

Multi-Sensor Satellite Data Assessment of Spatio-Temporal Dynamics of Air Pollution in Abuja FCT and Adjoining States in Nigeria

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Abstract

Nigeria's Federal Capital Territory (FCT) of Abuja has witnessed rapid urbanization, and this urbanization has significantly impacted the development of neighbouring states with the attendant increase in air pollution. This study presents a comprehensive multi-sensor satellite assessment of the spatiotemporal fluctuations of key pollutants—nitrogen oxides (NO_x), sulfur dioxides (SO₂), carbon (II) oxides (CO), methane (CH₄), ozone (O₃), and formaldehyde (HCHO), and the absorbing aerosol index (AI)—across Abuja and its neighbouring states (Nasarawa, Kogi, Niger, and Kaduna) from 2019 to 2024. Using satellite remote sensing data from Sentinel-5P/TROPOMI together with other atmospheric data, the temporal dynamics of pollutants and their connections to parameters such as ambient temperature, Normalized Difference Vegetation Index (NDVI), and precipitation have been investigated. NO₂ and HCHO were found to be increasing around Suleja, Abuja, and Lokoja, as SO₂ and CO were found to be decreasing, indicating an improved, efficient use of fuel and emission control. A positive correlation ($r = 0.62$) between precipitation and ozone was found, showing there is more convective transport and photochemical production during the rainy season. The effects of plants on the absorption of air pollution were shown through the negative correlations between NDVI, CO, and AI. Methane, on the other hand, moved from north to south in space, which was the same direction as changes in the intensity of farming. The findings show how unified policies, such as proper city planning, vegetation protection, and emission reduction, are important in sprawling urban areas for air pollution reduction.

Keywords: Air pollution, urban area, remote sensing, Sentinel-5P, TROPOMI

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Introduction

Rapid urbanization in sprawling cities of developing countries produces atmospheric pollutants that have debilitating effects on public health, the environment, and sustainable development [1]. General development across Nigerian cities has contributed to the increase in atmospheric pollutants by resulting in industrial waste products in the environment, along with biomass burning and increased human waste production. There is a growing epidemic of air, water, and soil pollution in the rapidly growing capital city of Nigeria, Abuja, due to enhanced industrial activities, increased construction activities, and ever-increasing vehicular traffic [2, 3]. Elevated environmental pollutants can lead to various health issues, such as respiratory problems and diseases carried by water bodies [4, 5].

The impacts of reduced air quality on human health in Nigeria are a well-documented phenomenon: studies in epidemiology, such as Omole *et al.* [6] and Liu *et al.* [7], have shown the strong associations between deteriorating air quality and elevated incidences of illnesses such as infections of the respiratory tract, chronic obstructive pulmonary disease (COPD),

asthma, and ischemic heart disease. The World Health Organization [8] has linked high urban pollution in cities like Abuja to increased mortality rates. Besides human health issues, the effects of elevated atmospheric pollution have been found to significantly affect the health of vegetation and the degradation of soils, thereby impacting agricultural output. Atmospheric pollution also affects how solar radiation reaches the Earth's surface, which negatively impacts both global and regional climates [9].

Ground-based instruments for the monitoring of the atmospheric pollutants are sparsely available with a minimal temporal resolution [10]; this makes the availability of satellite remote sensing platforms a more efficient and cost-effective way to monitor atmospheric pollutants over a large area with a very high temporal resolution [11, 12]. Sensors onboard satellites are capable of monitoring atmospheric pollutants such as formaldehyde, methane, ozone, nitrogen dioxide, sulfur dioxide, carbon (II) oxide, and aerosols, thereby providing essential data for use in assessments of the environmental impacts of air pollutants [13, 14].

Investigations of air pollution in African cities have been demonstrated in recent studies; for instance, Omokpariola *et al.* [15] used Sentinel-5P and 3A/B offline datasets to study pollutant concentrations across Nigeria, linking them to atmospheric parameters such as temperature. Timofeev and Neroblov [8] highlight the importance of satellite data for assessing the atmospheric composition of the globe, emphasizing its application in developing regions where *in situ* observation data might be scarce. Research on atmospheric pollution in Abuja, given its rapid urbanization and political importance, remains inadequate.

In this study, we aim to investigate the dynamics of pollutants in and around the Nigerian capital city of Abuja and relate the temporal variation to some atmospheric variables.

Materials and Methods

Study area

The study area is within the central region of Nigeria, bounded by latitude 6.0 °N and 12.0 °N as well as longitude 3.0 °E and 9.5 °E, as shown in Fig. 1. The area includes the Federal Capital Territory of Abuja, Kogi State, Nasarawa State, Niger State, and Kaduna State, with the focus on Abuja Central District, being the seat of the Nigerian government. The study area spans ~70,000 km² with a climate of tropical savannah characterized by a distinct wet season in the months of May to October and a dry season in the months of November to April. There is a period of heavy dust influx from the Sahara Desert known as the harmattan period within the months of November, December, and January [16]. The seasonality of rainfall and temperature strongly influences the atmospheric chemistry and the dispersion of pollutants in this area.

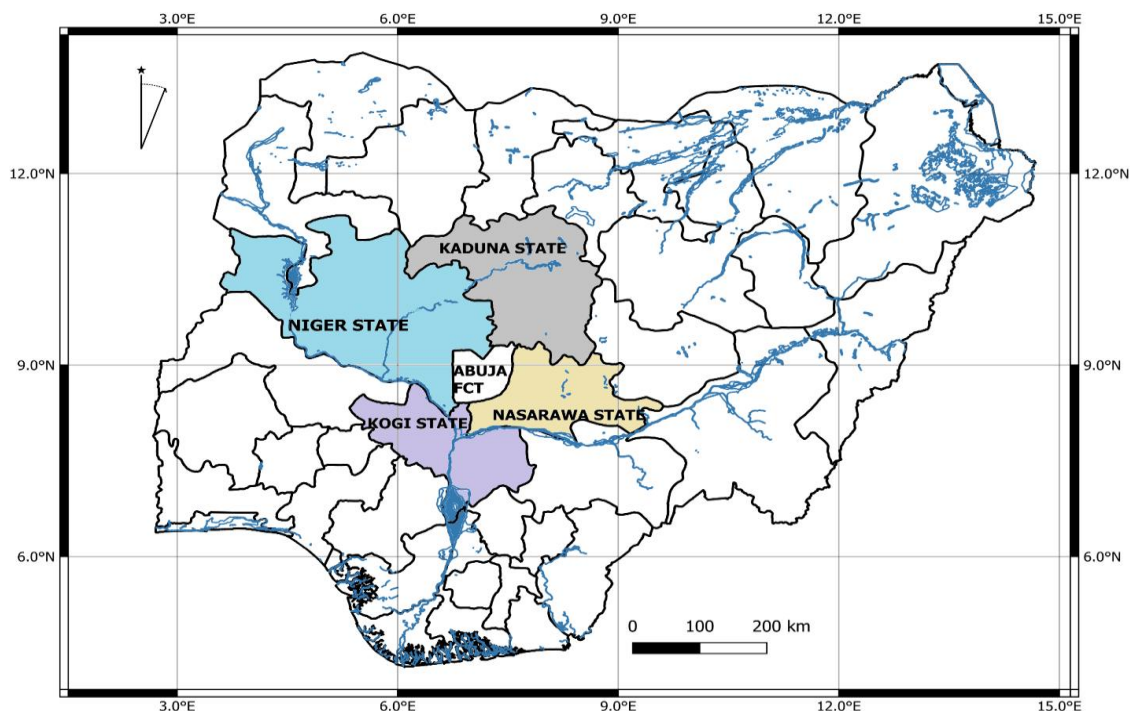


Figure 1: Map of the study area in Nigeria

Data sources and processing

Pollutant data were obtained from the Google Earth Engine platform hosting Sentinel-5 Precursor air quality products provided by Copernicus Atmosphere Monitoring Service (CAMS), using a TROPOMI instrument, which employs a multispectral sensor to record wavelength reflectance to infer the values of pollutants in the earth's troposphere, including clouds, at a resolution of 0.01°.

Temperature data were obtained from the ERA5-Land Reanalysis provided by the Copernicus Climate Data Store through the GEE. ERA5-Land temperature data is a 2-meter, 9 km resolution [17]. Precipitation data were obtained from the Climate Hazards Center InfraRed Precipitation with Station data (CHIRPS), through the GEE, at a resolution of 0.05° [18]. Normalized

Difference Vegetation Index (NDVI) was calculated from the Landsat 8 images, courtesy of the U.S. Geological Survey through the GEE, using Equation 1,

$$NDVI = \frac{(SR_{B5}) - (SR_{B4})}{(SR_{B5}) + (SR_{B4})} \quad 1$$

where SR_B4 is the red band and SR_B5 is the near-infrared band.

Mapping of spatial distribution was completed for consistent colour scales using the QGIS platform, while the time-series plots and correlation heatmaps were developed in Python using pandas, matplotlib, and numpy with transparency of axes/ticks for interpretability.

