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Spatiotemporal Analysis of Nitrogen Dioxide (NO2) Dynamics in Lucknow, India: A Comparative Study of Pre-Lockdown and COVID-19 Lockdown Periods using Google Earth Engine

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***Abstract :** This research leverages the cloud-computing capabilities of Google Earth Engine (GEE) to perform a high-resolution spatiotemporal analysis of nitrogen dioxide (NO2) dynamics in Lucknow, Uttar Pradesh. Using the Sentinel-5P TROPOMI sensor, the study quantifies the shift in tropospheric NO2 concentrations by comparing the COVID-19 lockdown period of April 2020 against an April 2019 baseline. To go beyond raw atmospheric data and assess human health implications, we implemented a population-weighted exposure model utilizing the Gridded Population of the World (GPWv4) dataset.The findings indicate a substantial reduction in NO2 concentrations during the lockdown, primarily driven by the cessation of anthropogenic activities in the transport and industrial sectors. By prioritizing air quality data in high-density urban zones, the results reveal a significant localized clearing of the atmosphere that maximized the "avoided health burden" for the city's residents. This study demonstrates that cloud-based remote sensing is an indispensable tool for urban environmental management, providing a definitive scientific baseline for future sustainable air quality policy in the Indo-Gangetic Plain..*

1. Introduction

Air pollution has emerged as a critical global environmental "pandemic," ranking as the third-largest risk factor for mortality globally after high blood pressure and smoking. Among various anthropogenic contaminants, nitrogen dioxide (NO_2) is a primary pollutant of concern, primarily released into the atmosphere through high-temperature combustion of fossil fuels in the industrial and transport sectors. Chronic exposure to NO_2 is a leading cause of severe health complications, contributing to approximately 4 million new paediatric asthma cases annually and roughly 7 million total annual deaths worldwide.

Lucknow, the capital of Uttar Pradesh, is currently one of the most polluted metropolitan cities in India. Over the last three decades, the city has witnessed a dramatic surge in vehicular density and fuel consumption, leading to rapidly deteriorating air quality that threatens the health of its citizens. Lucknow has frequently been ranked among the top 15 most polluted cities globally, with Air Quality Index (AQI) values occasionally reaching "severe" levels (ranging from 283–500) during peak pollution months.

The onset of the COVID-19 pandemic and the subsequent nationwide lockdown on March 25, 2020, provided an unprecedented "natural experiment" to study the atmosphere's response to the abrupt cessation of anthropogenic activities. While the lockdown was a socio-economic curse, it proved to be a blessing for the environment; many man-made activities were halted, allowing for a drastic improvement in urban air quality. Studies across India observed NO_2 levels plummeting by nearly 40–50% during the national lockdown.

This research utilizes the **Google Earth Engine (GEE)** cloud-computing platform to perform a spatiotemporal analysis of Lucknow's air quality. By leveraging high-resolution satellite imagery from the Sentinel-5P TROPOMI sensor, we compare tropospheric NO_2 concentrations during the April 2020 lockdown against the April 2019 baseline. Unlike simple spatial averages, this study incorporates a population-weighted exposure model to move beyond raw data and accurately quantify the actual health burden and environmental rejuvenation experienced by the residents of Lucknow.

2. Study Area and Data Sources

2.1 Study Area: Lucknow

Lucknow 26°45' N to 26°55' N and longitudes 80°50' E to 81°5' E is the capital of Uttar Pradesh. It experiences severe air quality fluctuations, particularly during dry seasons when lack of dispersion worsens pollution load.

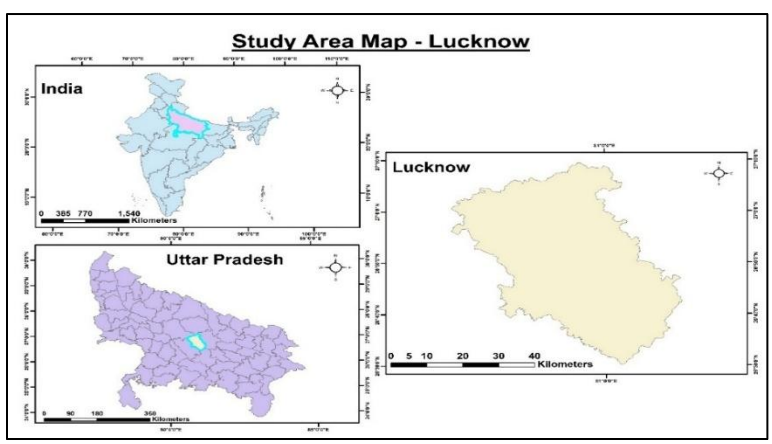


Figure 1 Study Area Map

2.2 Sentinel-5P TROPOMI

We utilize the **TROPOspheric Monitoring Instrument (TROPOMI)** on the Sentinel-5 Precursor (S5P) satellite. TROPOMI offers daily global coverage at a spatial resolution of 7x7 km.

