TIME-SERIES ANALYSIS OF SATELLITE-BASED TRACE GASES CONCENTRATIONS IN PORT AREAS IN THE PHILIPPINES USING SENTINEL-5P

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KEY WORDS: Air Quality, Ports, Remote Sensing, Time Series Analysis

ABSTRACT:

This study examined the temporal variations of Nitrogen Dioxide (NO_2) and Sulfur Dioxide (SO_2) concentrations retrieved from Sentinel-5P TROPOMI in six port areas in the Philippines, representing different climate types. The results demonstrate that the COVID-19 lockdowns led to a significant decrease in NO_2 levels, while SO_2 concentrations varied due to factors such as volcanic activity. Seasonal analysis of NO_2 and SO_2 retrievals, considering the four climate types in the Philippines, revealed that the wet season values for both pollutants were higher than the dry season values for most ports. This disparity contradicted the general trend of higher air pollutant levels during the dry season and lower levels during the wet season. The authors attributed this to the nature of port activities during inclement weather, where ships are more likely to be docked with continuously operating engines, leading to continuous emissions within the port buffer zones. Temporal analysis and time series decomposition analysis revealed patterns and trends, identifying the months of minimum and maximum pollutant concentrations and the overall trend throughout the study period.

1. INTRODUCTION

1.1 Background

Air pollution is one of the main environmental challenges faced by the Philippines, wherein urban areas continue to grapple with increased air pollutant levels in areas densely populated or characterized by heavy traffic (Cariaso, 2022). Up to 25% of the Filipino population faces annual average particulate matter concentrations that exceed WHO guidelines by at least five times, signifying that virtually all Filipinos are exposed to polluted air.

Port and coastal areas often serve as hotspots for air pollutants. It is estimated that the shipping industry contributes approximately 940 million tons of carbon dioxide emissions annually, constituting 2.5% of the total global carbon dioxide emissions (UK Research and Innovation, 2021). Given the alarming pollutant concentrations in the country, there's a pressing need for efficient air quality monitoring systems. The ability to fully monitor air quality will allow us to gain adequate information to inform urgent mitigation measures of the harmful effects of poor air quality on human health and the environment.

This study aims to utilize Sentinel-5P TROPOMI data in assessing the temporal trends and variations in Nitrogen Dioxide (NO_2) and Sulfur Dioxide (SO_2) concentrations over select major port areas in the Philippines. Moreover, this study aims to employ statistical summary methods and time series analysis to assess seasonality in air pollutant concentrations.

This study can be used as a source of information for better environmental management in ports in the Philippines. Addressing air quality issues from industrial and transportation sources and promoting accessible monitoring tools are essential to achieving the targets set out in the Sustainable Development Goals on Good Health and Well-being as well as on Climate Action, as many of the air pollutants emitted by ports contribute to emissions that harm public health and drive climate change.

2. MATERIALS AND METHODS

2.1 Study Areas and Data Gathering

Seasonal and climatic patterns are major factors influencing air pollutant concentrations in the atmosphere (Balogun et al., 2015). Thus, the researchers selected study areas representative of each climate type. The country's climate can be classified into two major seasons (dry and wet) and four distinct climate types based on temperature, rainfall, and its distribution (PAGASA, 2014).

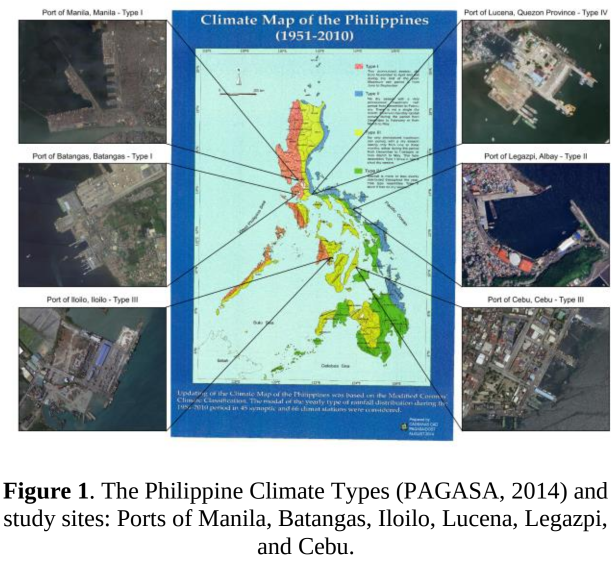

Figure 1. The Philippine Climate Types (PAGASA, 2014) and study sites: Ports of Manila, Batangas, Iloilo, Lucena, Legazpi, and Cebu.

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The Ports of Manila and Batangas, Port of Legazpi, Ports of Iloilo and Cebu, and Port of Lucena represent climate types I, II, III, and IV respectively. Figure 1 shows the Philippine climate types, their characteristics, and the study sites.

Data of nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) were accessed from the Sentinel-5P TROPOMI instrument via the Google Earth Engine platform covering the time period from July 2018 to March 2023 for NO_2 and December 2018 to March 2023 for SO_2.