Results and Discussion

Nitrogen oxides (NO_x)

Anthropogenic activities such as fossil fuel (with a large amount from vehicular traffic and industrial activities) and biomass burning/combustion, together with natural processes such as lightning, wildfires, microbial processes in soils, etc., produce atmospheric nitrogen oxides (NO_x), which is used to represent a combination of nitrogen (IV) oxide (NO₂) and nitrogen (II) oxide (NO). Bacterial activities in the soil produce atmospheric dinitrogen monoxide (NO); this then travels to the upper atmosphere and stratosphere, where atomic oxygen, a result of ozone dissociation, reacts with it to form NO [19]:



The nitrogen (II) oxide is then further reacted with ozone to form nitrogen (IV) oxide and molecular oxygen [19].

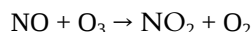


Figure 2 shows the distribution of atmospheric nitrogen dioxide across Abuja FCT and the four adjoining states. Fig. 2 displays the capital cities and a major city for each state. Major cities such as Suleja in Niger State and Masaka in Nasarawa are very close to and at the boundary with the FCT; hence, air quality in these places could affect the air quality in the FCT. The unit of measurement is mol/m^2 , and on Fig. 2, this value ranges from 4.49 to $72.9 \text{ mol}/\text{m}^2$ across the region within the two years shown (2019 and 2024). The spatial spread of nitrogen dioxides shows an increase in 2024 compared to 2019.

Urbanization, with its attendant high vehicular emissions coupled with fossil fuel combustion and industrial activity effects on the atmospheric concentration of NO_x, can be seen in Fig. 2, with urban areas such as Abuja Central, Kaduna, Suleja, and Masaka, and also industrial locations such as Obajana, which hosts a major cement manufacturing industry, showing elevated NO_x concentration levels. It is important to note that cities like Lafia, Lokoja, and Keffi, despite being capital cities with significant sprawl, have very little industrial activity and a much smaller human population compared to Abuja, Suleja, or Kaduna.

From Fig. 2, it can be observed that only Suleja and Masaka may have interaction and influence on the NO_x pollution in Abuja, with a stronger influence observed to be from Masaka and its environs.

The maps from 2019 and 2024 reveal an increase in NO_x atmospheric concentration, particularly in Kaduna State. Although slight increments are observed in other states, these increases align with findings from studies in Nigeria, including those by AbdulRaheem *et al.* [20] and Oluleye [21], and reflect the ongoing urbanization and industrialization trends in the country.

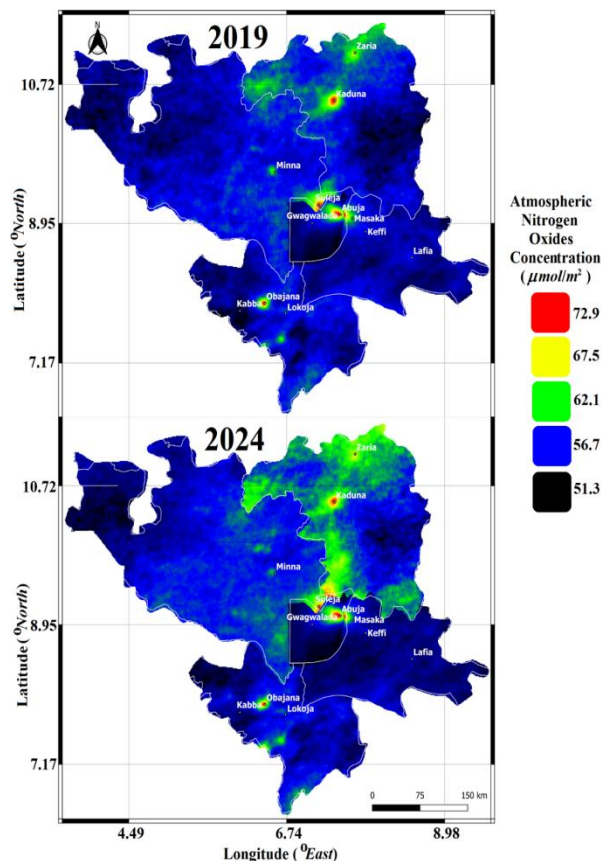


Figure 2: Spatio-temporal distribution of nitrogen oxides (NO_x) in Abuja FCT and adjoining states for the years 2019 and 2024

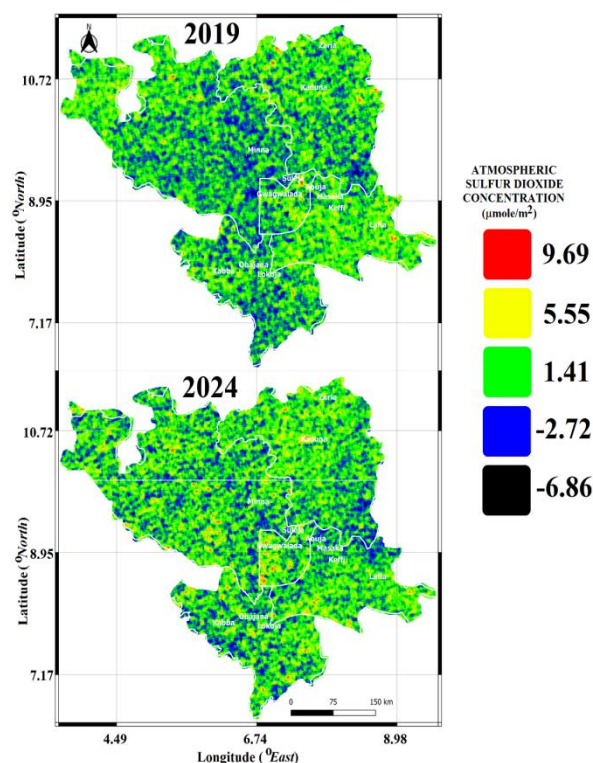


Figure 3: Spatio-temporal distribution of sulfur oxide (SO₂) in Abuja FCT and adjoining states for the years 2019 and 2024



Sulfur dioxide (SO₂)

There are both natural and man-made sources of sulfur dioxide (SO₂) in the air. The main natural source of SO₂ is when hydrogen sulfide (H₂S) is oxidized in geothermal activities and when volcanoes erupt. Anthropogenic sources of sulfur dioxide in the atmosphere include emissions from cars, factories, power plants, and the burning of fossil fuels like coal and oil. In Nigeria, especially in the oil-producing regions in the south, gas flaring contributes significantly to the atmospheric sulfur dioxide pollution [22, 23].

Atmospheric SO₂ pollution can cause serious damage to the soil and water bodies through the formation of acid rain, which results when SO₂ reacts with atmospheric oxygen and water vapor. Contamination of soil and water bodies in this manner will have serious negative effects on the aquatic ecosystem as well as cause damage to plants by interfering with the photosynthesis process. Inhalation of SO₂ can cause respiratory discomfort, including coughing, breathing difficulties, and a sore throat; prolonged exposure may lead to cardiovascular diseases and throat infections.

Figure 3 shows the spatial distribution of SO₂ (in $\mu\text{mol}/\text{m}^2$) for the years 2019 and 2024 across the region of interest. The values shown are characteristics of satellite UV products, such as those of TROPOMI; the bias correction often leads to negative values that should be interpreted as “near-zero background” instead of actual negative values [24].

In 2019, the background atmospheric sulfur dioxide levels were predominantly low (indicated by greens to blues), with scattered localized enhancements (shown by yellow to red) occurring near urban and industrial corridors, including areas around Abuja, the AMAC/Gwagwalada axis, the Keffi-Lafia corridor in Nasarawa State, certain locations around Minna in Niger State, and parts of southern Kaduna State. The spotty sulfur dioxide enhancements, as observed, can be attributed to vehicular traffic and small-scale industrial sources, coupled with energy usage in urban centres, instead of a single dominant source.

The pattern of sulfur dioxide distribution does not differ appreciably in 2024, save for some mild reduction in the spatial extent of high concentration centers around the FCT Central and the Keffi-Lafia corridor, with some more background distribution of sulfur dioxide. High concentrations of sulfur dioxide in some localized areas around major roads and settlement clusters are a typical sign of short-lived bursts in sulfur dioxide, resulting from biomass combustion and small industries. The observed subtle yearly variation in sulfur dioxide is in agreement with the recent report of marginal changes in sulfur dioxide between 2018 and 2022, with an observed dip during the COVID-19 period and subsequent rebounds [25, 26].

Formaldehyde (HCHO)

In the troposphere, one of the low-lifetime volatile organic compounds (VOC) is formaldehyde. The primary source of formaldehyde in the atmosphere is

vehicular traffic, industrial emissions, and emissions from the burning of biomass. Formaldehyde is also an oxidation byproduct of hydrocarbons such as isoprene. The spatial distribution and temporal dynamics of formaldehyde are critical sources of data on regional air pollution, photochemistry, and potential for ozone formation [27].

Figure 4 depicts the atmospheric concentration of formaldehyde in Abuja FCT, Nasarawa State, Kogi State, Niger State, and Kaduna State, with values ranging from $266.9 \mu\text{mol}/\text{m}^2$ to $155.9 \mu\text{mol}/\text{m}^2$. It can be observed that in 2019, urban fringe settlements around Abuja, such as Gwagwalada, Suleja, Masaka, and Keffi, show some elevated levels of atmospheric formaldehyde; this elevated level, which exceeds $239 \mu\text{mol}/\text{m}^2$, can also be observed around parts of Kabba and Lokoja in Kogi State. These observed values are consistent with the association of atmospheric formaldehyde with enhanced emissions from high traffic density, the burning of biomass in urban settings, and varied domestic energy usage. Moderate atmospheric levels of formaldehyde of about $211 \mu\text{mol}/\text{m}^2$ can be observed around Minna in Niger State and southern Kaduna in Kaduna State, indicating a combination of anthropogenic sources from urban areas and natural emissions of volatile organic compounds (VOCs). Conversely, northern Kaduna in Kaduna State and remote rural areas have lower atmospheric formaldehyde levels of between 156 and $184 \mu\text{mol}/\text{m}^2$. This pattern demonstrates that human activities and vegetation, the source of isoprene emissions, influence atmospheric formaldehyde levels [28].

