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(Research Article)

An assessment of air quality indicators Sentinel-5P TROPOMI data were used to examine the NO_2 SO_2 O_3 AEROSOL levels in Uttar Pradesh before, after, and during the COVID 19 phase

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Abstract

Significantly affecting human activities and economic sectors were the COVID-19 pandemic and related lockdowns. Nevertheless, despite these difficulties, the environment saw some improvement, especially in terms of the air quality. A dearth of thorough research comparing air quality indicators before, during, and after the epidemic has been noted despite the many studies that have emphasized the decrease in pollutants across India during the early phases of the pandemic. In-depth analyses of four important air quality indicators nitrogen dioxide (NO_2), sulphur dioxide (SO_2), ultraviolet aerosol index (UVAI) and ozone (O_3) are conducted in this work. We examined the patterns on the Google Earth Engine (GEE) platform, specifically for the state of Uttar Pradesh in India, utilizing data from the TROPOMI (Tropospheric Monitoring Instrument) during a five-year period, focusing on the same three-month timeline each year. For several atmospheric variables (NO_2, SO_2 , O_3, Aerosol,), the given data from 2019 to 2023 includes monthly averages and standard deviations. The overall trend from 2019 to 2023 shows varying quantities of pollutants, with some, like NO2, rebounding after an initial decrease and others, like aerosols, exhibiting considerable annual changes, underscoring the dynamic character of environmental circumstances over time.

Keyword: Sentinel-5p; Google Earth Engine (GEE); European Space Agency (ESA); COVID-19; TROPOMI (Tropospheric Monitoring Instrument); Uttar Pradesh

1. Introduction

Air quality has long been a crucial factor in determining public health, and its deterioration has been connected to a wide range of illnesses, including cardiovascular disorders and respiratory illnesses [1]. One of the most populous states in India, Uttar Pradesh, has frequently struggled with the problem of declining air quality brought on by a combination of industrial, vehicular, and agricultural activity. An unplanned global experiment was brought about by the rapid arrival of the COVID-19 pandemic: widespread lockdowns that restricted the majority of human activity [2], which led to a momentary relief for the environment. A wave of unprecedented challenges hit the world in early 2020 with the start of the COVID-19 pandemic [3]. Strict lockdown measures were implemented as nations fought to stop the virus from spreading, which resulted in a dramatic decrease in business operations, transportation, and general human movement. Observable changes in the environment, particularly in the air quality, arose as an unanticipated result, even though the main concerns remained public health and the economic effects of lockdowns [3]. In this perspective, Uttar Pradesh, one of India's most populous states, offers an intriguing case study. The state offered a special chance to look at the short-term environmental effects of decreased human activity because it has historically been beset by air quality issues brought on by a combination of industrial pollutants, vehicle pollution, and agricultural practices. These changes may be seen from above thanks to satellite data, particularly that from the Sentinel-5P satellite operated by the Copernicus program of the European Union [4]. The Tropomi instrument on the satellite has proven essential in determining

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different air pollution all around the world. This study aims to comprehend how the air quality in Uttar Pradesh changed prior to, during, and following the COVID-19 lockdowns. We intend to measure changes in important pollutants, uncover patterns of regional distribution, and correlate these results with decreases in particular human activities using data from the Sentinel-5P satellite. The findings of this study not only shed light on how humans affect the environment, but they also point to opportunities for evidence-based policy development and increased public awareness. Historical Context Historically, cities like Kanpur, Lucknow, and Varanasi in Uttar Pradesh have grappled with air quality issues. Observing changes in these cities, particularly during reduced human activities [5], can shed light on their resilience and capacity to rejuvenate. Such insights can aid in formulating localized solutions to combat the persistent air quality challenges they face. Diverse Pollution Sources Uttar Pradesh's diversity in pollution sources offers a comprehensive lens to view the air quality dynamics. While urban and industrial areas contribute their share, rural zones too play a role activities like stubble burning significantly impact air quality. A holistic study encompassing all these sources is pivotal for a comprehensive understanding of the state's air quality. Policy Implications Uttar Pradesh's prominence makes it an influential state in India's policy landscape. Understanding its environmental dynamics can shape policymaking, both at the state and national levels. Solutions formulated for UP can set precedents and benchmarks for other regions, given its significant footprint. Data Abundance Given Uttar Pradesh's stature, it's fortunate that ample data is available to supplement research. Ground-based health measures and air quality data can augment and validate the findings from satellite data. This synergy of information sources can enhance the accuracy and reliability of research outcomes. Societal Repercussions The societal implications of changes in Uttar Pradesh's air quality cannot be understated. Given the immense population density, even a marginal improvement in air quality can translate to significant health benefits for millions. Therefore, any conclusions drawn from such studies bear enormous importance in shaping public health strategies and interventions.