2.2 Data Processing

Mean concentrations for both NO_2 and SO_2 were calculated for the six port study sites annually from 2019-2022 and for each season (dry and wet) as per PAGASA's Philippine Climate Types. Temporal profiles of NO_2 and SO_2 concentrations were generated on a monthly basis from 2018 to 2023. Moreover, temporal box plots were utilized to analyze the temporal trends of various pollutant parameters. These plots provide a comprehensive summary of the dataset's distribution, including the minimum and maximum values, upper and lower quartiles, and the median.

Time series decomposition was performed with the X-12-ARIMA model in R software, separating the data into seasonal, trend, and irregular components. This allowed for a clearer understanding of underlying patterns and trends (UK Office for National Statistics, 2007; Findley et al., 1998). Since the study focused on understanding NO_2 and SO_2 vertical column densities, no parameters were utilized for forecasting trends (Brownlee, 2017).

3. RESULTS AND DISCUSSION

3.1 Temporal Analysis of Air Quality in Port Areas

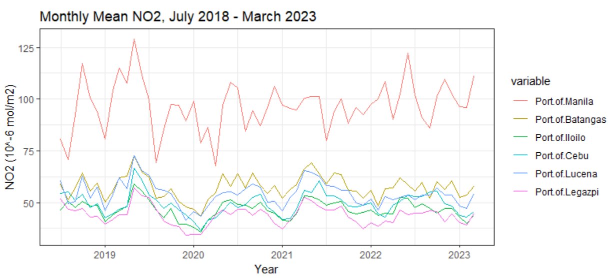

Figure 2. Monthly mean NO_2 concentrations in the study sites from 2018 - 2023.

The analysis of NO_2 mean concentrations in the port areas, shown in Figure 2, showed a significant decline in values from 2019 to 2020. In 2021**,** there was a rebound in NO_2 concentrations, particularly in the Port of Manila.

From the values presented in Table 2, percent change in the annual mean NO_2 concentrations in the study sites within their respective 10 KM buffer zone were generated. There was a significant decline in the values of NO_2 emissions in all of the study sites from 2019 to 2020. Quantitatively, this decline is represented by the -6.30%, -7.21%, -2.21%, -3.73%, -7.93%, -2.29% percent change in the annual mean NO_2 concentrations in the Port of Manila, Port of Lucena, Port of Batangas, Port of Legazpi, Port of Cebu, and Port of Iloilo, respectively.

Port	Annual Mean NO_2 Concentrations within 10KM buffer zone (10^{-6} mol/m^2)			
	2019	2020	2021	2022
Port of Manila	98.93	92.70	95.22	101.19
Port of Lucena	56.37	52.31	56.08	52.64
Port of Batangas	57.55	56.27	59.83	56.98
Port of Legazpi	44.30	42.65	44.78	43.12
Port of Cebu	50.18	46.20	50.43	50.38
Port of Iloilo	46.68	45.61	47.46	47.30

Table 2. Climate types and seasonality of study areas.

An increase in the NO_2 concentrations in the area of Port of Manila was observed, with a 6.28%, the only positive percent change from 2021 to 2022. Overall, from 2019 to 2022, the Port of Manila has the highest percent change of 2.29%, followed by Port of Iloilo (1.32%), Port of Cebu (0.39%), Port of Batangas (-0.99%), Port of Legazpi (-2.66%) and Port of Lucena (-6.62%). It can also be inferred that the less industrialized or urbanized cities recorded lower footprints of NO_2 concentrations from 2019 to 2022, and the events of the COVID-19 lockdowns had significant effects on the temporal trends of NO_2 concentrations.

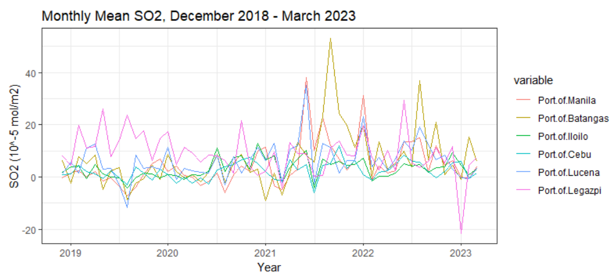

Figure 3. Monthly mean SO_2 concentrations in the study sites from 2018 - 2023.

Moreover, the analysis of SO_2 concentrations, as depicted in Figure 3, revealed a notable increase in values in the Port of Batangas (212.93%) and Port of Manila (772.00%) from 2019 to 2020. The Port of Legazpi also experienced a significant 47.68% increase in SO_2 emissions from 2021 to 2022.

Port	Annual Mean SO_2 Concentrations within 10KM buffer zone (10^{-6} mol/m^2)			
	2019	2020	2021	2022
Port of Manila	0.14	1.20	9.08	8.84
Port of Lucena	3.34	4.35	9.13	9.79
Port of Batangas	0.10	3.12	12.14	10.53
Port of Legazpi	14.49	8.19	6.57	9.70
Port of Cebu	1.20	1.88	3.30	3.14
Port of Iloilo	0.91	4.07	4.67	3.38

Table 3. Climate types and seasonality of study areas.

