiveness of these policies. Moreover, our findings underscore the varying regional impacts of ship pollution, suggesting that the effectiveness of pollution policies may differ across regions. For instance, in the Mediterranean, which has more stringent local regulations and higher terrestrial background emissions, the trend of NO_2 levels remained relatively constant, although the highest in this study, indicating that regional measures might have effectively countered the potential increase due to global trends in shipping activities. Interestingly, our analysis also showed a dip in NO_2 concentrations during the COVID-19 pandemic, when many countries enforced lockdowns that limited economic activity and reduced ship traffic. This observation suggests that even temporary changes in shipping activities can significantly affect air quality, providing valuable insights into what can be achieved with effective pollution policies. However, the challenge lies in maintaining such improvements in the long term without resorting to drastic measures like halting economic activities. Thus, developing sustainable shipping practices, such as using cleaner fuels and energy-efficient technologies, is paramount. In conclusion, while current policies like those by the IMO provide a foundation for reducing ship pollution, our results highlight the need for enhanced monitoring capabilities, localized policy measures, and sustainable shipping practices to effectively curb ship pollution across different regions.

5.3 The Impact of Coastal Areas and Cities on Ship Pollution

The results of our analysis draw attention to the significant role that coastal areas and nearby cities play in shaping ship pollution patterns. Our study revealed distinct regional variations in the presence of ship-related NO_2 emissions, with marked influences from coastal areas and urban centers. Coastal areas, in particular, play a critical role in modulating ship pollution. Our results showed that these areas often exhibit higher pollutant concentrations due to the convergence of emissions from marine and terrestrial sources. Ships release considerable pollutants, especially those in ports or anchored off the coast. Concurrently, coastal cities contribute significantly to air pollution through various terrestrial sources such as vehicles, power plants, and industrial facilities. Combining these sources can create air pollution hot spots in coastal regions, which may have profound implications for air quality and public health. In the case of the Mediterranean region, detecting ship tracks was particularly challenging due to the overlapping influence of high ship activity and the proximity of large cities. The dispersion and mixing of NO_2 emissions from ships with pollutants from urban centers diluted the distinct signal that ship emissions would typically provide. Such interaction between ship emissions and terrestrial pollution sources underscores the need for integrated management strategies that address marine and terrestrial emissions.

It also demonstrates the potential value of satellite monitoring for its ability to provide comprehensive and spatially detailed information about pollution sources and their impacts across diverse environments. Cities also play a crucial role in shaping ship pollution patterns. Our study showed that cities can contribute significantly to regional air pollution, with their influence extending well beyond their geographic boundaries. In densely populated and industrialized regions, terrestrial emissions from cities can mix with ship emissions, complicating the attribution of observed pollution levels to specific sources. Moreover, the study found that the impact of the COVID-19 pandemic was more pronounced in regions like the Mediterranean, where the reduction in economic activities and travel significantly affected air quality. This observation underscores the potential vulnerability of cities and their surrounding regions to changes in economic activity and transportation patterns. Our findings emphasize the interconnections of marine and terrestrial pollution sources and the need for integrated, region-specific strategies for managing air quality.

6. CONCLUSION/SUMMARY

Using satellite data to assess ship pollution has provided a unique and invaluable perspective. Our study has highlighted the prominent role of shipping activities in contributing to air pollution, especially in high-traffic maritime regions such as the Gulf of Aden, the Bay of Bengal, and the Mediterranean. Our correlation analysis found a strong association between the distribution of ship traffic (as indicated by AIS messages) and the concentrations of nitrogen dioxide. In contrast, sulfur dioxide could not be linked to shipping activities. This result underscores the significant contribution of ships to atmospheric pollution and the potential for utilizing AIS data as a supplementary tool for monitoring and enforcing pollution regulations. The time series analysis has painted a mixed picture, with areas like the Gulf of Aden and the Bay of Bengal showing an upward trend in NO_2 levels. At the same time, the Mediterranean remained relatively stable, with pronounced seasonal changes. Through our analysis of more significant geographic regions, we identified the complexities of ship pollution in coastal emissions and urban centers. This highlights the need for comprehensive, region-specific strategies in managing maritime emissions that consider the broader context of terrestrial pollution sources and the potential for cross-boundary pollutant transport. The limitations of satellite data, particularly the distinction between the sources of NO_2 emissions in offshore areas and coastal regions, were also acknowledged. Nevertheless, satellite data has proven to be an indispensable tool in monitoring and understanding ship pollution, providing global coverage and the ability to capture regional trends and variations. Our study underscores the pressing need for more robust, more effective pollution control measures in the shipping industry, specifically focusing on high-traffic regions. The findings also reinforce the value of a multi-pronged approach, encompassing enhanced regulatory efforts, adopting cleaner technologies and fuels, and ongoing monitoring and research efforts. In conclusion, our work has shed light on the feasibility of identifying the contributions of maritime activities to global pollution levels and the necessity of innovative strategies and cross-boundary cooperation to mitigate their environmental impact. We hope this research will guide policy-making, stimulate further research in this critical area, and lead to a more sustainable future for global shipping.

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