Moving to the year 2024, it could be observed that there is a similarity in the spatial distribution of atmospheric formaldehyde in the study area, with Abuja and its environment together with areas along the Lokoja corridor, showing some lingering hotspots. Notwithstanding, the high concentration regions of atmospheric formaldehyde can be observed to have increased, in particular, regions southward towards Lokoja as well as eastward into Nasarawa. Enhanced levels of atmospheric formaldehyde persist in the urban sprawl centered on Abuja, emphasizing the dependence of urbanization, household energy consumption, and increases in vehicular activities. On the other hand, in 2024, places such as Kaduna and Zaria, in the northern region, show some reductions in atmospheric formaldehyde, which can be linked to clean energy and its effect on pollution dispersion.

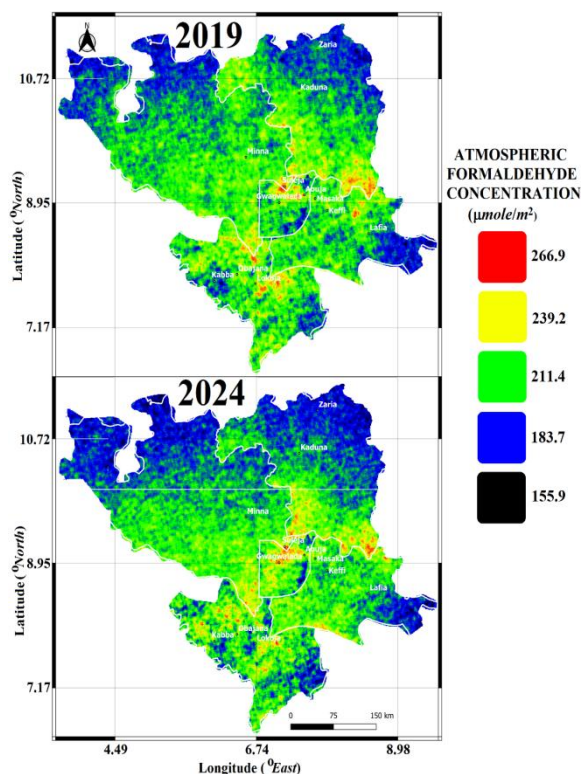


Figure 4: Spatio-temporal distribution of formaldehyde (HCHO) in Abuja FCT and adjoining states for the years 2019 and 2024

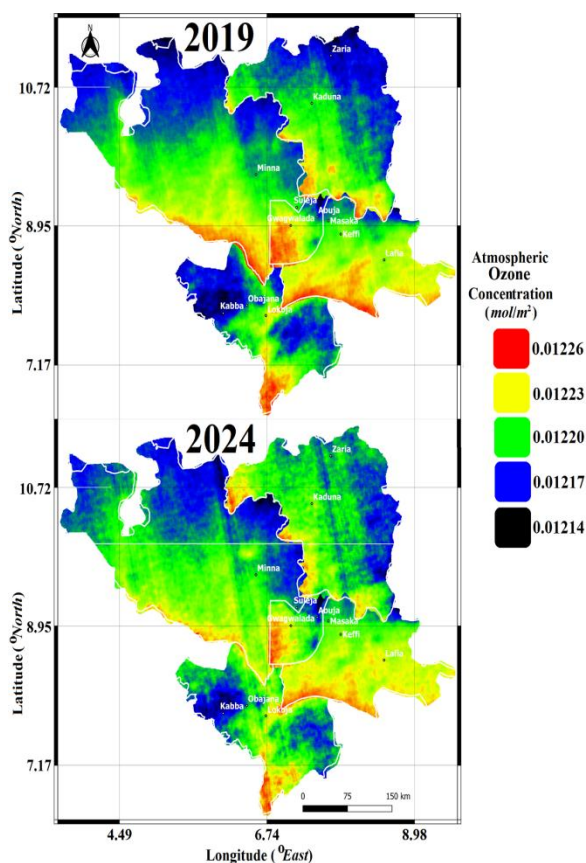


Figure 5: Spatio-temporal distribution of ozone (O₃) in Abuja FCT and adjoining states for the years 2019 and 2024

Ozone (O₃)

Ozone in the troposphere arises from the photo-induced chemical oxidation of a class of volatile organic compounds, for instance, formaldehyde; this reaction is usually in the presence of nitrogen oxides. Atmospheric circulations together with solar radiation greatly influenced the atmospheric distribution of ozone, with about 90% of the atmospheric ozone residing in the stratosphere at about 15 to 30 km above the earth's surface, in a zone called the ozone layer [29].

Figure 5 shows the distribution of atmospheric ozone (in units of mol/m^3) across Abuja FCT and the neighbouring states of Nasarawa, Kogi, Niger, and Kaduna for the years 2019 and 2024; the concentration of ozone could be observed to range from 0.01226 mol/m^3 to about 0.01214 mol/m^3 . For the year 2019, an enhanced level of ozone concentration of around 0.01226 mol/m^3 could be observed at the southern fringe of the map, especially around Lokoja and Obajana, stretching to the suburban area of Abuja. This high ozone level area corresponds to the geographic area with a high level of atmospheric formaldehyde observed for 2019, showing that volatile organic compounds strongly drive the formation of ozone in urban and industrial areas. Abuja Central, which has heavy vehicular traffic and nitrogen oxide combustion emission sources, shows atmospheric ozone levels that are between moderate and high levels. Kaduna and Zaria, in Kaduna state, as well as northern Niger state, display a contrasting lower atmospheric ozone level of between 0.01214 mol/m^3 and 0.01217 mol/m^3 ; this range again corresponds to regions of lower formaldehyde in 2019, indicating low-level anthropogenic emissions in this region.

There is a subtle shift in atmospheric ozone by the year 2024 within the study area; localized and constantly higher values of ozone can be observed around the southern part of Nasarawa State (along the bank of the River Benue), the eastern part of Abuja FCT, and the southern part of Kogi State. Nevertheless, moderate ozone levels can be observed in the northern part of Niger State, the eastern part of Kaduna State, and the western part of Kogi State, indicating a slight decline in regional atmospheric ozone levels. The decline in ozone aligns with the observed decrease in formaldehyde from 2019 to 2024, indicating that reductions in volatile organic compound precursors directly impact the variability of atmospheric ozone. However, the consistently high levels of atmospheric ozone observed around Abuja indicate that rapid urban growth and the resulting high energy demand contribute to the formation of photochemical smog.

Carbon (II) oxide (CO)

Carbon (II) oxide (CO), which is a primary atmospheric pollutant, is a by-product of fossil fuels' incomplete combustion; it is also emitted from the burning of biomass and from domestic burnings. Carbon (II) oxide is a notable hazardous pollutant that adversely affects human health and indirectly contributes to climate warming; it alters hydroxyl radical (OH) reactivity and



facilitates the development of secondary pollutants by serving as a precursor in tropospheric photochemistry [30]. Fig. 6 shows the atmospheric concentration of carbon (II) oxide across Abuja FCT, Nasarawa State, Kogi State, Kaduna State, and Niger State for the years 2019 and 2024, with a range of 52.3 mmol/m^2 to a lower value of about 43.3 mmol/m^2 .

In 2019, around Abuja Central, Obajana, Gwagwalada, Lokoja, and Suleja, atmospheric CO exceeds 50 mmol/m^2 , forming hotspots around these places. These places, particularly Obajana with its cement manufacturing industry, exhibit high vehicular traffic and industrial activity. Additionally, extensive use of fuel-burning electricity-generating systems can be observed in these areas. Moderate carbon (II) oxide of around 47.8 mmol/m^2 and 50.0 mmol/m^2 can be observed around Lafia in Nasarawa State, Kaduna in Kaduna State, and Minna in Niger State, while lower concentrations of around 43.3 mmol/m^2 and 45.6 mmol/m^2 could be observed around Kabba in Kogi State and the northern parts of Kaduna and Niger States.

By the year 2024, the constant hotspots will still be present in areas such as Abuja Central, Obajana, and Lokoja; however, there will be a slight reduction in their spatial extent, indicating a minor improvement in air quality within the study area. Additionally, areas such as Zaria and Kaduna town in northern Kaduna State, the northern part of Niger State, Kabba in Kogi State, and the eastern region of Kogi State are observed to maintain low levels of atmospheric carbon (II) oxide (CO). This observation suggests a slight improvement in air quality in the study area and perhaps increased pollution dispersion aided by weather activities.