Shown in Table 3, there was a significant increase in the values of SO_2 emissions in most of the study sites from 2019 to 2020 likely due to the eruption of the nearby Taal Volcano. Quantitatively, this increase is represented by the 772.00%, 30.32%, 212.93%, 55.92%, 347.94% percent change in the annual mean SO_2 concentrations in the Port of Manila, Port of

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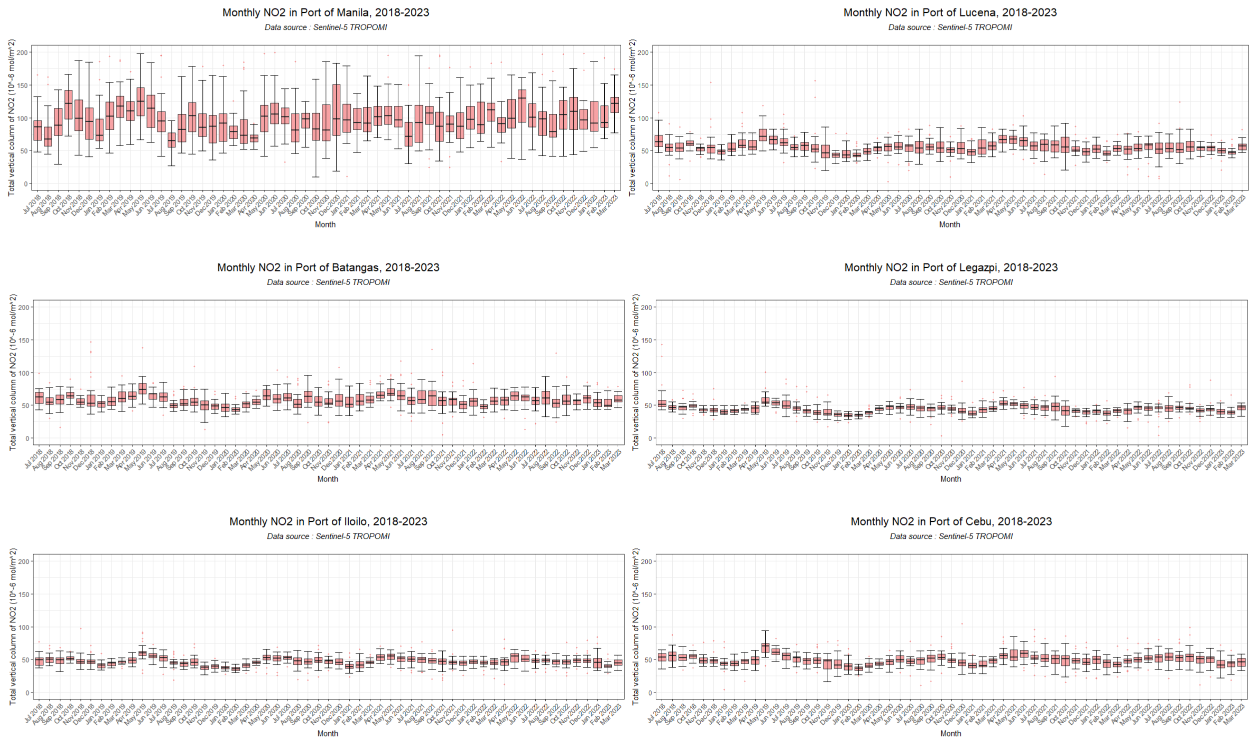

Figure 4. Box plots of monthly NO_2 concentrations in the study areas from 2018 – 2023.

Lucena, Port of Batangas, Port of Cebu, and Port of Iloilo, respectively.

It is evident that the Port of Legazpi drastically increased in terms of SO_2 emissions from 2021 to 2022, with a 47.68% percent change. The Mayon Volcano is within its vicinity; thus, this can be possibly caused by the emission of the volcano in October 2022. Moreover, the less industrialized or urbanized cities recorded lower footprints of SO_2 concentrations from 2019 to 2022, it can also be inferred that the cities nearby recent volcanic eruptions are prone to have higher records of SO_2 emissions than those that are distant to these volcanic activities.

3.1.1 Temporal Box Plots of NO_2 Concentrations in Port Areas: In Figure 4, the box plots display NO_2 concentration variability in various ports from July 2018 to March 2023. Each port was analyzed separately. In the Port of Manila, the highest variability was in June 2022, lowest in April 2020, with a peak in November 2021 and a notable outlier in June 2022.

Port of Batangas had its highest NO_2 variability in August 2022, lowest in February 2020, with a peak in December 2018 and an outlier in August 2022. At the Port of Legazpi, the highest variability was in October 2021, lowest in February 2020, with a peak in July 2018 and an outlier in October 2018.

Moving to the Port of Iloilo, the highest variability occurred in September 2018, August 2020, and June 2022, while the lowest was in March 2019. The peak NO_2 concentration was in November 2018, and a significant outlier was seen in July 2020. Lastly, in the Port of Cebu, the highest variability was noted in October 2021, lowest in December 2018, with a peak in December 2020 and an outlier in October 2022.

3.1.2 Temporal Box Plots of SO_2 Concentrations in Port Areas: Figure 5 displays SO_2 concentration variability in various ports from 2018 to 2023. In the Port of Manila, highest in July and August 2022, lowest in November 2022, peak in January 2022 with an outlier, and minimum in April 2019. For the Port of Lucena, September 2022 had the highest variability, while October 2020 and January 2023 had the lowest. The peak occurred in August 2022, and the minimum in February 2020.

