Evaluating the Correlation Between Satellite and Ground-Based NO_x Measurements in Eastern Africa: Identifying Main Sources of Pollution

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1. Abstract

Many developing regions, such as Eastern Africa, do not have enough access to expensive ground-based nitrogen oxides (NO_x) monitoring devices due to financial limitations. This research project evaluates whether the freely available satellite data from the Tropospheric Monitoring Instrument (TROPOMI) can serve as a supplement to the ground-based NO_x measuring instruments in Eastern Africa. Ground-level data were obtained from an NO_x analyzer providing hourly concentrations of NO, NO_2, and NO_x, while satellite-based daily NO_2 data were accessed via Google Earth Engine. As a consequence of correlation analyses, trend comparisons, and diurnal pattern evaluations, the study revealed that there is a weak correlation between NO_x concentrations from the two datasets, primarily due to spatial differences in measurement. Despite the fact that ground-based instruments measure concentrations in a specific location, satellite measurements calculate the average of vertical and horizontal concentrations in larger urban areas. However, both datasets successfully show the same overall decreasing trend in NO_2 concentrations from 2021 to 2025. The main reasons for this decline are the following: noticeable infrastructure improvements, the removal of the roadside cooking machines, and the enforcement of the 2022 Nairobi Air Quality Act. Moreover, consistent diurnal peaks during morning and evening hours indicate that vehicular

traffic remains a main source of air pollution in nearby urban areas. This research project concludes that we can use satellite-based NO_2 as a complementary tool to ground-level instruments in data-scarce regions such as Eastern Africa.

2. Introduction

2.1. Air Pollution and Challenge of Measuring It in Underrepresented Regions

Air pollution is one of the important factors for diseases and premature death in the world. It contributes to respiratory illnesses, cardiovascular problems, and reduced life expectancy. NO_x - which is the combination of nitric oxide (NO) and NO_2 - is a key contributor to urban air pollution. These gases are closely related to traffic emissions, industrial processes, and biomass burning (Goldberg et al.). The measurement of NO_x concentrations is crucial to understand pollution sources, identify health risks, and design policies against them.

However, many underrepresented regions, such as Eastern Africa, lack air quality monitoring devices. The deployment of ground-based NO_x Analyzers requires significant financial investment, which is not available for the resource-limited regions. As a consequence, policymakers have scarce information that can help them make proper decisions. They encounter severe data gaps. Hence, it is difficult to take the necessary steps and prevent pollution.

2.2. Expanding Access to Air Quality Monitoring

Satellite-based monitoring has advanced as an alternative to ground-based monitoring methods. Satellites such as the TROPOMI provide freely available daily observations of atmospheric NO_2. This technology was developed by the European Space Agency and NASA. It offers an important opportunity for regions suffering from financial shortages to prevent the establishment of enhanced ground-based systems.

By using satellite observations, researchers can create a more complete picture of pollution patterns in those areas. This study builds on prior work in other regions, such as Westervelt et al. (2025), who successfully used satellite and ground-based data to estimate particulate matter ($PM_{2.5}$). But this project focuses mainly on nitrogen dioxide concentrations in Eastern Africa.

2.3. Empowering Evidence-Based Decision-Making

NO_x measurements are essential for shaping urban planning, transportation policy, and public health strategies. Without accurate data, local governments are not able to make decisions. Incomplete or misleading information makes it very difficult. Satellite-derived data together with ground-based observations could provide a cost-effective opportunity for policymaking.

We know that high-quality monitoring networks from two different sources can improve model accuracy and enable environmental regulations. However, the applicability and reliability of this approach in Eastern Africa remain underexplored. Our project addresses this gap by comparing satellite-derived NO_2 concentrations with continuous ground-based NO_x measurements.

2.4. Promoting Climate and Environmental Justice

The unequal distribution of environmental monitoring devices is a key driver of global disparities in climate research. The atmospheric science literature has historically focused on North America, Europe, and East Asia. Africa, South America, and South Asia remain underrepresented. This imbalance limits the scientific understanding of air pollution in these regions.

Validating the use of freely available satellite observations in this African region, this study contributes to inclusive monitoring efforts. Satellite-based approaches democratize access to air quality information. As a result, it empowers communities, researchers, and decision-makers. In this way, it may help them have the resources for continuous ground monitoring. In this way, they support the broader goals of climate and environmental justice by ensuring that all regions can track pollution trends and advocate for cleaner air.

2.5. Goals and Scope of This Research

The primary goal of this study is to evaluate the reliability of TROPOMI-derived NO_2 data as a supplement to ground-based NO_x measurements in Eastern Africa. Our scope is intentionally focused on NO_x in Nairobi, reflecting both the availability of continuous ground-based measurements there and the city's relevance as a main populated hub in Eastern Africa.

3. Methods

3.1. Study Area

This study was conducted in Nairobi, Kenya, which is a rapidly urbanizing city with approximately four million residents. It was expected to have several sources of air pollution, including vehicular traffic, industrial activities, and roadside biomass burning. Nairobi was mainly selected as the study site because it hosts a ground-based NO_x Analyzer set up by our team, which makes it one of the important centers in Eastern Africa.

3. 2. Ground-Based Measurements

Ground-level NO_x concentrations were measured using an NO_x Analyzer located in Nairobi. The instrument detects NO directly through its reaction with ozone to produce chemiluminescence. NO_2 is quantified after catalytic conversion to NO (Sokolosky). The total NO_x concentration is then calculated as the sum of NO and NO_2. The analyzer operates continuously and provides hourly data.

3.3. Satellite Observations

Satellite-based nitrogen dioxide data were obtained from the TROPOMI aboard the Sentinel-5 Precursor satellite, operated by the European Space Agency and NASA. Data were accessed through the Google Earth Engine. It provides open access to satellite products. Column densities were changed from the units of mol/m^2 to mol/cm^2 (Eskes et al.).

3.4. Data Processing and Analysis

To enable direct comparison between the two different datasets, the 1:00 PM and 2:00 PM ground-based NO_x measurements were averaged to approximate 1:30 PM. It was done to correspond to 1:30 PM, when TROPOMI observations are made each day (Eskes et al.). Only days that had valid data from both the ground-based analyzer and the satellite instrument were taken for analysis. The statistical relationship between ground-based NO_x concentrations and satellite-derived NO_2 concentrations was assessed using correlation analysis. Scatter plots were created to visualize the association, and linear regression lines were drawn.

Long-term changes in pollutant levels were examined for both datasets from 2021 to 2025. Time series plots were created to assess consistency in yearly trends between the two measurements. In addition, diurnal cycles of NO_x and black carbon were computed from the ground-based dataset. It was done by averaging hourly concentrations over years and generating daily patterns. These diurnal profiles were compared with known traffic activity patterns in Nairobi to explore the influence of vehicular emissions on the pollutants (Aerosol d.o.o.).

3.5. Limitations and Assumptions

Several limitations should be considered when we interpret the results. Ground-based measurements capture point-specific concentrations. However, satellite retrievals represent an average of the vertical and horizontal lines over a larger spatial area. It introduces potential scale mismatches. The two methods also differ in pollutant scope, as the analyzer measures

NO, NO_2, and NO_x. But TROPOMI measures only NO_2. Furthermore, satellite retrievals are affected by cloud cover. It leads to data gaps during Nairobi's rainy seasons. Finally, the satellite's overpass occurs at approximately 01:30 PM each day and captures midday conditions only. On the other hand, the ground-based instrument records data continuously throughout the day. While this mismatch was corrected, the differences in spatial and chemical representation influence the level of correlation observed between the two datasets.

4. Results

This section presents the observed patterns and relationships between ground-level NO_x concentrations and satellite-based NO_2 data in Nairobi, Kenya, from 2021 to 2025. It first outlines the yearly trends observed from both ground and satellite datasets. Then weekday and diurnal variations follow. Finally, it explores the potential sources of pollution using additional pollutant indicators such as black carbon and biomass burning activity.