Figures 3 and 6, for sulfur dioxide and carbon (II) oxide, respectively, demonstrate correspondence between atmospheric SO_2 and atmospheric CO within and around Abuja and Lokoja, indicating similar sources, for instance, emissions from industries, vehicular traffic, and domestic. However, isolated spikes in atmospheric SO_2 are observed in Nasarawa and Niger states, which are characterized by specific industrial emissions, while the distribution of CO is more widespread due to biomass burning and vehicular traffic [31]. There is an observed strong similarity between the distribution of CO and formaldehyde (HCHO), as can be seen in Figs 3 and 4; some spikes in Abuja and Lokoja indicate these pollutants are from volatile organic compounds and incomplete combustion emissions. The CO is known to be long-lived in the atmosphere and hence can disperse more widely, whereas HCHO, being a product of anthropogenic VOCs and local oxidation of biogenic sources, shows sharper hotspots [32]. Formation of ozone is closely linked to CO and HCHO, being a carbon precursor with the influence of solar radiation [29], and these patterns can be observed in Figs 3, 4, and 5. Since nitrogen oxides and meteorological conditions also influence atmospheric ozone, we can observe a wider spatial distribution of ozone.

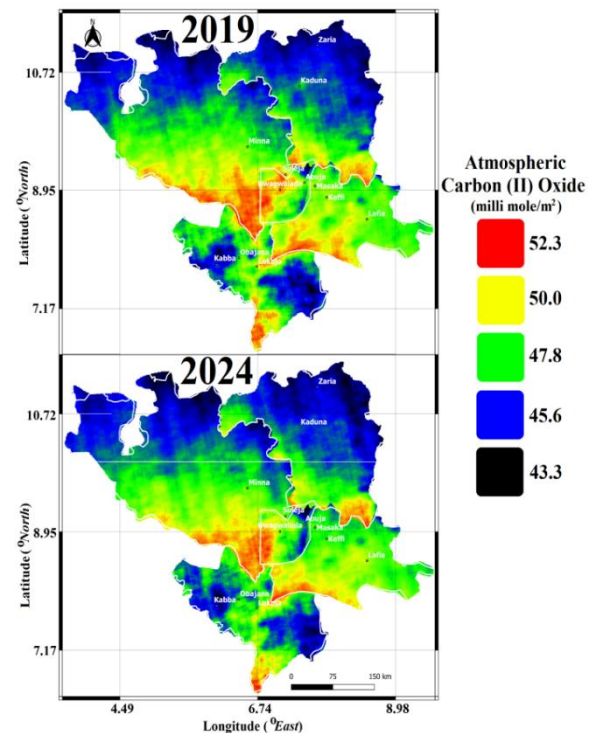


Figure 6: Spatio-temporal distribution of carbon(II) oxide (CO) in Abuja FCT and adjoining states for the years 2019 and 2024

Methane (CH_4)

Methane has a significant impact on the earth's climate, ranking very close to CO_2 on the global climate over a short period of time and ranking higher than CO_2 over a longer period of more than 100 years [33]. Aside from being a greenhouse gas, CH_4 functions as a secondary atmospheric pollutant by acting as a precursor to the formation of tropospheric ozone consequent upon photochemical oxidation and hence impacts human health, crop yields, and vegetation health. Methane is also a significant contributor to Earth's radiative forcing due to its strong absorption in the infrared spectrum band [34].

Methane spatial distribution across the study area for the years 2019 and 2024 is shown in Fig. 7 with a scale ranging from 1959.9 ppb to around 1922.2 ppb . Methane values exceeding 1950 ppb are observed to predominate in the northern part of the study area, especially around the towns of Kaduna and Zaria in Kaduna State in 2019. These elevated methane zones are associated with methane emissions from agricultural activities such as livestock rearing and rice farming; burning of waste can also be observed in these regions. Areas close to Abuja Central, such as Suleja, Gwagwalada, Keffi, and Masaka, can be observed to show moderately high levels of atmospheric methane of around 1945–1950 ppb due to vehicular traffic and industries. On the other hand, a relatively low atmospheric methane level of about 1925–1935 ppb can be observed around Minna and southern Kogi State, showing these areas to have less human-induced methane emission.

By 2024, we can observe a slight shift in the spatial distribution of atmospheric methane. Places such as Abuja Central, Lokoja in Kogi State, and Lafia in Nasarawa State are now showing higher levels of atmospheric methane of around 1945 to 1955 ppb. Meanwhile, the northern regions of Kaduna State, particularly around Kaduna and Zaria, are currently experiencing a moderate reduction in methane levels. The observed spatial methane redistribution suggests dynamism of the sources of methane emission; for instance, the human population is growing in Abuja and Kogi State, leading to more waste production and burning, while there is a stabilization in methane production due to agricultural practices in Kaduna State. The Lokoja-Obajana axis is observed to be increasing in methane emissions due to more industrial emissions and greater agricultural activities. According to the work of Parker *et al.* [35], there is agreement between the observed methane concentration over Abuja and that observed over West Africa, with an average atmospheric Methane level range from approximately 1900 to 2000 ppb, exhibiting seasonal variations due to biomass burning and agricultural activities. The methane levels recorded for Ghana and Cote d'Ivoire, which are significantly influenced by rice farming and waste combustion [36], closely resemble those found in this study.

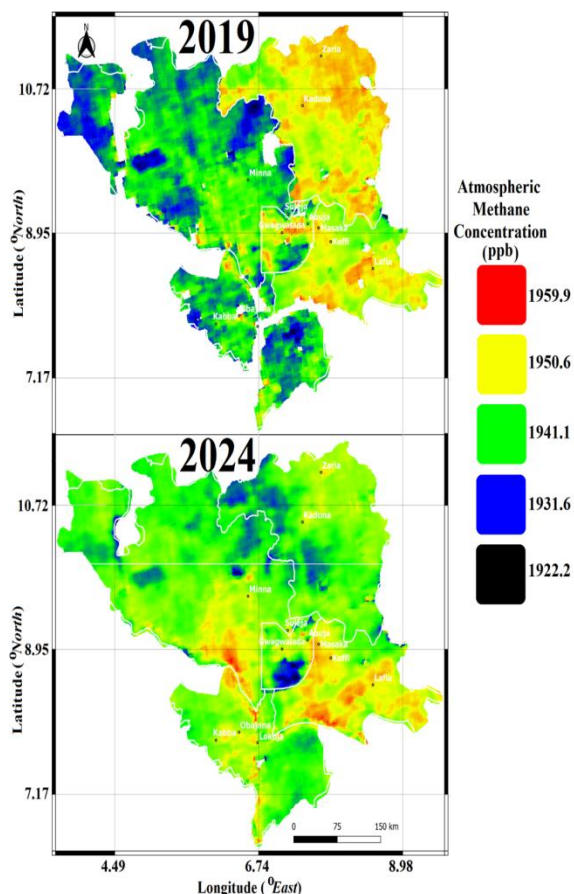


Figure 7: Spatio-temporal distribution of methane (CH_4) in Abuja FCT and adjoining states for the years 2019 and 2024

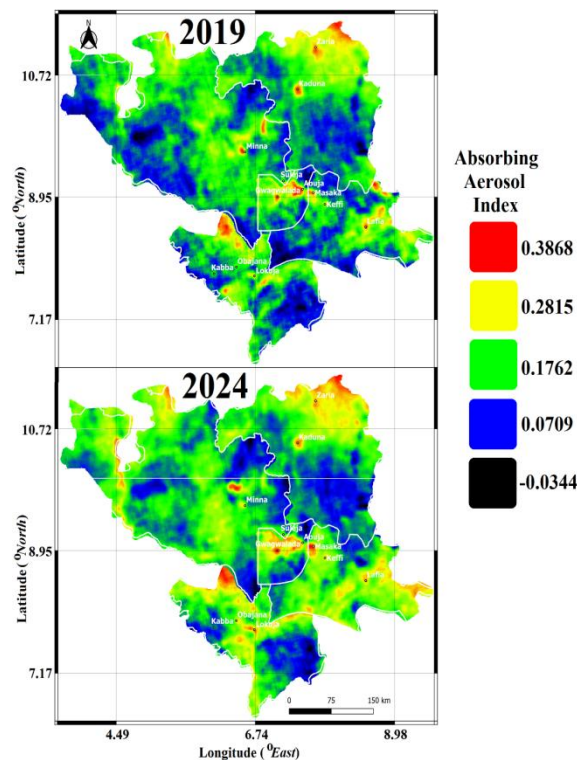


Figure 8: Spatio-temporal distribution of the aerosol index in Abuja FCT and adjoining states for the years 2019 and 2024

Aerosol index (AI)

The absorbing aerosol index (AAI or AI) is based on wavelength-dependent changes in Rayleigh scattering in the ultraviolet (UV) spectral range for a pair of wavelengths. The positive value indicates dust and smoke and is suitable for tracking episodes of aerosol plumes from dust outbreaks, carbon black, mineral dust, volcanic ash, and biomass burning, while the negative value indicates non-absorbing aerosols, such as sulfate aerosols [37, 38].

Figure 8 shows the spatial distribution of aerosol load deduced from aerosol index for the years 2019 and 2024 over the study area. For the year 2019, places such as Abuja, Minna, Zaria, and Kabba show localized enhanced aerosol index values of around 0.28 to about 0.39, indicating possible sources from industrial emissions, widespread biomass burning, and transport of dust from the Sahara Desert. The aerosol index along the Abuja-Suleja-Gwagwalada corridor reflects the effects of urbanization, including heavy vehicular traffic and waste burning.