At the Port of Batangas, September 2021 had the highest variability, with the lowest in July 2019, February 2020, October 2020, December 2020, July 2021, and December 2022. The peak was in September 2021 with an outlier, and the minimum in January and December 2019. In the Port of Legazpi, August 2019 had the highest variability, while December 2018 and June 2019 had the lowest. The peak was in June 2022, and the minimum in February 2019, July 2020, March 2021, and May 2022.

In the Port of Iloilo, the highest variability was in May and December 2020, with the lowest in May 2021. The peak was in August 2021 with an outlier, and the minimum in April 2020 and November 2021. Lastly, in the Port of Cebu, August 2019 and July 2022 had the highest variability, while December 2019 had the lowest. The peak was in July 2019, and the minimum in July 2020.

3.2 Seasonal Trends of Air Quality in Port Areas

Studies suggest that air pollutants tend to be lower during wet season in comparison to dry season due to a decrease in the removal of particles through wet processes during the dry season (Emekwuru & Ejohwomu, 2023). During the dry season,

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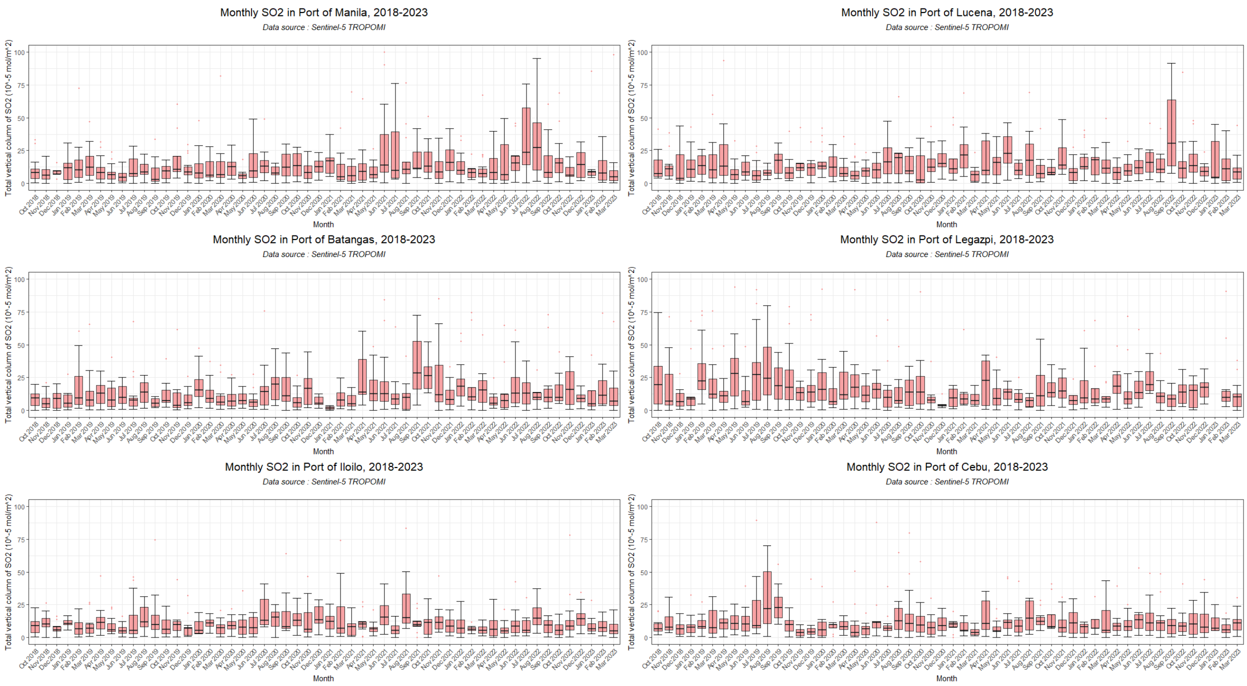

Figure 5. Box plots of monthly SO_2 concentrations in the study areas from 2018 - 2023.

elevated land surface temperature and low precipitation were observed to coincide with higher concentrations of air pollutants such. Conversely, during the wet seasons, a decrease in air pollutant concentrations was observed, which aligns with the washout effect (Canlas et. al., 2022).

Port	Mean NO_2 Concentrations within 10KM buffer zone (10^{-6} mol/m^2)	
	Dry Season	Wet Season
TYPE I CLIMATE (Dry Season: Nov - April, Wet Season May - Oct)		
Port of Manila	93.32	96.48
Port of Batangas	53.10	60.09
TYPE III CLIMATE (Dry Season from Mar - May, Wet Season from June - Feb)		
Port of Cebu	48.96	49.41
Port of Iloilo	48.10	46.34

Table 4. Summary table of annual mean NO_2 concentrations in the study areas.