4. 1. Long-Term Temporal Trends in NO_x and NO_2

On the one hand, Figure 1 illustrates monthly average concentrations of NO, NO_2, and NO_x. These concentrations are measured by the ground-based NO_x Analyzer between January 2021 and June 2025. Concentrations remained relatively stable from January to July each year. Then, it is followed by sharp peaks in August. After these peaks, all three pollutants declined steadily by the end. There was a declining trend in pollutant levels. On the other hand, Figure 2 shows TROPOMI-based monthly average tropospheric NO_2 from January 2021 to November 2024. This dataset reveals a consistent seasonal pattern with the ground-level data. Concentrations rose from April and peaked in September. Then it declined by December. An overall decreasing trend is observable in the later years.

Similarly, Figure 3 presents ground-based data of NO, NO_2, and NO_x across the full study period. The time series highlights a gap in data collection from December 2021 to mid-

2022. It is due to the instrument's malfunction and maintenance. Once measurements resumed, concentrations continued on a declining path through mid-2025. It reinforces the trend identified in Figure 1. Figure 4 complements these findings with a time series of monthly average NO_2 from the TROPOMI satellite. This data ends in November 2024. But a clear downward slope in the trend line supports the observation that tropospheric NO_2 levels in Nairobi have been decreasing over time.

4. 2. Weekly Patterns in NO_x and NO_2 Concentrations

Figure 5 displays average NO_x concentrations by day of the week, based on ground-level data. NO_x levels are consistently higher on weekdays than weekends. This graph has a peak on Wednesdays. There is a consistent decline in NO_x concentrations across all weekdays from 2021 to 2025. It suggests overall air quality improvements. Similarly, Figure 6 presents weekday averages of TROPOMI-derived NO_2. Like the ground-based data, NO_2 concentrations peak on Wednesdays and Thursdays. But the concentration falls to their lowest levels on Sundays. The highest concentrations across the dataset occurred in 2022 and began to decline in subsequent years.

4. 3. Correlation Between Ground-Level and Satellite NO_2 Observations

The next plot (Figure 7) compares daily average ground-level NO_2 concentrations in ppb with satellite-derived NO_2 column densities in mol/cm². The scatter plot has a regression line to show a slight upward trend. It indicates a weak positive correlation between the two measurements. The upcoming graph (Figure 8) shows monthly averages of ground and satellite NO_2. Here, each point has been color-coded by month. The regression line demonstrates very low correlation, where the R^2 value is 0.02. It indicates minimal agreement between the datasets on a monthly scale.

Figure 9 examines this relationship across all months, where there is an individual regression line fitted. Correlations vary significantly for each month. But there is no strong and consistent relationship found. Here we can conclude that while general trends may be similar, monthly values do not align closely. Figure 10 enhances our analysis further. It evaluates seasonal correlations between ground and satellite NO_2 values. Months were grouped into wet seasons (March, April, May, October, November, December) and dry seasons (January, February, June, July, August, September). The dry season has an R^2 equal to 0.028. The wet season showed a slightly stronger correlation of R^2 equal to 0.075. Both seasonal relationships can be considered to be very weak.

4. 4. Diurnal Patterns and Pollution Source Indicators

The graph (Figure 11) shows the average diurnal pattern for NO, NO_2, and NO_x between 2021 and 2025. Each pollutant shows a peak from 7:00 to 8:00 AM. It corresponds with morning traffic. A smaller secondary rise occurs in the evening, mainly in 2021. The intensity of both peaks declines steadily through 2025. It supports the observation of improving air quality over time. The next plot (Figure 12) illustrates the hourly average concentrations of black carbon (BC6), which peaks sharply at 6:00 AM with nearly 47 $\mu g/m^3$, suggesting a burst of emissions in the early morning. The second peak appears at 8:00 PM. But concentrations remain low throughout midday and late night.

Figure 13 displays the hourly average of the wood combustion indicator. It shows a prominent evening peak for 2 hours between 8:00 PM and 10:00 PM. It implies that wood-burning activity increases at night. A smaller rise is also observed between 6:00 and 7:00 AM. The other graph (Figure 14) tracks the diurnal variation in biomass burning percentage (BB%). The BB% is highest between 1:00 AM and 2:00 AM. It decreases steadily until 8:00 AM. After fluctuating during the day, it spikes again at 5:00 PM. Then it is followed by additional increases between 6:00 PM and 11:00 PM.

These results provide a foundation for further analysis of satellite data as a supplementary monitoring tool. It also highlights key behavioral patterns that may inform air quality policy in data-scarce urban regions.

5. Discussion

This study found out that the correlation between ground-level and TROPOMI nitrogen dioxide concentrations is very weak. However. One of the prominent patterns this study found was the gradual decline in NO, NO_2, and NO_x concentrations from 2021 to 2025. This trend can be observed in both ground-based and satellite-derived datasets. It suggests an improvement in Nairobi's urban air quality. The decline may be attributed to several factors. These factors include infrastructure improvements, the removal of roadside cooking machines, and the partial enforcement of the Nairobi Air Quality Act signed in 2022.

Diurnal variation was another strong point that this research discovered. NO_x and BC6 concentrations peaked in the early morning and the evening. This pattern remained consistent across years. It is characteristic of urban environments dominated by vehicular emissions. Moreover, the contribution of biomass burning appears to be secondary. The wood combustion indicator peaked during the evening hours and did not show the same level of concentration as traffic-related markers. Similarly, the biomass burning percentage showed variability across hours. Yet it was also not consistent with the largest pollution sources. These findings mean that biomass burning occurs; however, it is not the main driver of NO_x pollution in Nairobi and nearby large cities.

When examining seasonal effects, the study discovers that the pollution levels measured with ground-level and TROPOMI data were less consistent during the dry months

(January, February, June, July, August, September) than in the wet months (March, April, May, October, November, December). The high level of clouds can be an underlying reason.

These results align with previous findings in similar urban contexts across Eastern Africa, where the model showed weak correlation of satellite with ground-based NO_2 measurements (Beata Opacka et al., 2024). However, this study contributes new insight by combining high-resolution ground-level and satellite datasets in Nairobi, Kenya.

The current study also has some limitations and they should be addressed in future work. For example, differences in spatial scale such as point vs. horizontal and vertical averages make it difficult to directly compare the data from two different datasets. Additionally, the analysis did not account for other variables such as wind speed, temperature, and atmospheric pressure. The removal of these limitations could improve the interpretation of satellite-surface mismatches.

These findings have implications for environmental monitoring and policy development in other data-scarce urban environments. They can be used to track general pollution trends, identify priority areas for intervention, and validate the impacts of air quality regulations.

In conclusion, this study provides strong evidence that satellite-based NO_2 observations do not perfectly match ground-level NO_x measurements in Nairobi. Yet it captures some meaningful trends and patterns over time. The findings reinforce the utility of TROPOMI data as a complementary tool for environmental monitoring in areas with low investment.

6. Conclusion

This study set out to evaluate whether freely available satellite data can reliably supplement ground-based NO_x monitoring in data-scarce regions such as Eastern Africa. Despite a weak statistical correlation between satellite-derived and ground-level NO_2

measurements, both sources consistently revealed a clear and steady decline in NO_x levels from 2021 to 2025. This agreement in long-term trends suggests that satellite data can be a useful tool to monitor nitrogen oxides where ground-level infrastructure is limited.

New insights from this research include the identification of strong diurnal and weekday pollution patterns closely tied to traffic activity. This reinforces the fact that vehicular emissions are the dominant contributor to air pollution in large cities of Eastern Africa. While biomass burning and domestic combustion were present, their influence appeared secondary.