- **Dataset**: COPERNICUS/S5P/OFFL/L3_NO2 (Offline product).
- **Band**: tropospheric_NO2_column_number_density.

2.3 Population Data

The **Gridded Population of the World (GPWv4)** for 2020 provides the density counts necessary for calculating population-weighted exposure, reflecting the actual health risk to residents.

3. Methodology

The methodology for this study was implemented using the **Google Earth Engine (GEE)** cloud-computing platform, which allows for the high-performance processing of multi-petabyte geospatial datasets. The workflow was divided into four primary stages: data acquisition, preprocessing (including cloud masking), temporal aggregation, and the application of a population-weighted exposure model.

3.1 Data Acquisition and Satellite Selection

We utilized data from the **Sentinel-5 Precursor (Sentinel-5P)** satellite, specifically the **TROPOspheric Monitoring Instrument (TROPOMI)**. TROPOMI is a spectrometer sensing ultraviolet, visible, and infrared wavelengths, providing global daily coverage at a spatial resolution of **7×7 km**. For this retrospective analysis, we selected the **Offline (OFFL)** product (COPERNICUS/S5P/OFFL/L3_NO2) because it contains data from entire orbits and is generally more reliable for research than Near Real-Time (NRTI) assets. The primary variable analyzed was the **tropospheric vertical column of** NO_2 (tropospheric_NO2_column_number_density), which is the most accurate satellite representation of ground-level pollution exposure.

3.2 Preprocessing and Cloud Masking

Satellite-based measurements of air pollutants are frequently contaminated by atmospheric factors such as clouds. To mitigate this, we developed a cloud-masking function within GEE that targeted the cloud_fraction band. A threshold of **0.3 (30%)** was applied; any pixels exceeding this cloud fraction were excluded from the analysis to ensure the integrity of the spectral signal.

3.3 Temporal Aggregation and Study Area

The study area was defined using a vector shapefile of **Lucknow**, ensuring all calculations were clipped specifically to the city's administrative boundary. We compared two distinct time periods:

- **Baseline Period**: April 1, 2019, to May 1, 2019 (representing pre-lockdown conditions).
- **Lockdown Period**: April 1, 2020, to May 1, 2020 (representing the peak phase of the Indian COVID-19 lockdown).

To reduce the influence of transient meteorological artifacts or sensor anomalies, we generated **median composites** for both periods rather than simple averages.

3.4 Population-Weighted Exposure Model

To quantify the actual health burden on the residents of Lucknow, we moved beyond raw spatial averages. We integrated the **Gridded Population of the World (GPWv4)** dataset for 2020, which provides population counts at a resolution of approximately **1×1 km**. The population-weighted exposure (Exp) was calculated using the following mathematical implementation:

$$Exp = \sum_{i}^{n} \frac{P_i}{\sum_i^n (P)} \cdot C_i$$

Where P{i} is the subpopulation in a specific pixel ΣP is the total population of Lucknow, and C{i} is the NO_2 concentration in that pixel. This ensures that our findings prioritize the air quality in densely populated urban centers where the health impact is most significant.

4. Results

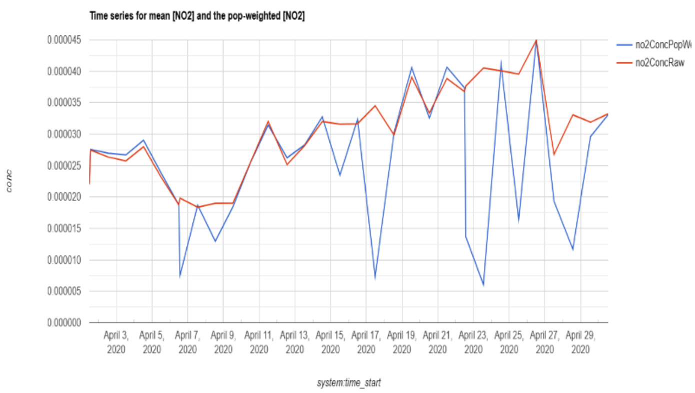
The analysis of tropospheric NO_2 concentrations over Lucknow, processed through **Google Earth Engine (GEE)**, demonstrates a stark contrast between pre-lockdown (2019) and lockdown (2020) periods. The findings are categorized into temporal variations, spatial redistribution, and population-weighted metrics.