Port	Mean SO_2 Concentrations within 10KM buffer zone (10^{-6} mol/m^2)	
	Dry Season	Wet Season
TYPE I CLIMATE (Dry Season from Nov - April, Wet Season from May - Oct)		
Port of Manila	3.63	5.55
Port of Batangas	4.46	9.27
TYPE III CLIMATE (Dry Season from Mar - May, Wet Season from June - Feb)		
Port of Cebu	1.37	2.68
Port of Iloilo	1.477	3.78

Table 5. Summary table of annual mean SO_2 concentrations in the study areas.

In contrast, the resulting mean concentrations of NO_2 and SO_2 within the vicinity of ports in areas with Type I and Type III climates (climate types with pronounced dry and wet seasons) suggest the opposite; mean concentrations during the wet season show higher values in comparison to dry season, as shown in Tables 4 and 5.

To test the hypothesis that the air pollutant concentration values during the wet season are greater than the values during the dry season in the port study areas, T-test for two independent-samples at 95% confidence interval was applied to each of the six ports and each of the two trace gasses.

For NO_2, the wet season values demonstrated significantly higher concentrations than dry season values for Port of Manila, $t(1540) = -5.339$, $p = <0.0001$, Port of Batangas, $t(1094) = -51.083$, $p = <0.0001$, and Port of Cebu, $t(1552) = -2.675$, $p = 0.004$. However, mean concentrations of Port of Iloilo during the wet season showed no significant difference than during the dry season, $t(2426) = 39.441$, $p = 1.000$. For SO_2, the T-test for two independent samples at 95% confidence interval showed consistent results. The wet season values proved to be significantly greater than the dry season values for the four ports: Port of Manila, $t(1514) = -18.612$, $p = <0.0001$; Port of Batangas, $t(878) = -17.774$, $p = <0.0001$; Port of Iloilo, $t(3300) = -25.549$, $p = <0.0001$; and Port of Cebu, $t(1552) = -13.721$, $p = <0.0001$.

This disparity in the seasonal trends of air pollutant concentrations indicated by the findings of the study can be attributed to the nature of port activities. During the onset of the wet season, ships are advised to seek shelter in ports until the winds and waves subside (PAGASA, n.d.). This leads to an increase in volume and number of ships docked in ports during inclement weather. For instance, the Philippine Fisheries Development Authority (PFDA) reported a 3.71% increase in weekly unloading volume at its Regional Fish Ports (RFP) from May 31 to June 6, 2021, coinciding with the onset of the rainy season (Cudis, 2021).

Most large ships maintain idle engines especially during storms and monsoon seasons while docked so that the machinery and operation systems in the ships are regularly warmed up so that they can return to service quickly (Healey, 2021). As a result, their auxiliary engines continuously operate, leading to continuous emissions (FathomShipping, 2013).

While the majority of emissions from the maritime sector are released over vast oceanic areas during a ship's journey between two points, the most noticeable emissions occur when ships are berthed in ports. Dalsøren et al. (2008) estimate that approximately 5% of total emissions from navigation activities can be attributed to ships' operations in or around ports. In fact, it is estimated that a ship can emit more than 2.5 tonnes of pollutants during an eight-hour stay in port (Climate Institute, 2010).

3.2.1 Port of Manila and Port of Batangas (Type I Climate): Manila and Batangas, which represent climate type I, undergo two distinct seasons characterized by dry season from November to April and wet season from May to October. The patterns in NO_2 and SO_2 concentrations in Port of Manila and Port of Batangas follow a distinct pattern of a gradual increase during the dry season, and a gradual decline during the wet season.

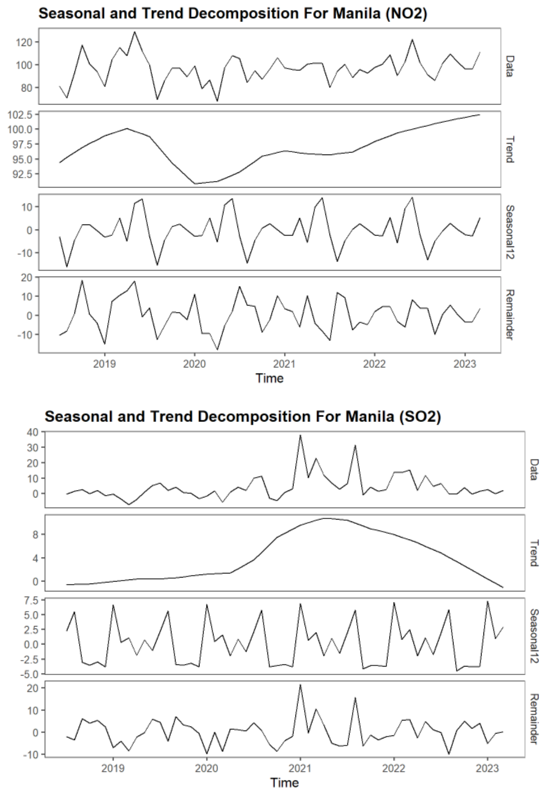

Figure 6. Time series decomposition for NO_2 and SO_2 concentrations in Port of Manila from 2018-2023.