2. Material and methods

2.1. Study Area

Uttar Pradesh (UP), with its burgeoning population of over 200 million, grapples with dense habitation that often leads to heightened vehicle emissions, escalating industrial outputs from cities like Ghaziabad, Kanpur, and Noida, and augmented waste generation. This densely populated landscape, inherently intertwined with air pollution, is further exacerbated by its agricultural backbone. The widespread practice of crop residue burning in UP, post-harvest, acts as a significant pollutant source. Additionally, its geographic closeness to Delhi, especially the western parts falling under the National Capital Region (NCR), means it's impacted by the capital's notorious pollution crises. The air quality is further strained by the sheer volume of vehicles, many of which may adhere to outdated emission standards. As UP races towards rapid urbanization, infrastructure projects, such as road constructions, inadvertently disperse more dust and pollutants into the atmosphere. Coal-reliant power generation adds another layer of environmental concern [6]. Moreover, certain cultural norms and practices, like the bursting of fireworks during festivities or the use of traditional biomass stoves [7], have been overlooked as sources of air pollution. It's noteworthy that cities like Kanpur and Lucknow in UP have an existing history of compromised air quality[8], emphasizing the critical need for comprehensive pollution studies. Such assessments can pivotally inform policy decisions, ensuring that both the government and relevant organizations strategize interventions effectively and allocate resources judiciously. Uttar Pradesh (UP), with its burgeoning population of over 200 million, grapples with dense habitation that often leads to heightened vehicle emissions, escalating industrial outputs from cities like Ghaziabad, Kanpur, and Noida, and augmented waste generation. This densely populated landscape, inherently intertwined with air pollution, is further exacerbated by its agricultural backbone. The widespread practice of crop residue burning in UP, post-harvest, acts as a significant pollutant source. Additionally, its geographic closeness to Delhi, especially the western parts falling under the National Capital Region (NCR), means it's impacted by the capital's notorious pollution crises. The air quality is further strained by the sheer volume of vehicles, many of which may adhere to outdated emission standards. As UP races towards rapid urbanization, infrastructure projects, such as road constructions, inadvertently disperse more dust and pollutants into the atmosphere. Coal-reliant power generation adds another layer of environmental concern. Moreover, certain cultural norms and practices, like the bursting of fireworks during festivities or the use of traditional biomass stoves, have been overlooked as sources of air pollution. It's noteworthy that cities like Kanpur and Lucknow in UP have an existing history of compromised air quality, emphasizing the critical need for comprehensive pollution studies. Such assessments can pivotally inform policy decisions, ensuring that both the government and relevant organizations strategize interventions effectively and allocate resources judiciously.