By integrating satellite and ground-based observations, this work demonstrates a practical path forward for cities in Eastern Africa and other under-monitored regions seeking to build more cost-effective air quality systems. The findings emphasize that while satellites cannot fully replace ground-based sensors, they can meaningfully support data-driven environmental policy. In any case, future initiatives should focus on the creation of monitoring networks where possible and incorporate them to enhance accuracy and interpretation.

In sum, this research contributes important evidence toward closing air quality data gaps in the Global South. It also highlights the critical role of satellite data in promoting environmental justice and decision-making.

7. Recommendations

To build on the findings of this study, the authors recommend that Nairobi and other large cities in Eastern Africa invest in building their own ground-based monitoring systems. The integration of these local systems and satellite data would improve the accuracy of pollution measurements. Additionally, a detailed evaluation of the Nairobi Air Quality Act can help determine the effectiveness of such regulatory efforts. It would also guide future interventions.

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Acknowledgments

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Figures

Figure 1: NOx Analyzer — Monthly Average Concentrations of NO, NO2, & NOx (2021 Jan - 2025 June).

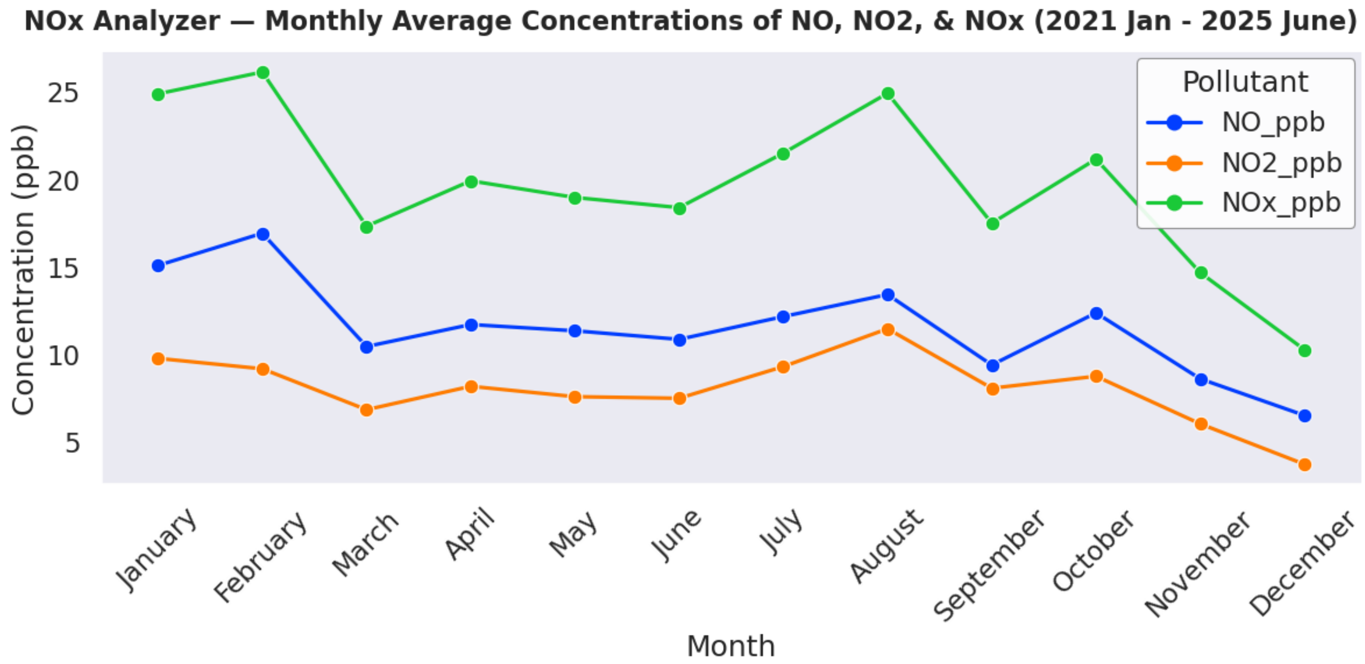


Figure 2: TROPOMI — Monthly Average Tropospheric NO_2 (2021 Jan – 2024 Nov).

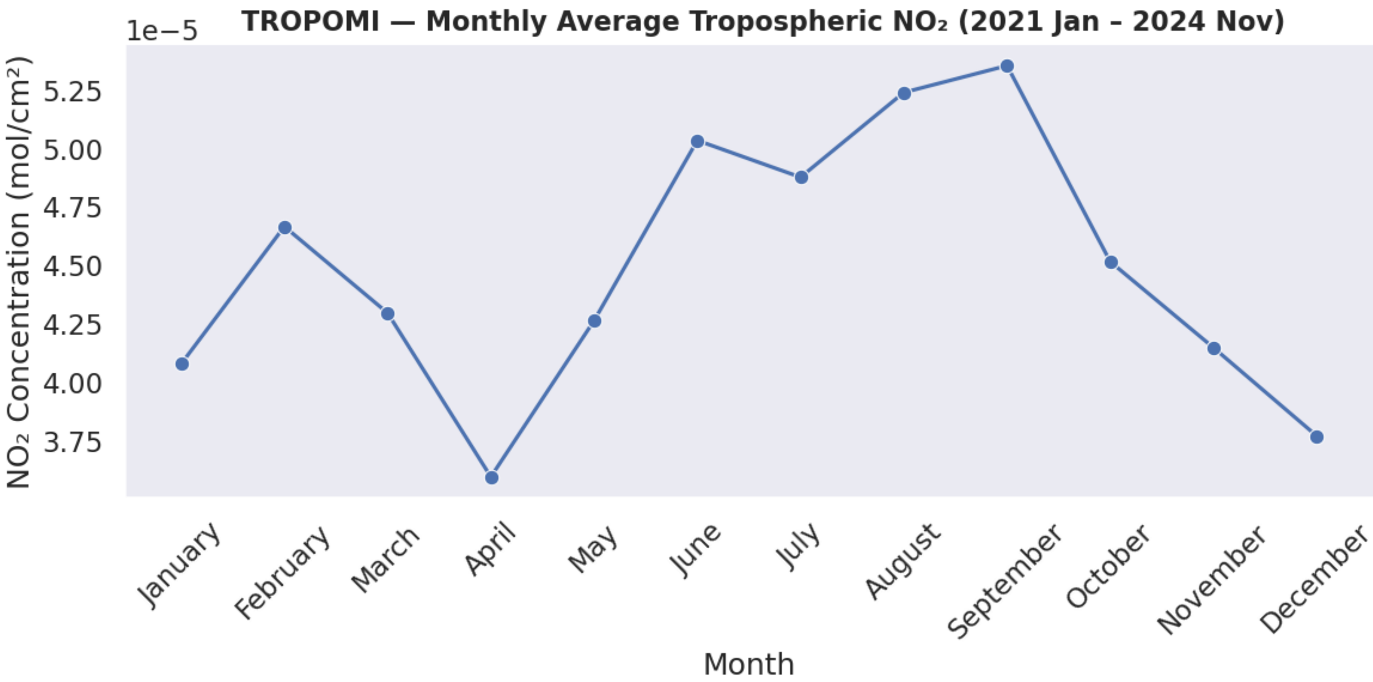


Figure 3: NOx Analyzer — Monthly Average of NO, NO_2, and NO_x in Nairobi, Kenya (January 2021 – June 2025)