A slight increase in the aerosol index at the hotspots can be observed in the year 2024, with places like Zaria, Abuja, Suleja, Masaka, and Lokoja observed to retain high values of aerosol index. Regions along the major rivers of Niger and Benue can be observed to have increased aerosol index in 2024, probably due to increased agricultural activities along the riverbanks and increased biomass burning. We can also observe increased urbanization and anthropogenic emissions as a result of the increased atmospheric aerosol load.



Correlation structure of pollutants and meteorological drivers

Figure 9 is a statistical correlation heat map for the pollutants, ambient temperature, precipitation, and normalized differential vegetation index (NDVI) for Abuja Central Zone, Masaka, Gwagwalada, and Suleja. The Pearson correlation coefficient is used to offer additional details about the dynamics of the pollutants along with the meteorological and environmental variables. The interactions between pollution emission sources, atmospheric chemical processes, and meteorological dynamics and their influence on the spaces above Abuja FCT and its suburban environment can be observed in the correlational pattern in Fig. 9.

In Abuja Central and the adjoining suburban towns surrounding it, it can be observed that the correlation between nitrogen dioxides and sulfur dioxide shows the highest positive correlation of 0.68 in Gwagwalada, 0.73 in Abuja, 0.57 in Masaka, and 0.71 in Suleja, as summarized in Table 1. In these places, the dominant pollutant sources are the burning of biomass and fossil fuels, as well as industrial activities and vehicular traffic. This finding is in agreement with the results of Fioletov *et al.* [24] and Fioletov *et al.* [39], which were done in Lagos and other African megacities and showed the unified anthropogenic sources of nitrogen oxides and sulfur dioxide.

On the other hand, moderately high negative correlations can be observed between both carbon (II) oxide and sulfur dioxide with precipitation, showing the efficiency of rainfall in wet deposition of the pollutants and cleansing of the atmosphere. The work of Krotkov

et al. [40] supports this finding by illustrating the correlation between rainfall and air quality dynamics in West Africa.

The role of vegetation in sinking pollutants can be observed in the normalized difference vegetation index (NDVI) correlations with the pollutants, most importantly, the aerosol and carbon (II) oxide; this result shows how the vegetation can act as regulators of pollutants and modifiers of the planetary boundary layer.

The correlational results, indicating the strongest positive and negative correlations, are given in Table 1.

Table 1: Strongest positive and negative Pearson correlations (2019–2024)

City	Strongest Positive Correlations	r-value	Strongest Positive Correlations	r-value
Abuja	NO ₂ – SO ₂	0.73	O ₃ – Precipitation	–0.64
	NO ₂ – CO	0.58	CO – NDVI	–0.52
	O ₃ – HCHO	0.62	Aerosol – NDVI	–0.48
Gwagwalada	NO ₂ – SO ₂	0.68	SO ₂ – Precipitation	–0.52
	NO ₂ – CO	0.55	CO – Precipitation	–0.47
	O ₃ – Temp	0.39	Aerosol – NDVI	–0.45
Masaka	CO – SO ₂	0.62	CO – Precipitation	–0.49
	NO ₂ – SO ₂	0.57	Aerosol – NDVI	–0.44
	O ₃ – HCHO	0.41	SO ₂ – Precipitation	–0.42
Suleja	NO ₂ – SO ₂	0.71	CO – Precipitation	–0.52
	NO ₂ – O ₃	0.48	SO ₂ – NDVI	–0.49
	CO – SO ₂	0.46	Aerosol – NDVI	–0.47

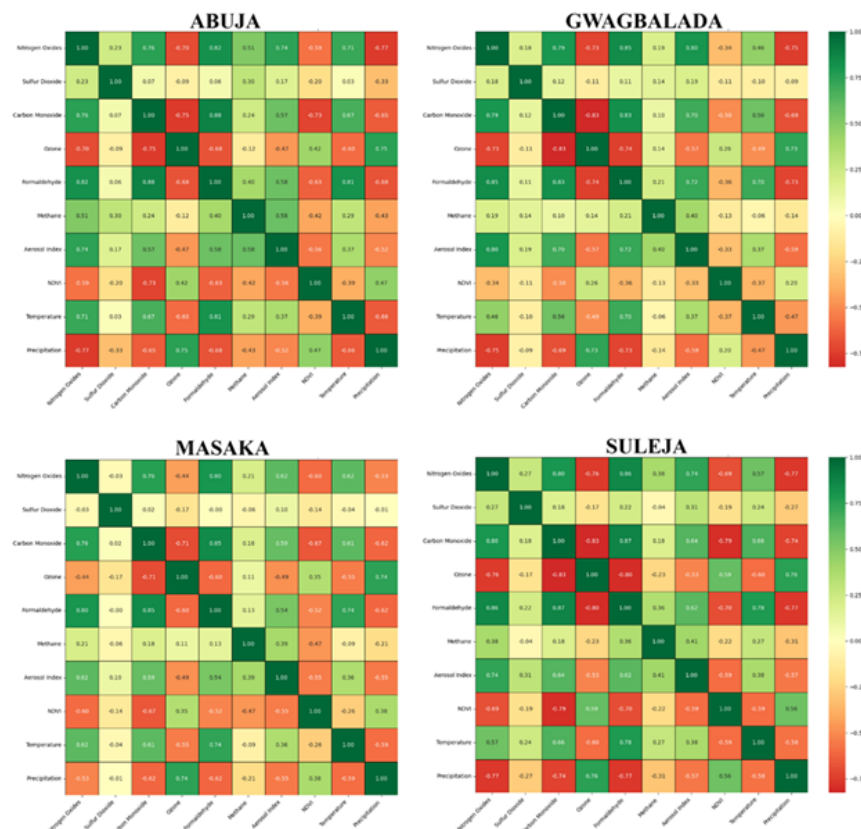


Figure 9: Pearson correlation coefficients between the pollutants, as well as other variables

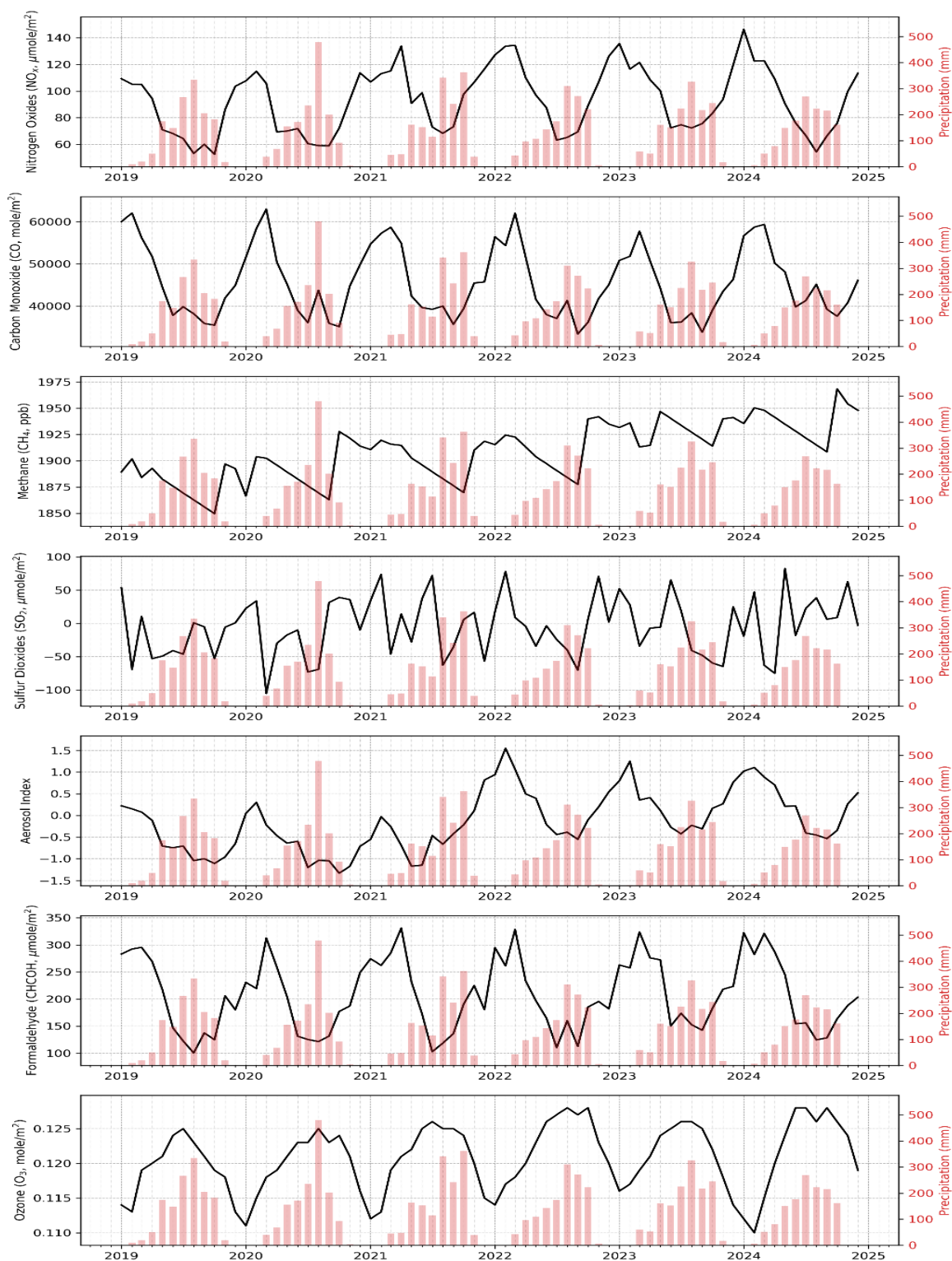


Figure 10: Time series visualization of the pollutants and precipitation in Abuja