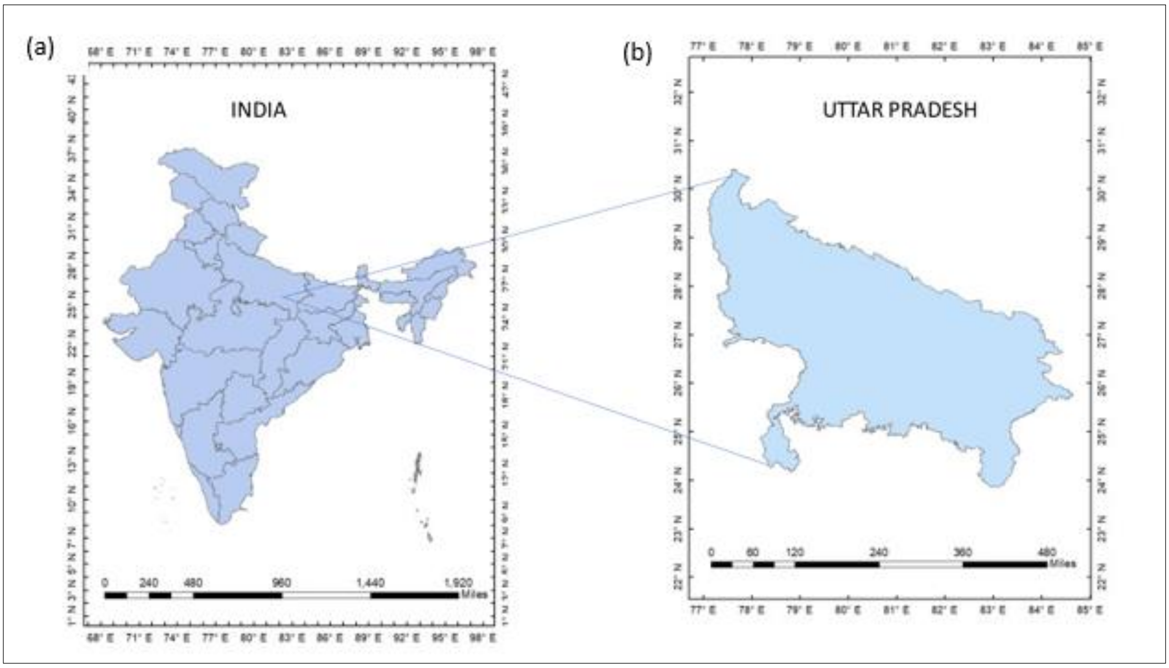


Figure 1 (a) Different regions in India and study area (b) Uttar Pradesh

2.2. Data Collection

The Copernicus Program includes Sentinel-5 Precursor, also referred to as Sentinel-5P, which was launched by the European Space Agency (ESA). Its importance stems from its main function, atmospheric monitoring [9]. The satellite can map a wide range of trace chemicals, including methane, carbon monoxide, formaldehyde, nitrogen dioxide, and ozone. All of these gases are essential because they have an impact on either the climate or human health, or both. Sentinel-5P's primary component is the TROPO spheric Monitoring Instrument, or TROPOMI. The ultraviolet (UV), near-infrared, and short-wavelength infrared light spectrums can all be detected by this cutting-edge spectrometer. This is used to track a variety of atmospheric substances, such as ozone, methane, formaldehyde, aerosol, carbon monoxide, NO_2, and SO_2. On October 13, 2017, Sentinel-5P launched into orbit. If the satellite remains healthy and its equipment is in good working condition after its initial seven-year mission, its operating lifespan might be increased [10]. Numerous unique datasets have been made available by Sentinel-5P. The information can be used for a number of purposes, including monitoring UV radiation and air quality as well as supporting climate models. The ability of policymakers to make fact-based decisions on matters like air quality and climate change depends on this information as well. There was a purpose behind the launch of Sentinel-5P. The SCIAMACHY instrument on the Envisat satellite left a data gap that was intended to be filled by this system. This tactical positioning made sure that monitoring would continue up until Sentinel-5 began operations. Sentinel-5P scans the entire Earth every day [11], demonstrating its capability. Rich databases are produced as a result, and they offer remarkably high temporal resolution insights into the status of the atmosphere. Depending on the gas and the detected spectral band, the spatial resolution changes. Resolutions between 3.5 x 7 km^2 and 7 x 7 km^2 are sufficient to identify pollution levels even over specific cities[12]. For this research, the TROPOMI Offline stream of SO_2, NO_2, O_3, and aerosol index concentration was used three times in 2019, 2020, 2021, 2022, and 2023. ArcGIS and the Google Earth Engine Code Editor (GEE) were used to examine the data.

2.3. Data Processing

From March 2019 to May 2023, the monthly fluctuations over Uttar Pradesh were examined using the Sentinel-5P TROPOMI dataset. As stated by [13], this research made substantial use of the Google Earth Engine (GEE) platform for analysis and the creation of numerous products. TROPOMI sensor data from the Sentinel-5P satellite are also included in this. The JavaScript editor provided in the GEE developer framework [14] was used to carry out all of the variable analyses. The research combined offline data and focused on a 15-month trend of four different air quality indices. This method provided a thorough understanding of the oscillations in the emission of important trace gases in the atmosphere. In addition, the air quality indicators over Uttar Pradesh were carefully evaluated during the months of March through May from 2019 through 2023. The GEE platform was skilfully designed to display a map showing the typical levels of NO_2, SO_2, O_3, and aerosol pollutants across the selected time and place. Throughout the months of March, April, and May for the years 2019 through 2023, this code was continuously used.

3. Results and discussion

Table 1 Monthly statistics for four indicators of air quality in Uttar Pradesh, India in 2019

	March 2019		**April 2019**		**May 2019**	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
NO_2	33.84	+25.04	41.685	26.765	43.141	20.894
SO_2	173.89	108.018	193.277	113.326	98.394	77.334
O_3	0.120017	0.002343	0.124171	0.000799	0.123509	0.00136
Aerosol	-0.81753	0.093878	-0.36045	0.14628	0.025635	0.222026

Table 2 Monthly statistics for four indicators of air quality in Uttar Pradesh, India in 2020

	March 2020		**April 2020**		**May 2020**	
Variable	Mean	SD	Mean	SD	Mean	SD
NO_2	29.095	18.231	33.173	23.658	38.692	17.661
SO_2	146.244	127.099	138.048	106.939	107.322	93.1
O_3	0.133107	0.001661	0.133107	0.001661	0.129307	0.000835
Aerosol	-1.33522	0.100486	-0.86123	0.133266	-0.52807	0.27094