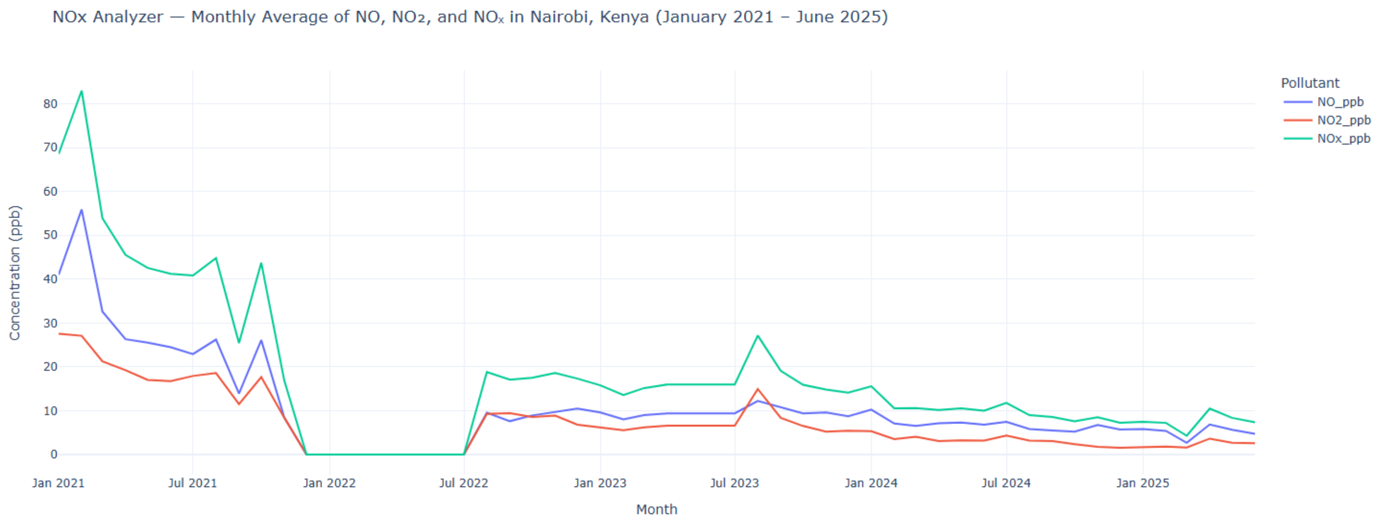


Figure 4: TROPOMI — Monthly Average NO_2 in Nairobi, Kenya (January 2021 – November 2024).

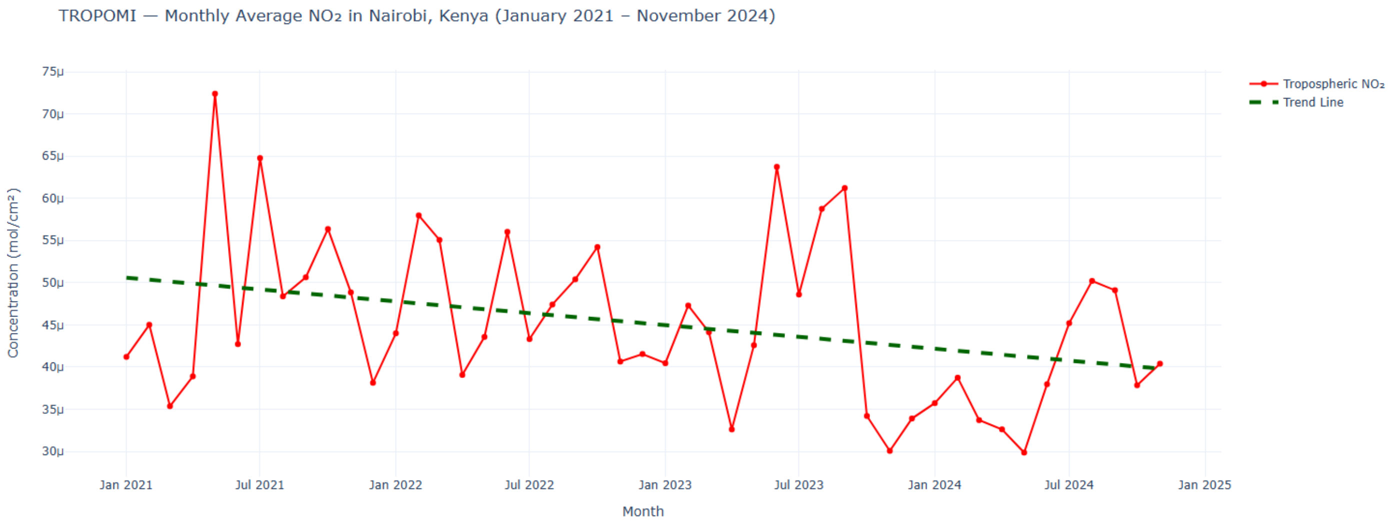


Figure 5: NOx Analyzer — Average NOx Concentration by Weekday.

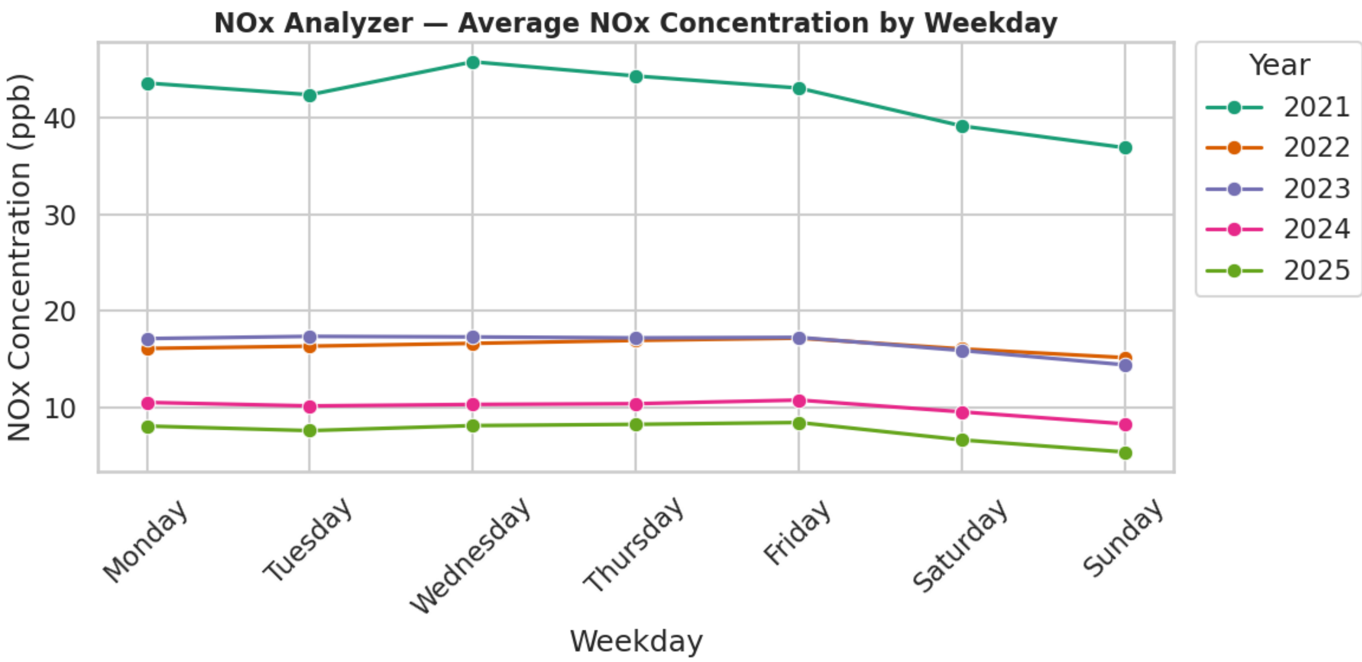


Figure 6: TROPOMI — Average Tropospheric NO_2 by Weekday.