Figure 6 shows that the seasonality of the data for NO_2 concentrations in Port of Manila from 2018-2023 peaks during the month of July and collapses in the month of September. In the Type I Climate, the month of July falls on the Dry Season while the Month of September falls on the Wet Season. The trend shows a drastic decline in the NO_2 values during the year 2020, coinciding with the COVID-19 lockdown, and then a gradual increase as the restrictions on port operations were lessened.

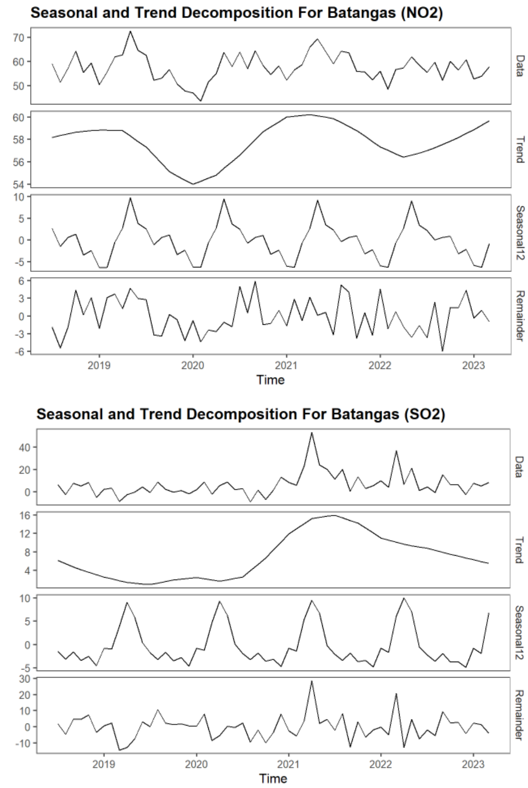

Figure 7. Time series decomposition for NO_2 and SO_2 concentrations in Port of Batangas from 2018-2023.

Similar trends can be observed for NO_2 emissions in Port of Batangas, wherein values increase during the dry season and decrease during the wet season. Figure 7 shows that the seasonality of the data for NO_2 concentrations in Port of Batangas from 2018-2023 peaks during the month of May and hits a minimum in the month of February. The trend implies that there is a drastic decrease in the NO_2 concentrations from 2019 to 2020 during the lockdown period. In 2021, however, the trend ballooned upward as these restrictions were eased to spur economic growth in the country.

On the other hand, time series decomposition of SO_2 concentrations in the Port of Batangas revealed that the minimum point is in the month of January while its highest point is in the month of May.

3.2.2 Port of Legazpi (Type II Climate): Legazpi City, representing climate type II, exhibits a distinct climatic pattern characterized by a prolonged rainy season from December to February, with no dry months.

Figure 8 shows that the seasonality of the data for NO_2 concentrations in Port of Legazpi from 2018-2023 peaks during the month of August and hits a minimum in the month of June. Notably, the year 2020 experienced substantial rainfall due to the occurrence of powerful typhoons Goni (Rolly) and Vamco (Ulysses) in November. These events, along with the implementation of quarantine measures, resulted in significant changes in the levels of NO_2. This shows in the overall trend wherein NO_2 tropospheric VCDs significantly decreased during the later parts of 2020.

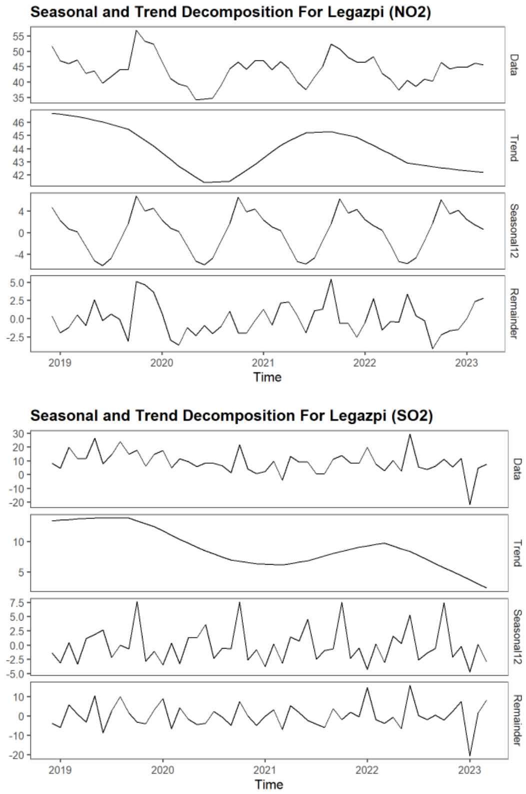

Figure 8. Time series decomposition for NO_2 and SO_2 concentrations in Port of Legazpi from 2018-2023.

The seasonal data statistics for SO_2 concentrations in Port of Legazpi from 2018 to 2023 reaches its highest point in October and the minimum in January. In the Type II Climate, the month of January falls into the minimum rainfall season. The trend and seasonality of SO_2 retrievals in Port of Legazpi are heavily influenced by the variable emissions from the Mayon Volcano, evident in the trend where concentrations peak during 2019 and 2020, years when the volcano had observable activities.