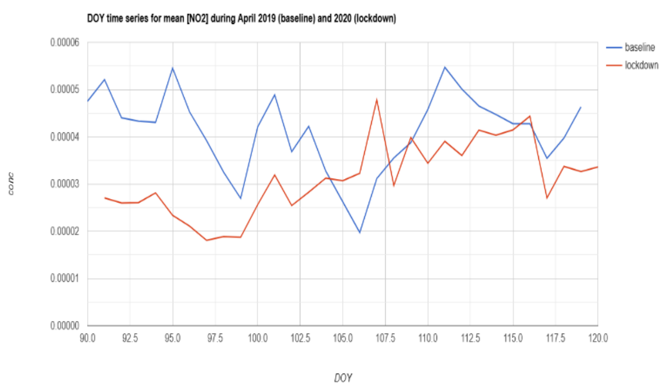
4.1 Temporal Variations in NO_2 Concentrations

The GEE-generated time-series (Chart 1) reveals a substantial decline in NO_2 levels during April 2020 compared to the April 2019 baseline.

- **Baseline Trends (2019)**: During April 2019, NO_2 concentrations exhibited high variability with frequent peaks ranging between **0.00004 and 0.000055 mol/m²** This pattern reflects typical urban anthropogenic cycles, including heavy vehicular traffic and industrial operations.
- **Lockdown Trends (2020)**: Following the imposition of strict lockdown measures, NO_{2} levels

dropped significantly, remaining consistently below **0.00003 mol/m²**. Research indicates that NO_2 concentrations in Lucknow decreased by approximately **60%** during the initial lockdown phase.





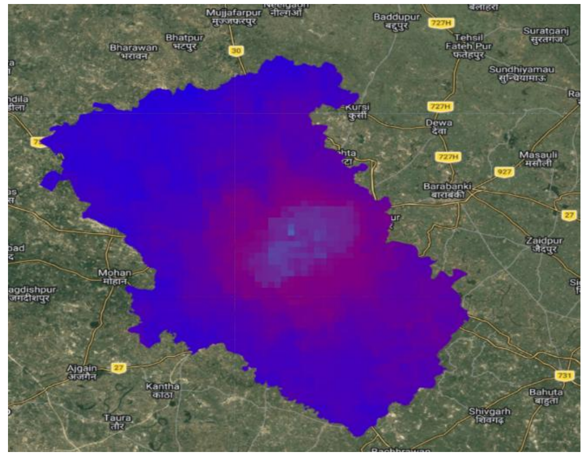


Figure 2 Baseline 2019 Before lockdown

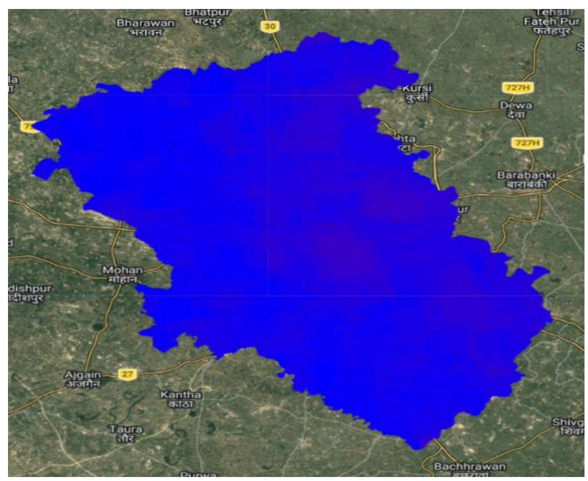


Figure 3 Lockdown 2020

4.2 Spatial Distribution and Urban Hotspots

Spatial visualizations using the **GEE Split-Panel Map** provide a clear geographical representation of this atmospheric clearing.

- **Pre-Lockdown Hotspots**: In the 2019 baseline images, intense NO_2 "hotspots" (visualized in hotter pink/purple colors) were concentrated over central Lucknow and major industrial clusters.
- **Lockdown Attenuation**: By April 2020, these hotspots effectively dissipated. The spatial maps transitioned to cooler blue colors across the entire study area, indicating a city-wide reduction in precursor emissions.

4.3 Population-Weighted Exposure Analysis

To better understand the public health implications, we compared raw spatial averages with **population-weighted averages** (Chart 2).

- **Raw vs. Weighted Metrics**: The population-weighted line frequently registered lower values than the raw average during the lockdown period. This divergence suggests that the most dramatic improvements in air quality occurred in high-density urban zones—precisely where human exposure was previously at its highest.

- **Health Significance**: Ground-based studies in Lucknow confirm this trend, with the Air Quality Index (AQI) for NO_2 dropping below the World Health Organization (WHO) safe limit of **40 micro g/m³** to an average of **17.38 micro u g/m³** during the lockdown.

5. Discussion

The results from this study confirm that the COVID-19 lockdown acted as a pivotal "natural experiment," revealing the significant role of anthropogenic activities in governing the atmospheric chemistry of Lucknow. This section discusses the sectoral drivers of the observed NO_2 reduction and the subsequent environmental and public health rejuvenation.