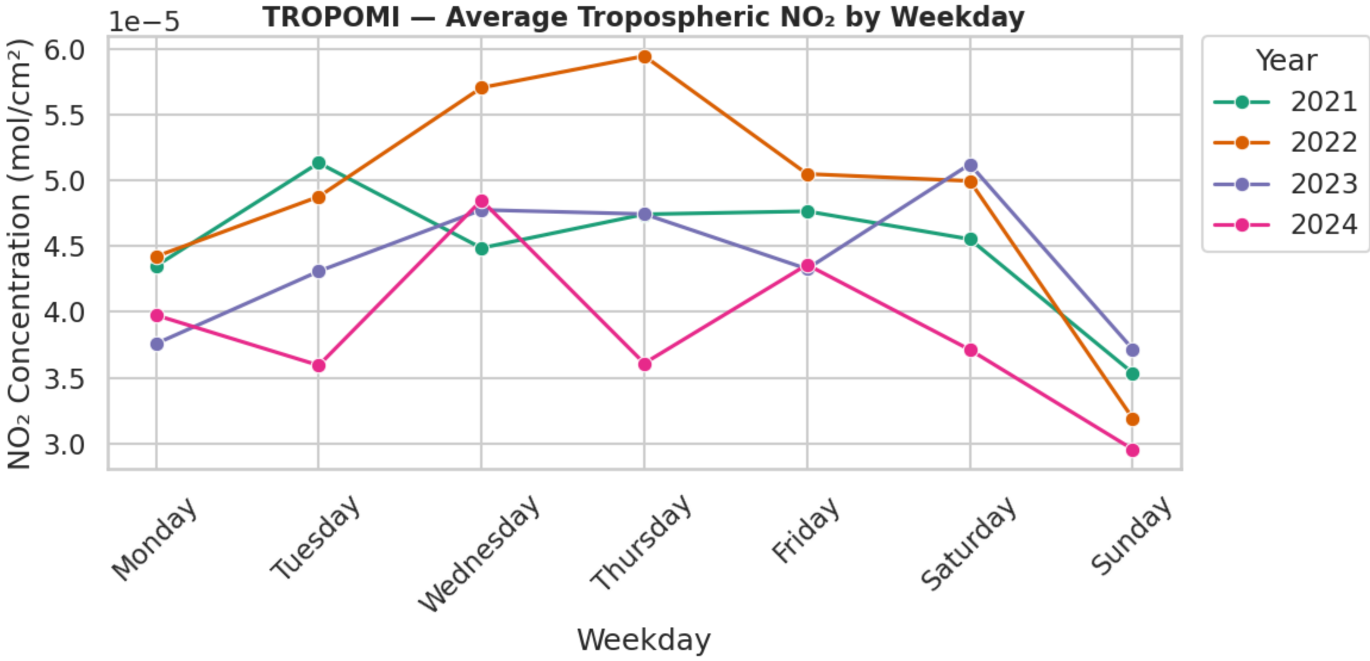


Figure 7: Ground-Level NO_2 (ppb) vs Satellite NO_2 (mol/cm²) with Regression Line

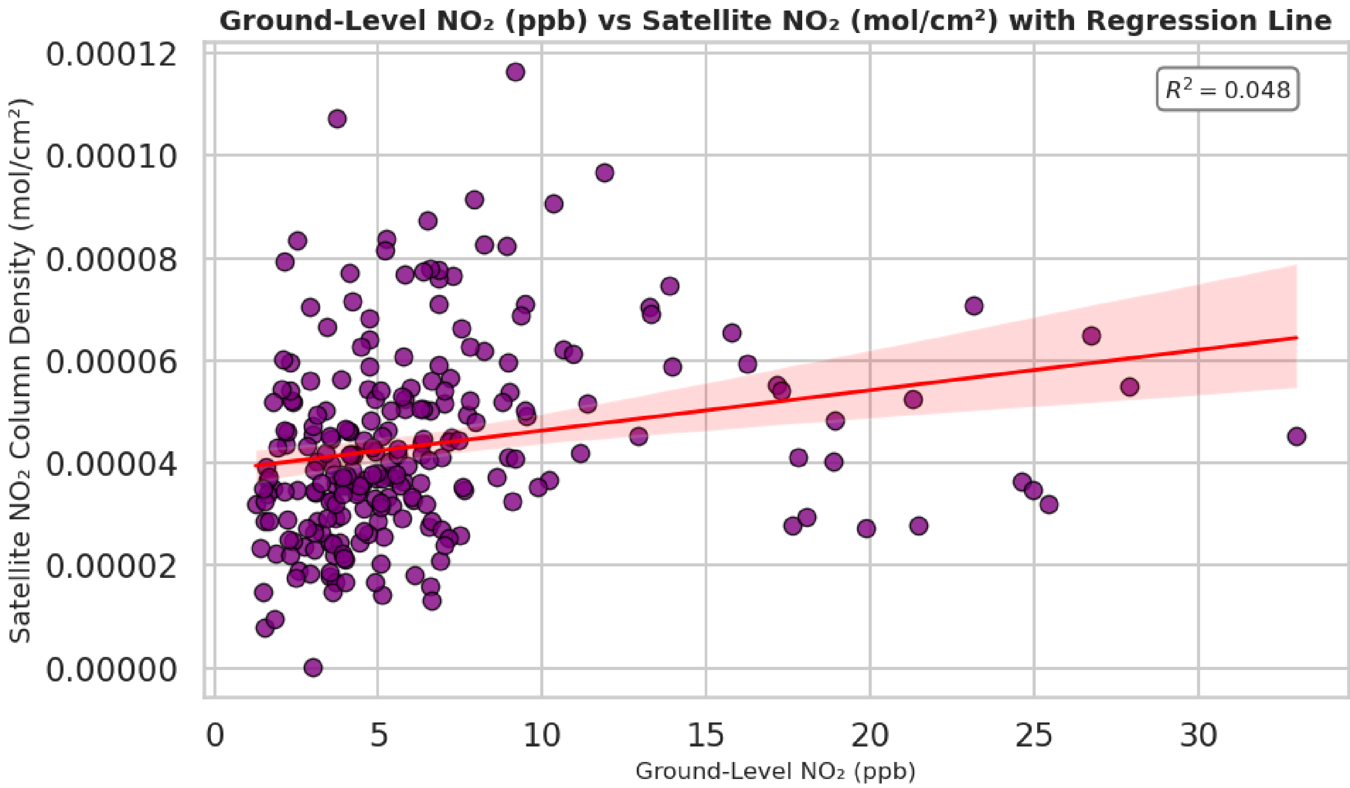


Figure 8: Monthly Avg: Ground-Level NO_2 vs Satellite NO_2 by Month Color.