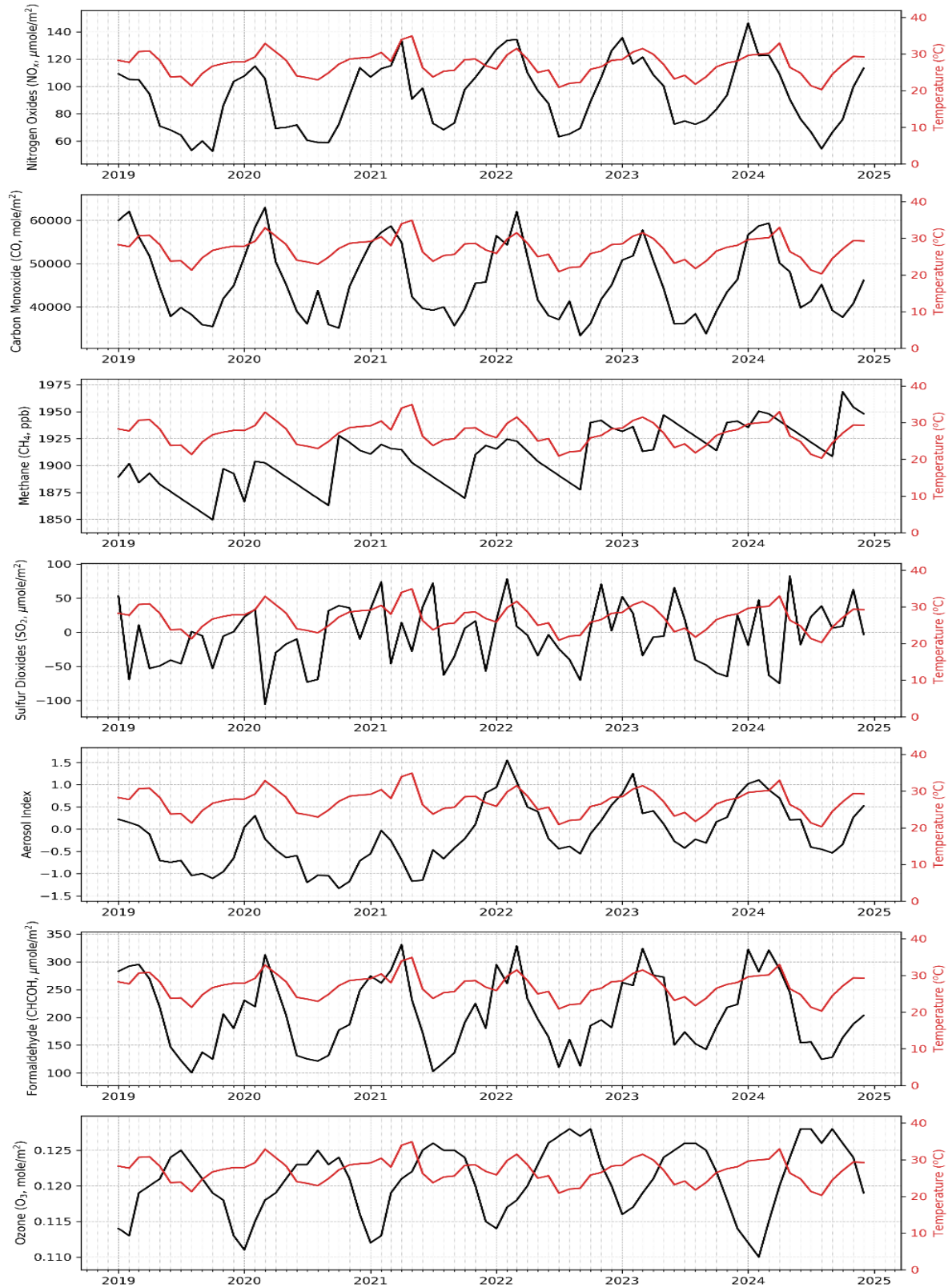


Figure 11: Time series visualization of the pollutants and ambient temperature in Abuja

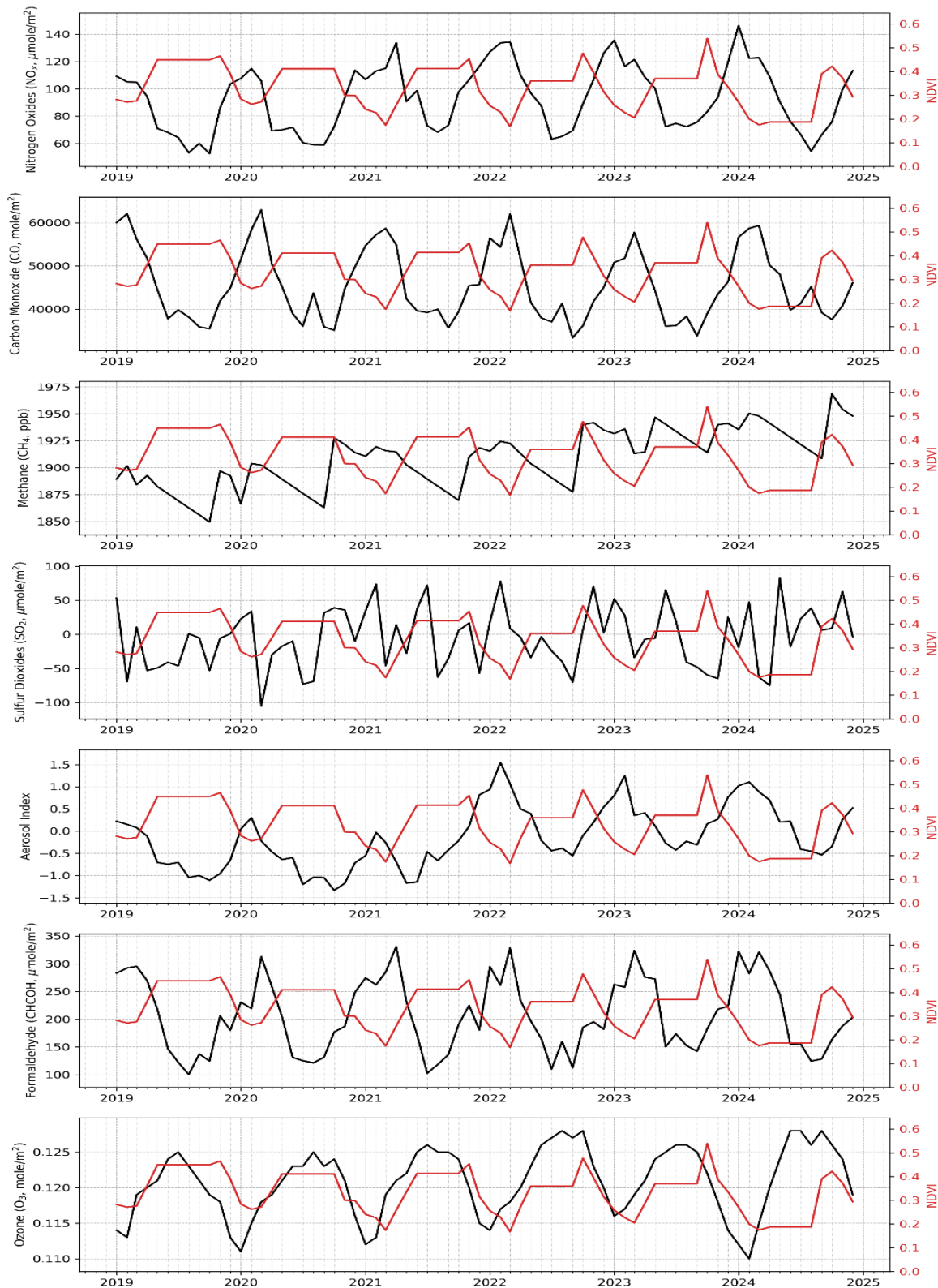


Figure 12: Time series visualization of the pollutants and normalized difference vegetation index (NDVI) in Abuja

Temporal evolution of pollutants and the role of precipitation, ambient temperature and vegetation

Figures 10, 11, and 12 illustrate the temporal evolution of pollutants from 2019 to 2025, alongside precipitation, ambient temperature, and the normalized difference vegetation index (NDVI).

Figure 10 shows the effect of wet scavenging by rainfall during the rainy season, coupled with the convective monsoon conditions that aid pollution dispersion during this period. The pollutants, nitrogen dioxides, carbon (II) oxide, formaldehyde, and aerosol, can be observed to show peaks during the dry season



months of December to March of each year, while the lows of the pollutants can be seen during the rainy season months of June to September of each year. Methane and sulfur dioxide show little variation with precipitation; this trend is connected with the relatively longer residence time of these pollutants in the atmosphere, and such is confirmed by the correlations in Fig. 9. On the other hand, ozone shows a positive correlation with precipitation, as shown in Fig. 9, and in Fig. 10, it is synchronized with precipitation, reaching peak values during peak precipitation periods and vice versa. This observation can be associated with the atmospheric convective transport, the impact of lightning activities on nitrogen oxides, solar recovery after rainfall, and emissions of volatile organic compounds by vegetation, as observed by researchers such as Brönnimann *et al.* [41], Fan *et al.* [42], Robertson *et al.* [43], and Kawichai *et al.* [44].