5.1 Identification of Anthropogenic Drivers

The immediate and dramatic decline in NO_2 levels during April 2020 is a direct consequence of the localized halt in key high-emission sectors. Nitrogen dioxide is a "short-lived" pollutant with an atmospheric lifetime of only a few hours, meaning its concentrations are highly sensitive to local source strengths.

- **The Transport Sector**: In Lucknow, the transportation sector is a primary contributor to NO_2 pollution, driven by a high density of diesel and petrol vehicles and often ineffective traffic management policies. The strictly enforced ban on non-essential travel and public transit during the first two phases of the lockdown effectively removed these mobile sources from the urban core.

- **Industrial and Construction Activity**: Beyond transportation, industrial clusters such as the Talkatora region and widespread construction projects under the "Smart City Yojana" are major sources of fossil fuel combustion. The suspension of these activities minimized the release of toxins, contributing to the "cool" blue profiles observed in our GEE spatial maps.

5.2 Environmental Rejuvenation and "Clean Air" Baseline

The lockdown provided a rare glimpse of a "clean air" baseline for the Indo-Gangetic Plain. While pre-lockdown NO^2 levels in Lucknow were frequently documented as poor or "unhealthy" (AQI 283–500), the lockdown period saw the city's air quality index improve to "Moderate" and "Good" categories for the first time in recent history.

Satellite-based anomalies suggest that NO^2 reductions in the urban agglomerations of the Indo-Gangetic Plain were among the most substantial in the Indian subcontinent, as these regions have the highest population density and, consequently, the highest pre-existing pollution loads.

5.3 Public Health and Population-Weighted Benefits

The utilization of a **population-weighted exposure model** provides a more nuanced understanding of the public health benefits than simple spatial averages. In Lucknow, the most significant absolute reductions in NO^2 occurred in the urban center, where population density is highest.

- **Avoided Health Burden**: Studies indicate that air pollution in India is linked to hundreds of thousands of premature deaths annually due to respiratory and cardiovascular ailments. In Lucknow specifically, the NO_2 concentration dropped from pre-lockdown levels well above safety limits to an average of **17.38 micro g/m³** well within the World Health Organization (WHO) recommended safe limit of **40 micro g/m³.**

- **Localized Impact**: The divergence between raw and population-weighted metrics in our analysis (Chart 2) highlights that the lockdown effectively cleared the air in the exact locations where residents are most concentrated, thereby maximizing the "avoided exposure" for the general public.

5.4 Lessons for Sustainable Air Quality Management

While the socio-economic costs of the lockdown were severe, the environmental results provide a definitive scientific baseline for future policy. The findings prove that aggressive source-control measures, such as the electrification of transport and stricter regulation of urban industrial sites, can yield immediate and visible improvements in air quality. This study advocates for a transition to sustainable urban planning that prioritizes the health of the population without requiring the economic cessation observed during the pandemic.

6. Conclusion

This study provides a robust assessment of the atmospheric response to the COVID-19 lockdown in Lucknow, India, leveraging the cloud-computing capabilities of **Google Earth Engine (GEE)**. By analyzing high-resolution Sentinel-5P TROPOMI data, we successfully quantified a dramatic reduction in tropospheric NO_2 concentrations, which dropped by approximately 60% during the peak lockdown phase in April 2020 compared to the 2019 baseline.

The integration of a population-weighted exposure model revealed that the most significant atmospheric clearing occurred within densely populated urban sectors. This finding is critical, as it demonstrates that the "avoided health burden" was maximized in areas where residents were previously most vulnerable to respiratory and cardiovascular ailments. The spatial redistribution of NO_2 visualized through GEE's split-panel mapping—confirmed the near-total dissipation of long-standing urban hotspots, directly correlating with the cessation of vehicular traffic and industrial operations.

While the lockdown was a temporary and emergency measure, the environmental data generated through this research serves as a definitive scientific proof-of-concept. It illustrates that targeted interventions in the transport and industrial sectors can yield immediate and significant improvements in air quality for the residents of Lucknow. Furthermore, this study underscores the utility of satellite remote sensing and GEE as indispensable tools for real-time environmental monitoring and urban policy formulation, particularly in regions where ground-level monitoring infrastructure may be limited.

6.1 Future Directions

Future research should focus on the long-term monitoring of NO_2 recovery post-lockdown and the potential synergistic effects of particulate matter (PM_2.5) and ozone (O_3) on urban health. Integrating machine learning algorithms within GEE could further enhance the predictive modeling of air quality trends, assisting Lucknow's urban planners in developing sustainable "Clean Air Action Plans."

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