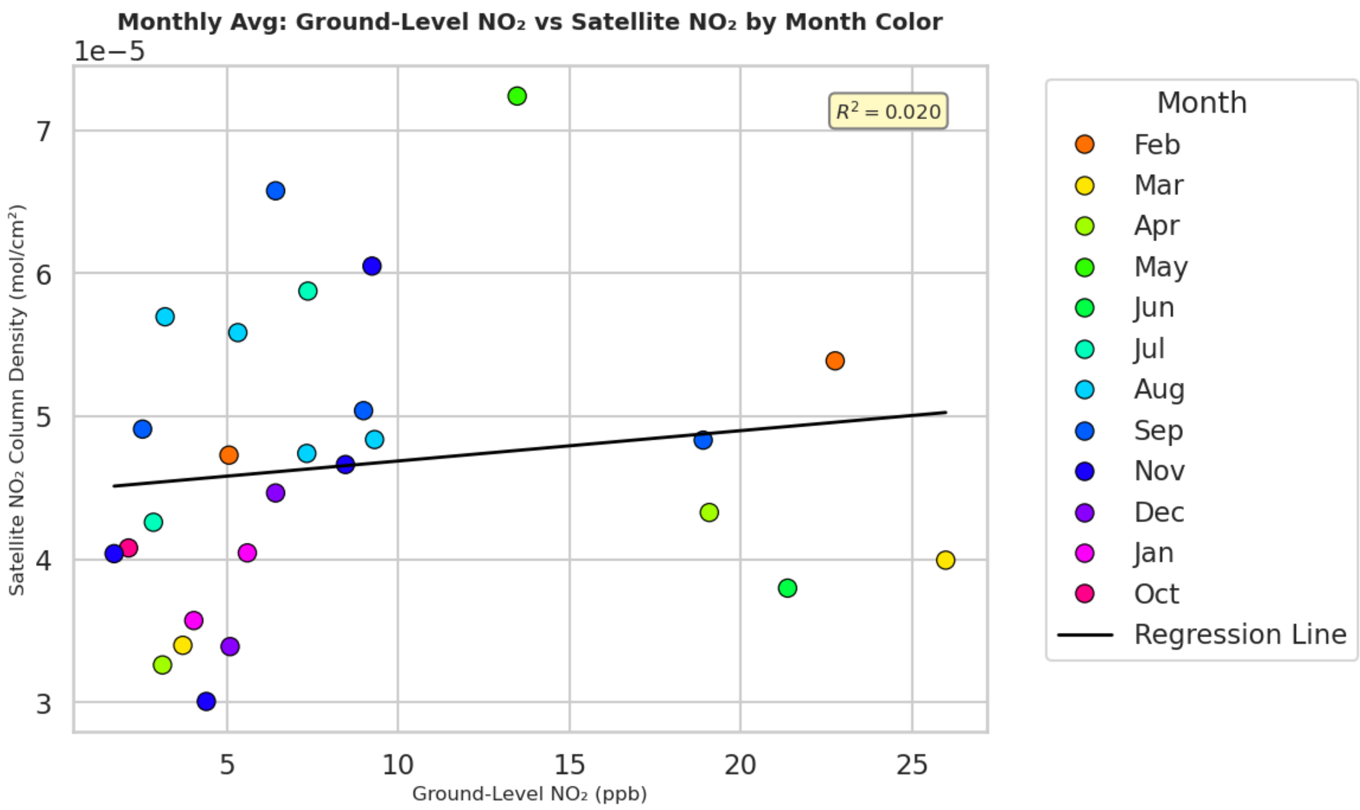
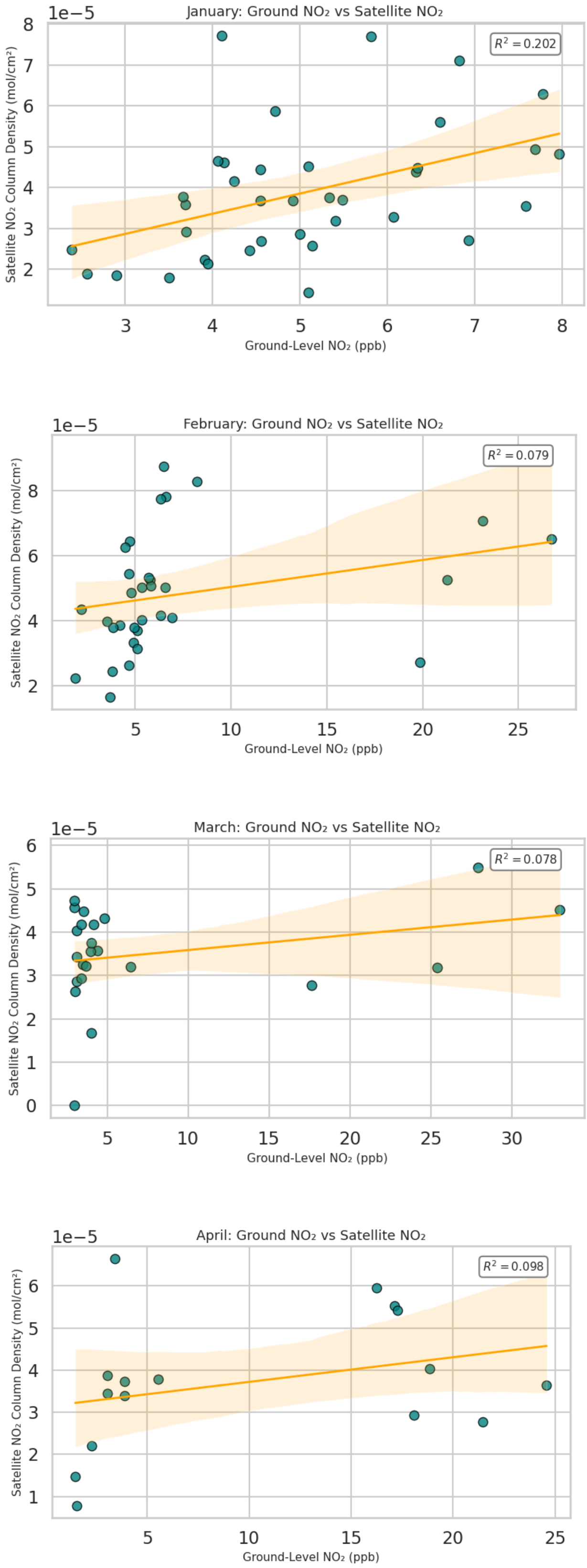
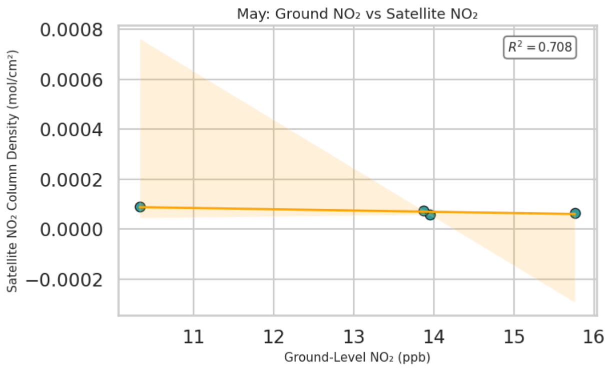
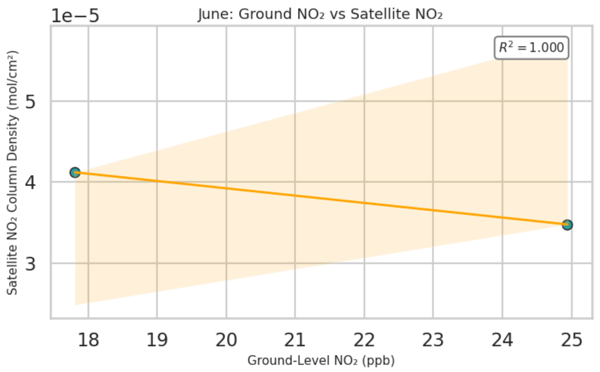
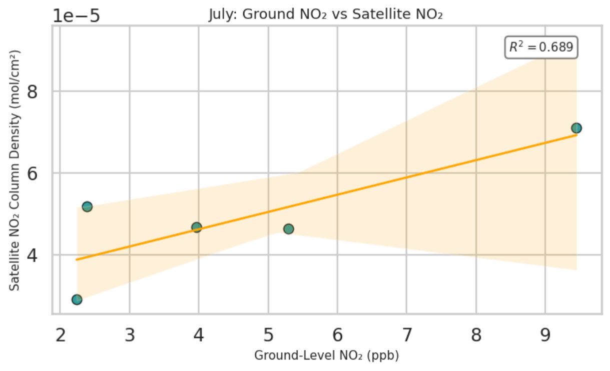


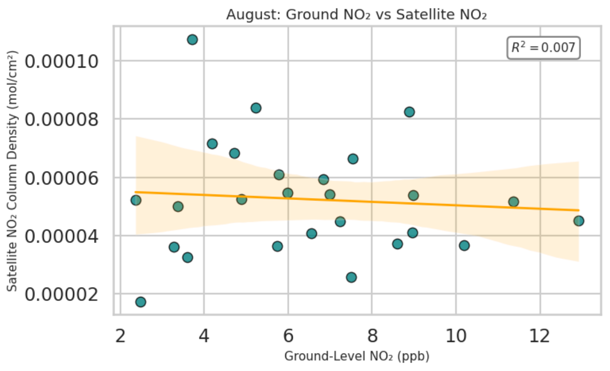
Figure 9: Monthly Avg: Ground NO₂ vs Satellite NO₂ with Monthly Regression Lines.