Figure 11 closely follows the time evolutions shown by Fig. 10, as ambient temperature variation is closely related to precipitation period; the rainy season is generally associated with lower temperature, while the dry season is associated with elevated ambient temperature. The effect of Saharan dust during the harmattan season is evident as the heavy atmospheric dust loading leads to a cooler atmosphere. The observed positive correlation of ozone and formaldehyde is an indication of the photochemical source of these pollutants.

The impact of vegetation on the dynamics of the atmospheric pollutants is more complex than that of precipitation or ambient temperature, even though vegetation evolution is closely related to precipitation and ambient temperature. Vegetation evolution, as measured by the NDVI, impacts the atmospheric pollutants in two important pathways: (1) the emission pathway and (2) the absorption pathway [45]. In Fig. 12, we can observe the absorption of pollutants during the rainy season when greenery is abundant, while the emission pathway in the case of ozone shows that this greenery leads to higher ozone levels.

Conclusion

This study demonstrates the utility of satellite remote sensing in tracking the evolution of air pollutants and identifying their links with anthropogenic activities, meteorology, and land surface dynamics in Abuja and its adjoining states. We found clear evidence of increasing nitrogen oxides and formaldehyde, reflecting persistent traffic and industrial emissions, while sulfur dioxide and carbon monoxide show slight reductions, likely due to improved combustion efficiency and partial transition to cleaner energy sources. The strong positive correlations between NO₂ and SO₂ suggest common combustion-related sources, whereas the negative correlations of CO and SO₂ with precipitation affirm the atmospheric cleansing role of rainfall. Ozone's positive association with precipitation further underscores the role of convective mixing, lightning NO_x production, and VOC-driven photochemistry in ozone generation during the wet season.

The spatial redistribution of methane emissions and increasing aerosol index hotspots highlight the dual challenge of agricultural expansion and biomass burning, which will continue to contribute to air quality deterioration if not managed. Vegetation dynamics, captured via NDVI, were shown to play a dual role by both modulating pollutant emissions (through VOC release) and facilitating pollutant removal, emphasizing the importance of preserving green cover in urban and peri-urban areas.

This synthesis of multi-pollutant observations, meteorological drivers, and land surface indices provides a robust evidence base for policymakers. The results call for integrated air quality management that includes emission reduction from transport and industry, enhancement of urban vegetation, promotion of clean cooking technologies, and regulation of biomass burning. Such strategies will not only improve air quality and public health outcomes but also contribute to climate mitigation targets under Nigeria's Nationally Determined Contributions (NDCs).

Conflict of interest: The authors declare that no conflicts of interest exist.

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References

- [1] Akanji, A. R., Francis, M. O. & Akintola, A. F. (2024). Air quality trends and pollution analysis in Nigerian cities using time series methods. *International Journal of Advanced Statistics and Probability*, 11(2), 108–123. <https://doi.org/10.14419/w5rj1f64>
- [2] Ezeigwe, N. M., Adinma, E. D., Okobia, E. L. & Schwander, S. (2024). Characterization and quantification of vehicular emissions in abuja municipality – Implications for public health. *Nigerian Medical Journal*, 65(3). <https://doi.org/10.60787/NMJ-V65I3-383>
- [3] Ibrahim, R., Dauda, M., Igwemmar, N., Salau, R. & Abdu, B. (2024). Estimating pollution indices of selected metals in the soils of Abuja Metropolis, Nigeria. *European Journal of Scientific Research and Reviews*, 0, 1. <https://doi.org/10.5455/ejsrr.20240714075837>
- [4] Mohebbichamkhorami, M., Arbabi, M., Mirzaei, M., Ahmadi, A., Hassanvand, M. S. & Rouhi, H. (2020). Ambient air particulate matter (PM₁₀) satellite monitoring and respiratory health effects assessment. *Journal of Environmental Health Science and Engineering*, 18(2), 1247–1258. <https://doi.org/10.1007/s40201-020-00542-4>

- [5] Ihedike, C., Mooney, J. D., Fulton, J. & Ling, J. (2023). Evaluation of real-time monitored ozone concentration from Abuja, Nigeria. *BMC Public Health*, 23(1). <https://doi.org/10.1186/s12889-023-15327-1>
- [6] Omole, D. O., Udemezue, C. C. & Agboola, O. S. (2025). Assessment of urban and industrial effluents on a receiving stream using statistical and quality indices. *Sci. Afri.*, 29, e02781. <https://doi.org/10.1016/j.sciaf.2025.e02781>
- [7] Liu, C., Calders, K., Origo, N., Disney, M., Meunier, F., Woodgate, W., Gastellu-Etchegorry, J.-P., Nightingale, J., Honkavaara, E., Hakala, T., Markelin, L. & Verbeeck, H. (2024). Reconstructing the digital twin of forests from a 3D library: Quantifying trade-offs for radiative transfer modeling. *Remote Sens Environ.*, 298, 113832. <https://doi.org/10.1016/j.rse.2023.113832>
- [8] Timofeev, Y. M. & Neroblov, G. M. (2024). Satellite investigations of the atmospheric gas composition. *Izv. Atmos. Ocean. Phys.* 60, 660–688. <https://doi.org/10.1134/S0001433824700658>
- [9] Locke, A. V., Heffernan, R. C., McDonagh, G., Yassa, J. & Flaherty, G. T. (2022). Clearing the air: a global health perspective on air pollution. *Int J Travel Med Glob Health*. 10(2), 46–49. <https://doi.org/10.34172/ijtmgh.2022.09>
- [10] Roy, A. (2021). Atmospheric pollution retrieval using path radiance derived from remote sensing data. *Journal of Geovisualization and Spatial Analysis*, 5(2). <https://doi.org/10.1007/s41651-021-00093-8>
- [11] Stratoulis, D., Nuthammachot, N., Dejchanchaiwong, R., Tekasakul, P. & Carmichael, G. R. (2024). Recent developments in satellite remote sensing for air pollution surveillance in support of sustainable development goals. *Remote Sensing*, 16(16), 2932. <https://doi.org/10.3390/rs16162932>
- [12] Ramadas, M. & Abraham, A. (2022). Segmentation on remote sensing imagery for atmospheric air pollution using divergent differential evolution algorithm. *Neural Computing and Applications*, 35(5), 3977–3990. <https://doi.org/10.1007/s00521-022-07922-x>
- [13] Clerbaux, C., Hadji-Lazaro, J., Turquety, S., George, M., Boynard, A., Pommier, M., Safieddine, S., Coheur, P.-F., Hurtmans, D., Clarisse, L. & Van Damme, M. (2015). Tracking pollutants from space: Eight years of IASI satellite observation. *Comptes Rendus. Géoscience*, 347(3), 134–144. <https://doi.org/10.1016/j.crte.2015.06.001>
- [14] Clark, C. D. (1993). Satellite remote sensing for marine pollution investigations. *Marine Pollution Bulletin*, 26(7), 357–368. [https://doi.org/10.1016/0025-326x\(93\)90182-j](https://doi.org/10.1016/0025-326x(93)90182-j)
- [15] Omokpariola, D. O., Nduka, J. N. & Omokpariola, P. L. (2024). Short-term trends of air quality and pollutant concentrations in Nigeria from 2018–2022 using tropospheric sentinel-5P and 3A/B satellite data. *Discov. Appl. Sci.*, 6, 182. <https://doi.org/10.1007/s42452-024-05856-8>
- [16] ClimeData (2025). Abuja Climate. <https://en.climate-data.org/africa/nigeria/federal-capital-territory/abuja-703/>
- [17] Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C. & Thépaut, J. (2021). ERA5-Land: a state-of-the-art global reanalysis dataset for land. *Earth Syst. Sci. Data*, 13(10), 4349–67. <https://doi.org/10.5194/essd-13-4349-2021>
- [18] Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. & Michaelsen, J. (2015). The climate hazards infrared precipitation with stations-a new environmental record for monitoring extremes. *Scientific Data*, 2, 150066. <https://doi.org/10.1038/sdata.2015.66>
- [19] Seinfeld, John H. (1975). *Air Pollution, Physical and Chemical Fundamentals*. McGraw-Hill, New York, p. 73.
- [20] AbdulRaheem, A. M. O., Adekola, F. A. & Obioh, I. O. (2009). The seasonal variation of the concentrations of ozone, sulfur dioxide, and nitrogen oxides in two Nigerian cities. *Environ. Model Assess*, 14, 497–509. <https://doi.org/10.1007/s10666-008-9142-x>
- [21] Oluleye, A. (2021). Satellite observation of spatio-temporal variations in nitrogen dioxide over West Africa and implications for regional air quality. *Journal of Health and Pollution*, 11(31), 210913. <https://doi.org/10.5696/2156-9614-11.31.210913>
- [22] Reuben, G. E. & Akporhonor, E. E. (2024). Evaluation of the concentration and distribution of selected air pollutants in some towns in Ukwuani LGA of Delta State, Nigeria. *Nigerian Journal of Science and Environment*, 22(3), 91–106.
- [23] Enuneku, A., Anani, O. A., Amaechi, C. F., Goodluck, O. M. & Nwulu, F. L. (2024). Monitoring of SO₂ and NO₂ levels around a gas flow station in the sub-saharan region using sentinel 5P satellite data. *J. Indian Soc. Remote Sens.* 52, 2375–2388. <https://doi.org/10.1007/s12524-024-01946-7>