3.2.3 Port of Iloilo and Port of Cebu (Type III Climate): Climate Type III experiences rainfall that is evenly spread throughout the year, with short periods of dry seasons occurring either from December to February or from March to May. This climate type is represented in this study by the Ports of Iloilo and Cebu.

The seasonality of the data for the NO_2 concentrations in Port of Iloilo from 2018-2023 is shown in Figure 9. It can be inferred that the highest point lies in the month of April, while the lowest point is in the month of February. The months of February and May fall during the wet and dry seasons, respectively, in the Type III Climate. The trend suggests that during the lockdown period from 2019 to 2020, NO_2 concentrations decreased dramatically. Despite this, the NO_2 produced an upward trend when the country eased its lockdown restrictions in 2021.

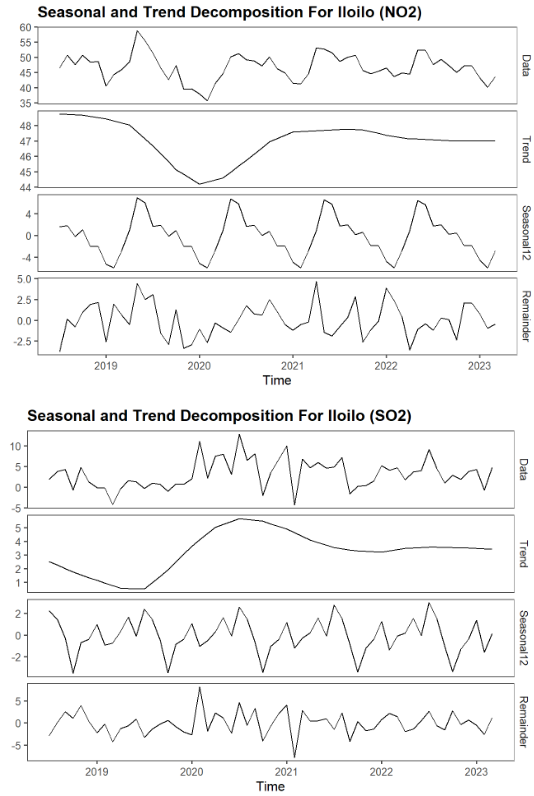

Figure 9. Time series decomposition for NO_2 and SO_2 concentrations in Port of Iloilo from 2018-2023.

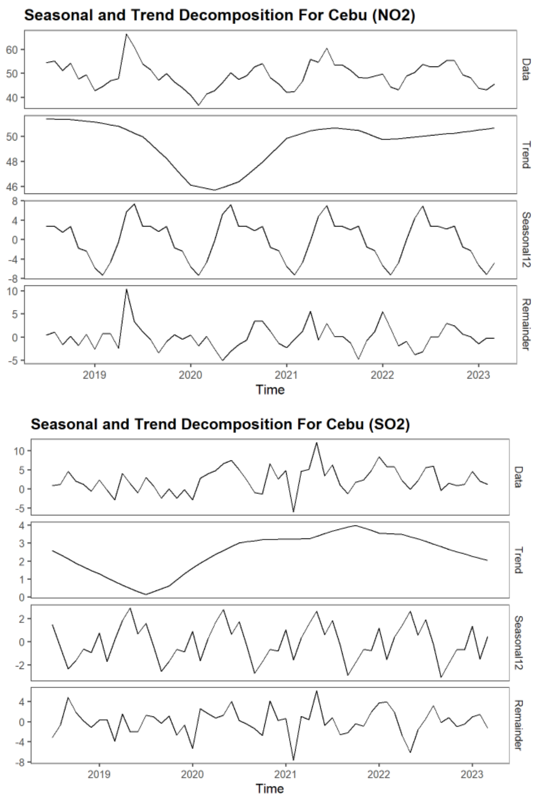

Figure 10. Time series decomposition for NO_2 and SO_2 concentrations in Port of Cebu from 2018-2023.

From 2018-2023, the seasonal data statistics for SO_2 concentrations in Port of Iloilo reached its highest point in July and its minimum in October as shown in Figure 4.20. In the Type III Climate, the months of July and October both fall in the Wet Season. Similarly, the trend implies that there is a drastic decrease in the SO_2 concentrations from 2019 to 2020 during the lockdown period. Given that there is no active volcano and any other volcanic activity within the vicinity of the Port of Iloilo, there was an increase in the 2021 SO_2 emissions in the area. This can be credited to the fact that the Philippines has eased its COVID-19 restrictions during that time.

Figure 10 shows that the seasonality of the data for NO_2 concentrations in Port of Cebu from 2018-2023 peaks during the month of July and collapses in the month of February. In the Type III Climate, the month of July corresponds to the Wet Season, while the month of February corresponds to the Dry Season. Trends show a significant decrease in NO_2 retrievals in 2020, coinciding with the COVID-19 lockdowns. The seasonal data statistics for SO_2 concentrations in Port of Legazpi from 2018 to 2023 reached its peak in May and its bottom in September. The months of May and September lie in the Dry and Wet Season, respectively, in the Type III Climate.