May: Ground NO₂ vs Satellite NO₂
$R^2 = 0.708$
Satellite NO₂ Column Density (mol/cm²)
Ground-Level NO₂ (ppb)
0.0008
0.0006
0.0004
0.0002
0.0000
−0.0002
11
12
13
14
15
16


June: Ground NO₂ vs Satellite NO₂
1e−5
$R^2 = 1.000$
Satellite NO₂ Column Density (mol/cm²)
Ground-Level NO₂ (ppb)
5
4
3
18
19
20
21
22
23
24
25


July: Ground NO₂ vs Satellite NO₂
1e−5
$R^2 = 0.689$
Satellite NO₂ Column Density (mol/cm²)
Ground-Level NO₂ (ppb)
8
6
4
2
3
4
5
6
7
8
9


August: Ground NO₂ vs Satellite NO₂
$R^2 = 0.007$
Satellite NO₂ Column Density (mol/cm²)
Ground-Level NO₂ (ppb)
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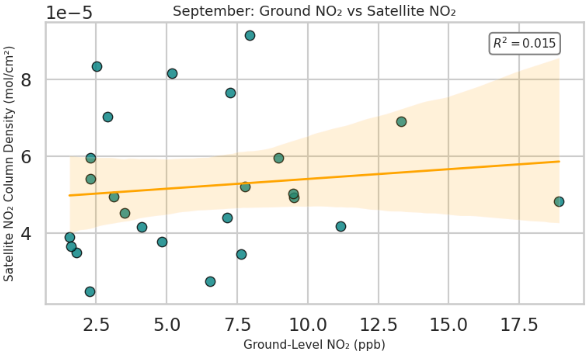
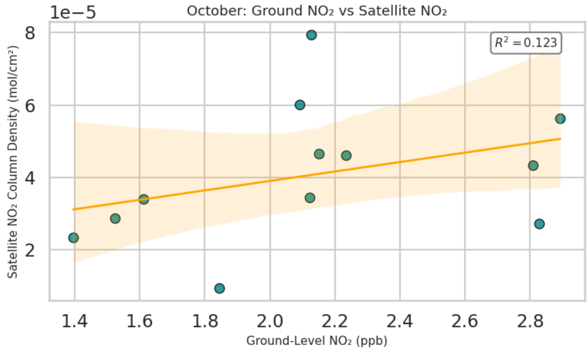
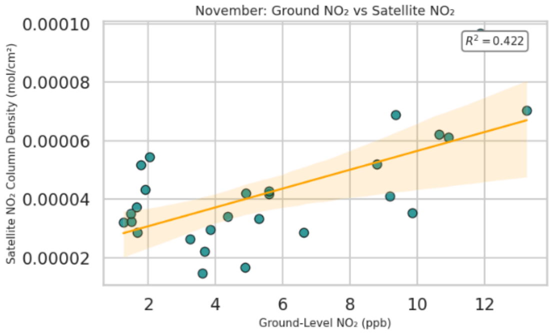
0.00008
0.00006
0.00004
0.00002
2
4
6
8
10
12


1e−5
September: Ground NO₂ vs Satellite NO₂
$R^2 = 0.015$
Satellite NO₂ Column Density (mol/cm²)
8
6
4
2.5
5.0
7.5
10.0
12.5
15.0
17.5
Ground-Level NO₂ (ppb)


1e−5
October: Ground NO₂ vs Satellite NO₂
$R^2 = 0.123$
Satellite NO₂ Column Density (mol/cm²)
8
6
4
2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
Ground-Level NO₂ (ppb)


November: Ground NO₂ vs Satellite NO₂
$R^2 = 0.422$
Satellite NO₂ Column Density (mol/cm²)
0.00010
0.00008
0.00006
0.00004
0.00002
2
4
6
8
10
12
Ground-Level NO₂ (ppb)

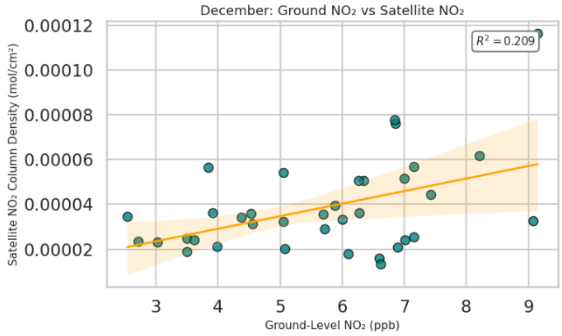

December: Ground NO₂ vs Satellite NO₂
$R^2 = 0.209$
Satellite NO₂ Column Density (mol/cm²)
0.00012
0.00010
0.00008
0.00006
0.00004
0.00002
3
4
5
6
7
8
9
Ground-Level NO₂ (ppb)

Figure 10: Ground-Level NO_2 vs Satellite NO_2 by Season (Nairobi, Kenya).

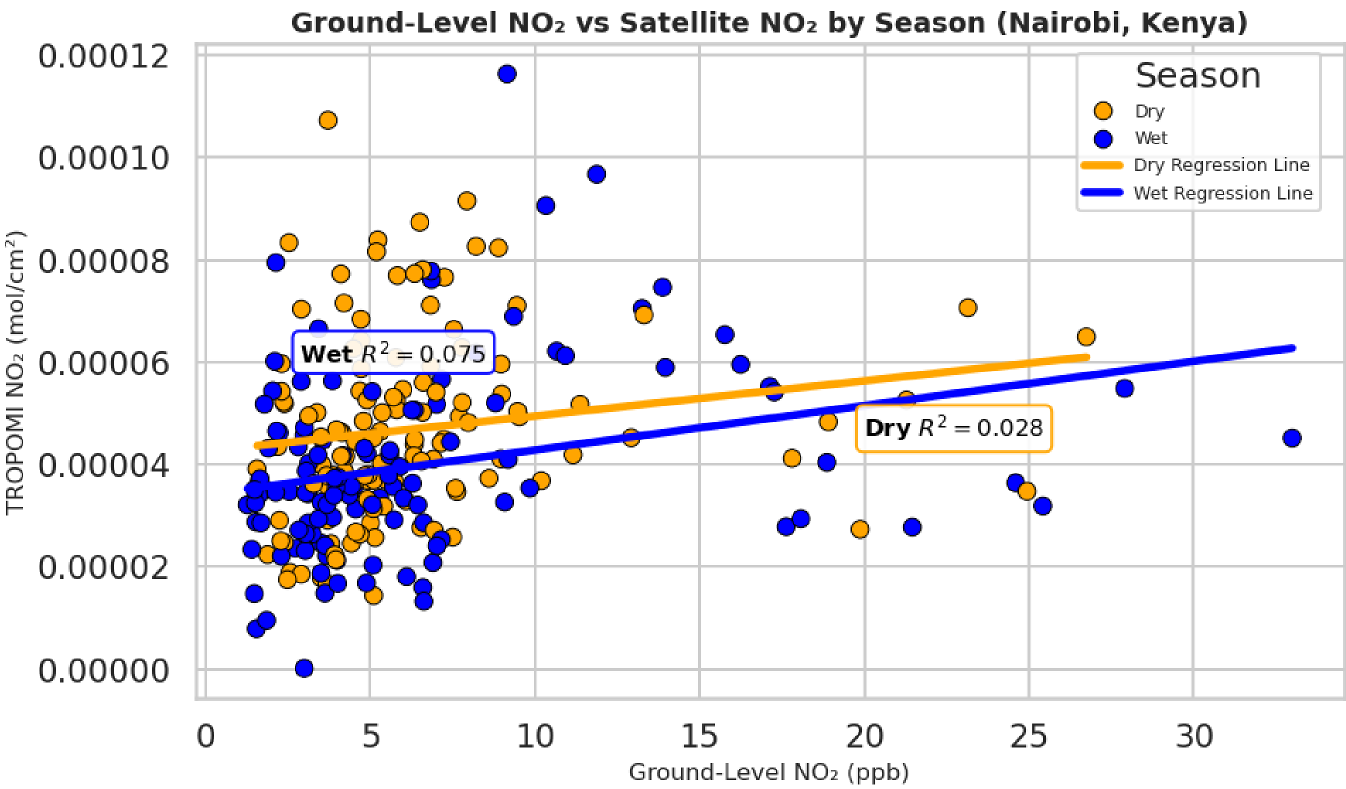


Figure 11: Diurnal nitrogen oxides concentrations.