- [24] Fioletov, V. E., McLinden, C. A., Griffin, D., Abboud, I., Krotkov, N., Leonard, P. J. T., Li, C., Joiner, J., Theys, N. & Carn, S. (2023). Version 2 of the global catalogue of large anthropogenic and volcanic SO₂ sources and emissions derived from satellite measurements (2005–2021). *Earth Syst Sci Data*, 15, 75–93. <https://doi.org/10.5194/essd-15-75-2023>
- [25] Mahmud, K., Mitra, B., Uddin, M. S. & Hridoy, A. E. E. (2023). Temporal assessment of air quality in major cities in Nigeria using satellite data. *Atmos. Environ. X*, 20, 100227. <https://doi.org/10.1016/j.aeaoa.2023.100227>
- [26] Fuwape, I. A., Okpalaonwuka, C. T. & Ogunjo, S. T. (2021). Impact of COVID-19 lockdown on air quality in selected Nigerian cities. *Air Qual. Atmos. Health*, 14, 149–55. <https://doi.org/10.1007/s11869-020-00921-8>
- [27] Dylan B. Millet, Daniel J. Jacob, Solène Turquety, Rynda C. Hudman, Shiliang Wu, Alan Fried, James Walega, Brian G. Heikes, Donald R. Blake, Hanwant B. Singh, Bruce E. Anderson & Antony D. Clarke (2006). Formaldehyde distribution over North America: Implications for satellite retrievals of formaldehyde columns and isoprene emission. *J. Geophys Res Atmos.* 111(D24). <https://doi.org/10.1029/2005JD006853>
- [28] De Smedt, I., Stavrou, T., Hendrick, F., Danckaert, T., Vlemmix, T., Pinardi, G., Theys, N., Lerot, C., Gielen, C., Vigouroux, C., Hermans, C., Fayt, C., Veefkind, P., Müller, J.-F. & Van Roozendael, M. (2015). Diurnal, seasonal and long-term variations of global formaldehyde columns inferred from combined OMI and GOME-2 observations. *Atmos. Chem. Phys.*, 15(21), 12519–12545. <https://doi.org/10.5194/acp-15-12519-2015>
- [29] Monks, P. S., Archibald, A. T., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K. S., Mills, G. E., Stevenson, D. S., Tarasova, O., Thouret, V., von Schneidemesser, E., Sommariva, R., Wild, O. & Williams, M. L. (2015). Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer. *Atmos. Chem. Phys.*, 15(15), 8889–8973. <https://doi.org/10.5194/acp-15-8889-2015>
- [30] Duncan, B. N., Logan, J. A., Bey, I., Megretskaia, I. A., Yantosca, R. M., Novelli, P. C., Jones, N. B. & Rinsland, C. P. (2007). Global budget of CO, 1988–1997: source estimates and validation with a global model. *J. Geophys Res. Atmos.*, 112(D22), D22301. <https://doi.org/10.1029/2007JD008459>
- [31] Streets, D. G., Bond, T. C., Carmichael, G. R., Fernandes, S. D., Fu, Q., He, D., Klimont, Z., Nelson, S. M., Tsai, N. Y., Wang, M. Q., Woo, J.-H. & Yarber, K. F. (2003). An inventory of gaseous and primary aerosol emissions in Asia in the year 2000. *J. Geophys Res Atmos.*, 108(D21), 8809. <https://doi.org/10.1029/2002JD003093>
- [32] Zhu Lei, Loretta J. Mickley, Daniel J. Jacob, Eloise A. Marais, Jianxiong Sheng, Lu Hu, Gonzalo González Abad & Kelly Chance (2017). Long-term (2005–2014) trends in formaldehyde (HCHO) columns across North America as seen by the OMI satellite instrument: Evidence of changing emissions of volatile organic compounds. *Geophys Res. Lett.*, 44(13), 7079–7086. <https://doi.org/10.1002/2017GL073859>
- [33] CCAC (2025). Methane—the world's second-largest contributor to global warming after carbon dioxide and a key ingredient in ground-level ozone pollution. *Climate and Clean Air Coalition*. <https://www.ccacoalition.org/short-lived-climate-pollutants/methane>
- [34] IPCC (2023). Climate Change 2021-The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report. Cambridge Univ. Press. <https://doi.org/10.1017/9781009157896>
- [35] Parker, R. J., Boesch, H., Byckling, K., Webb, A. J., Palmer, P. I., Feng, L., Bergamaschi, P., Chevallier, F., Notholt, J., Deutscher, N., Warneke, T., Hase, F., Sussmann, R., Kawakami, S. Kivi, R. Griffith, D. W. T. & Velasco, V. (2015). Assessing 5 years of GOSAT Proxy XCH₄ data and associated uncertainties. *Atmos Meas Tech.* 8(11), 4785–805. <https://doi.org/10.5194/amt-8-4785-2015>
- [36] Janardanan, R., Maksyutov, S., Tsuruta, A., Wang, F., Tiwari, Y. K., Valsala, V., Ito, A., Yoshida, Y., Kaiser, J. W., Janssens-Maenhout, G., Arshinov, M., Sasakawa, M., Tohjima, Y., Worthy, D. E. J., Dlugokencky, E. J., Ramonet, M., Arduini, J., Lavric, J. V., Piacentino, S., ... Matsunaga, T. (2020). Country-scale analysis of methane emissions with a high-resolution inverse model using GOSAT and surface observations. *Remote Sensing*, 12(3), 375. <https://doi.org/10.3390/rs12030375>
- [37] Torres, O., Bhartia, P. K., Herman, J. R., Sinyuk, A., Ginoux, P. & Holben, B. (2002). A long-term record of aerosol optical depth from TOMS observations and comparison to AERONET measurements. *J Atmos Sci.* 59(3), 398–413. [https://doi.org/10.1175/1520-0469\(2002\)059<0398:ALTROA>2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059<0398:ALTROA>2.0.CO;2)
- [38] Graaf, M. de, P. Stammes, Torres, O. & Koelemeijer, R. B. A. (2005). Absorbing Aerosol Index: Sensitivity analysis, application to GOME and comparison with TOMS, *J. Geophys. Res.* 110, D010201, <https://doi.org/10.1029/2004JD005178>

- [39] Fioletov, V., McLinden, C. A., Griffin, D., Theys, N., Loyola, D. G., Hedelt, P., Krotkov, N. A. & Li, C. (2020). Anthropogenic and volcanic point source SO₂ emissions derived from TROPOMI on board Sentinel-5 Precursor: first results. *Atmos. Chem. Phys.*, 20(9), 5591–5607. <https://doi.org/10.5194/acp-20-5591-2020>
- [40] Krotkov, N. A., McLinden, C. A., Li, C., Lamsal, L. N., Celarier, E. A., Marchenko, S. V., Swartz, W. H., Bucsela, E. J., Joiner, J., Duncan, B. N., Boersma, K. F., Veefkind, J. P., Levelt, P. F., Fioletov, V. E., Dickerson, R. R., He, H., Lu, Z. & Streets, D. G. (2016). Aura OMI observations of regional SO₂ and NO₂ pollution changes from 2005 to 2015. *Atmos. Chem. Phys.*, 16(7), 4605–4629. <https://doi.org/10.5194/acp-16-4605-2016>
- [41] Brönnimann, S., Jacques-Coper, M., Rozanov, E., Fischer, A. M., Morgenstern, O., Zeng, G., Akiyoshi, H. & Yamashita, Y. (2017). Tropical circulation and precipitation response to ozone depletion and recovery. *Environ. Res. Lett.*, 12, 064011. <https://doi.org/10.1088/1748-9326/aa7416>
- [42] Fan, C., Ding, M., Wu, P. & Fan, Y. (2019). The relationship between precipitation and aerosol: Evidence from satellite observation. *arXiv*, 1812.02036v2. <https://doi.org/10.48550/arXiv.1812.02036>
- [43] Robertson, L. S., Zhou, L. & Chen, K. (2020). Temperature, precipitation, ozone pollution, and daily fatal unintentional injuries in Jiangsu Province, China during 2015-2017. *Inj Epidemiol.*, 7(1), 42. <https://doi.org/10.1186/s40621-020-00268-9>
- [44] Kawichai, S., Kliengchuay, W., Aung, H. W., Niampradit, S., Mingkhwan, R., Niemanee, T., Srimanus, W., Phonphan, W., Suwanmanee, S. & Tantrakarnapa, K. (2025). The influence of meteorological conditions and seasons on surface ozone in Chonburi, Thailand. *Toxics*, 13(3), 226. <https://doi.org/10.3390/toxics13030226>
- [45] David J. Nowak, Daniel E. Crane & Jack C. Stevens (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, 4(3–4), 115-123. <https://doi.org/10.1016/j.ufug.2006.01.007>

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