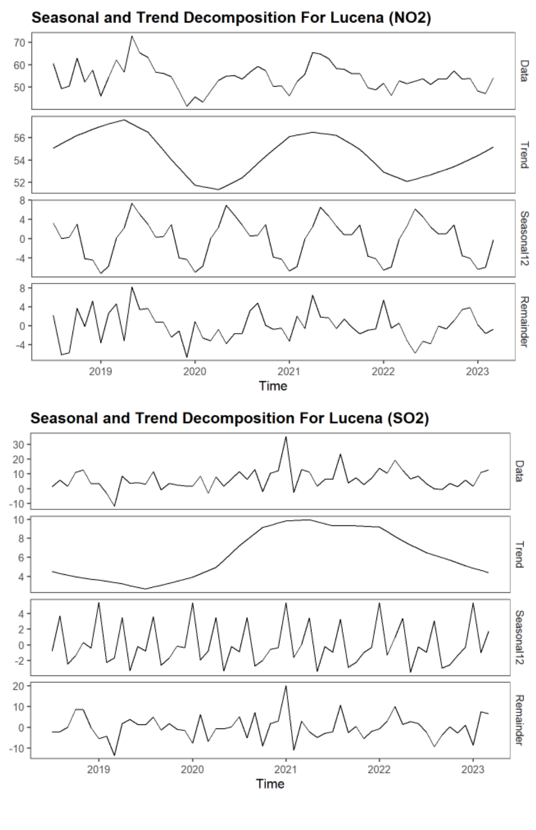

Figure 11. Time series decomposition for NO_2 and SO_2 concentrations in Port of Lucena from 2018-2023.

3.2.4 Port of Lucena (Type IV Climate): Lucena, which represents climate type IV, undergoes only the year round wet season as DOST-PAGASA characterized this type of climate to have no dry season. Figure 11 shows that the seasonality of the data for NO_2 concentrations in Port of Lucena from 2018-2023 peaks during the month of May and collapses in the month of January. Similar to other sites, the NO_2 levels at the Port of Lucena have decreased as a result of the COVID19 lockdown. However, also similar to others, the NO_2 VCDs have dramatically increased as the restrictions were uplifted in 2021.

The seasonality of the data for SO_2 concentrations in Port of Lucena from 2018-2023 oscillates all throughout the year. This may be due to the characteristic of the Type IV Climate in the Philippines, where there is a year round wet season. The trend indicated that, similar to other sites, the lockdown has impacted the decrease of SO_2 levels in the Port of Lucena. However, the SO_2 emissions produced by the unrest of Taal Volcano may contribute to the upward trend starting from 2021.

4. CONCLUSIONS

The temporal variability of air pollutants NO_2 and SO_2 in various port areas in the Philippines was studied through Sentinel-5P based tropospheric vertical column densities. Time series analysis of satellite-based NO_2 and SO_2 vertical column densities revealed several patterns and trends within the 10km vicinity of the six select port areas in the Philippines.

The analysis of NO_2 mean concentrations in the port areas showed a significant decline in values from 2019 to 2020 due to the COVID-19 lockdowns. As the country eased the lockdown measures in 2021, there was a rebound in NO_2 concentrations, particularly in the Port of Manila. Overall, the Port of Manila experienced the highest percent change in NO_2 concentrations from 2019 to 2022.

On the other hand, the analysis of SO_2 concentrations revealed a notable increase in values in the Port of Batangas and Port of Manila in 2020 due to the eruption of Taal Volcano. The Port of Legazpi also experienced a significant increase in SO_2 emissions from 2021 to 2022, likely influenced by the emissions from nearby Mayon Volcano. It can be inferred that less industrialized or urbanized cities recorded lower levels of both NO_2 and SO_2 concentrations compared to cities near recent volcanic eruptions.

T-test was performed to assess significance difference in air pollutant concentrations between dry and wet seasons. Contrary to general expectations, wet seasons showed higher NO_2 and SO_2 concentrations in most ports. These disparities in seasonal trends can be attributed to the nature of port activities during inclement weather, wherein ships are more likely to be docked with the engines continuously operating, leading to continuous emissions within the port buffer zones.

Time series decomposition analysis revealed the specific months when pollutant concentrations reached their highest and lowest points, influenced by the climate type of each port. The different climate characteristics of dry and wet seasons were observed to play a role in shaping the trends and behavior of air pollutants during different seasons. In general, NO_2 concentrations tend to experience a gradual increase during the dry season, hitting a peak at the start of the wet season, then a gradual decrease during the wet season. In contrast, SO_2 concentrations show less variation in relation to the seasons. The climate type of each port influences the specific months when pollutant concentrations reach their highest and lowest points.

Future studies related to air quality monitoring in ports using remote sensing techniques can benefit from the following recommendations to enhance the analysis of air pollutant retrievals. Other trace gasses such as CO and CH_4 as well as other pollutants such as Particulate Matter (PM) can be explored to provide valuable insights into their sources and impacts. In addition, incorporating ground in situ data can be valuable for validation of remote sensing observations and contributing factors of air pollution in ports (i.e. cargo traffic, port and ship activities, volcanic emissions). By applying these recommendations, future studies can improve the accuracy and reliability of air quality assessments using remote sensing techniques in port areas, ultimately contributing to a better understanding of emissions and their impact on the environment and human health.

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