Figure 12: Average Hourly BC6 Concentration.

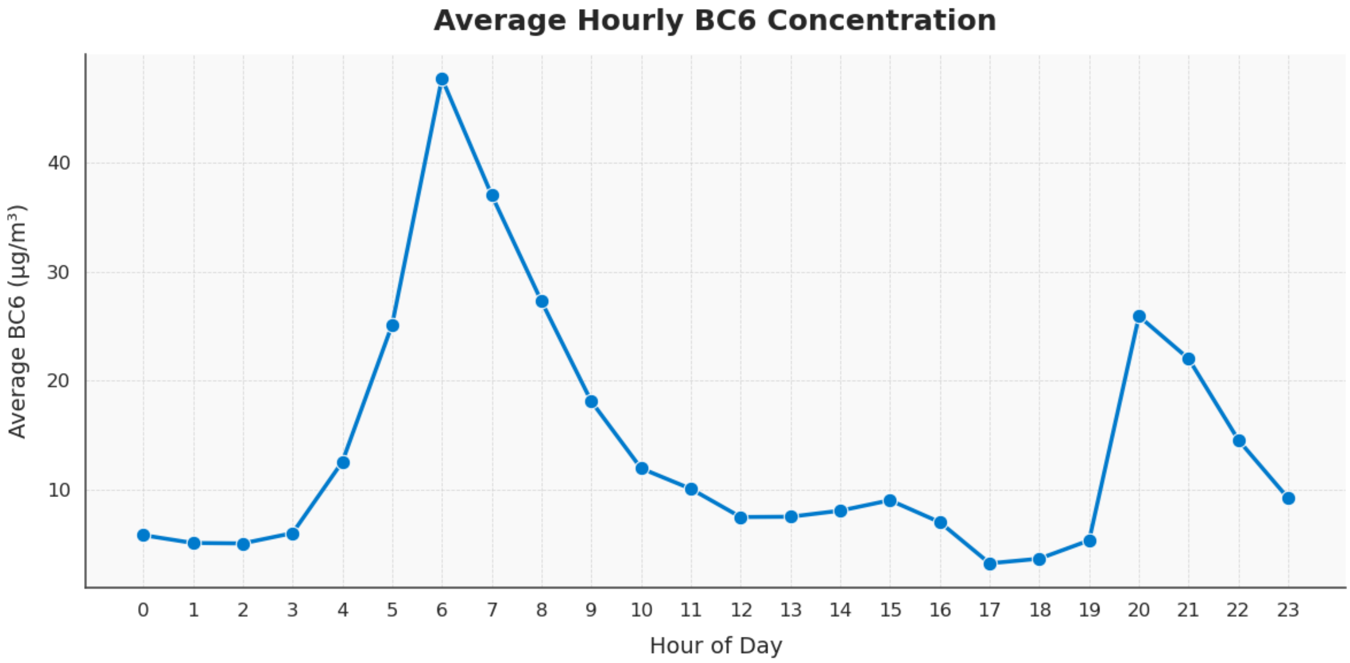


Figure 13: Average Hourly Wood Combustion Indicator.

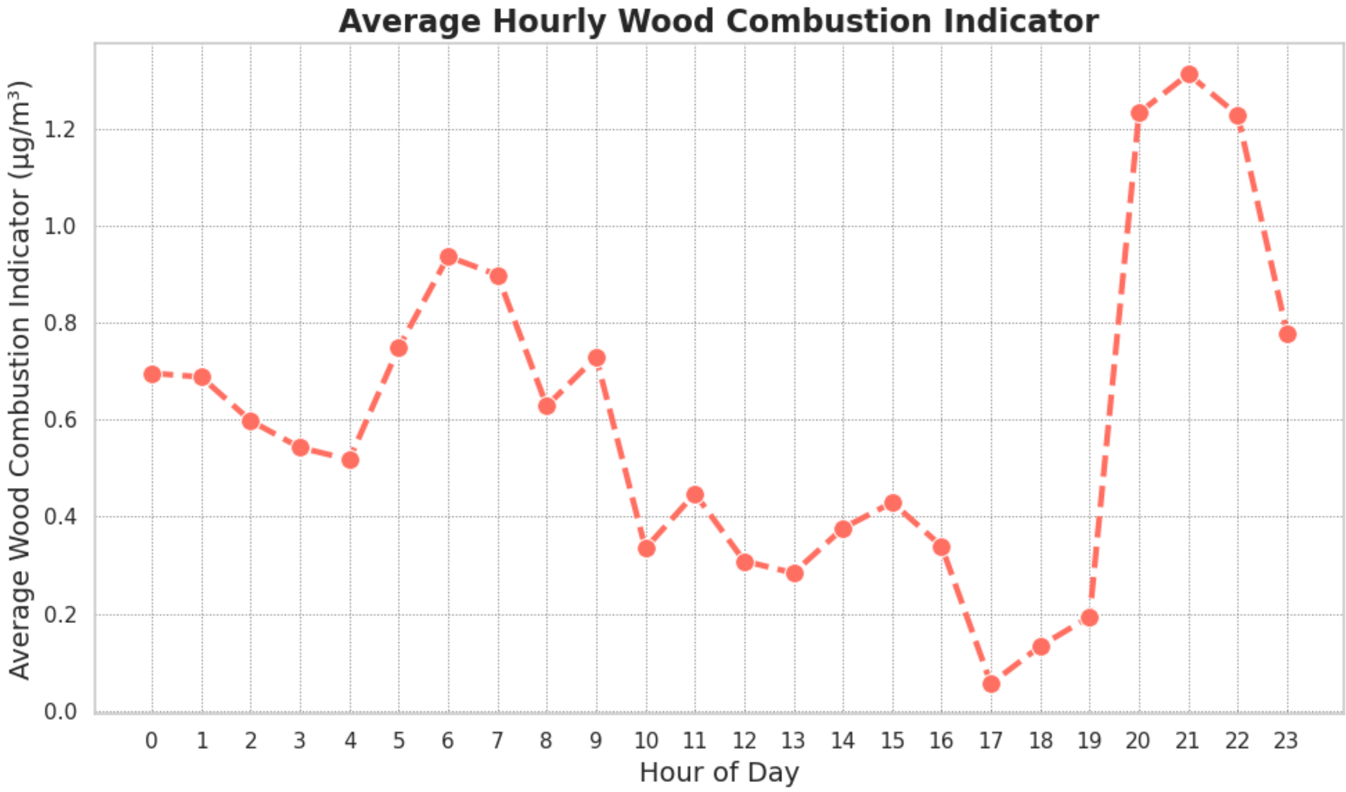


Figure 14: Hourly Diurnal Variation of BB (%).