Table 3 Monthly statistics for four indicators of air quality in Uttar Pradesh, India in 2021

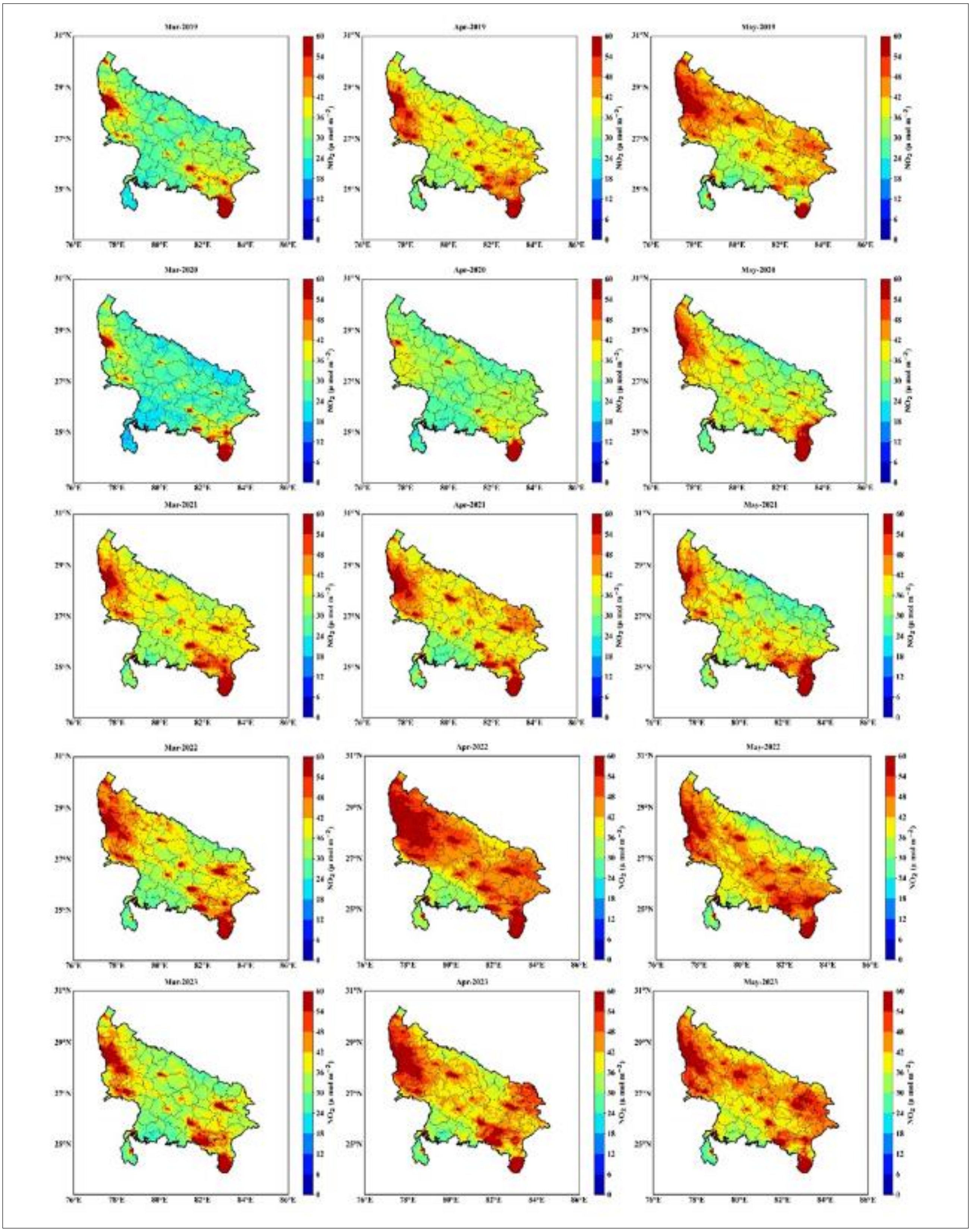
	March-2021		**April 2021**		**May 2021**	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
NO_2	41.068	21.637	42.192	23.907	38.935	17.882
SO_2	129.217	112.5369	197.157	96.94	114.434	106.242
O_3	0.124825	0.00239	0.12959	0.001972	0.129263	0.001276
Aerosol	-0.85532	0.138152	-0.4769	0.158985	-1.10682	0.180514

Table 4 Monthly statistics for four indicators of air quality in Uttar Pradesh, India in 2022

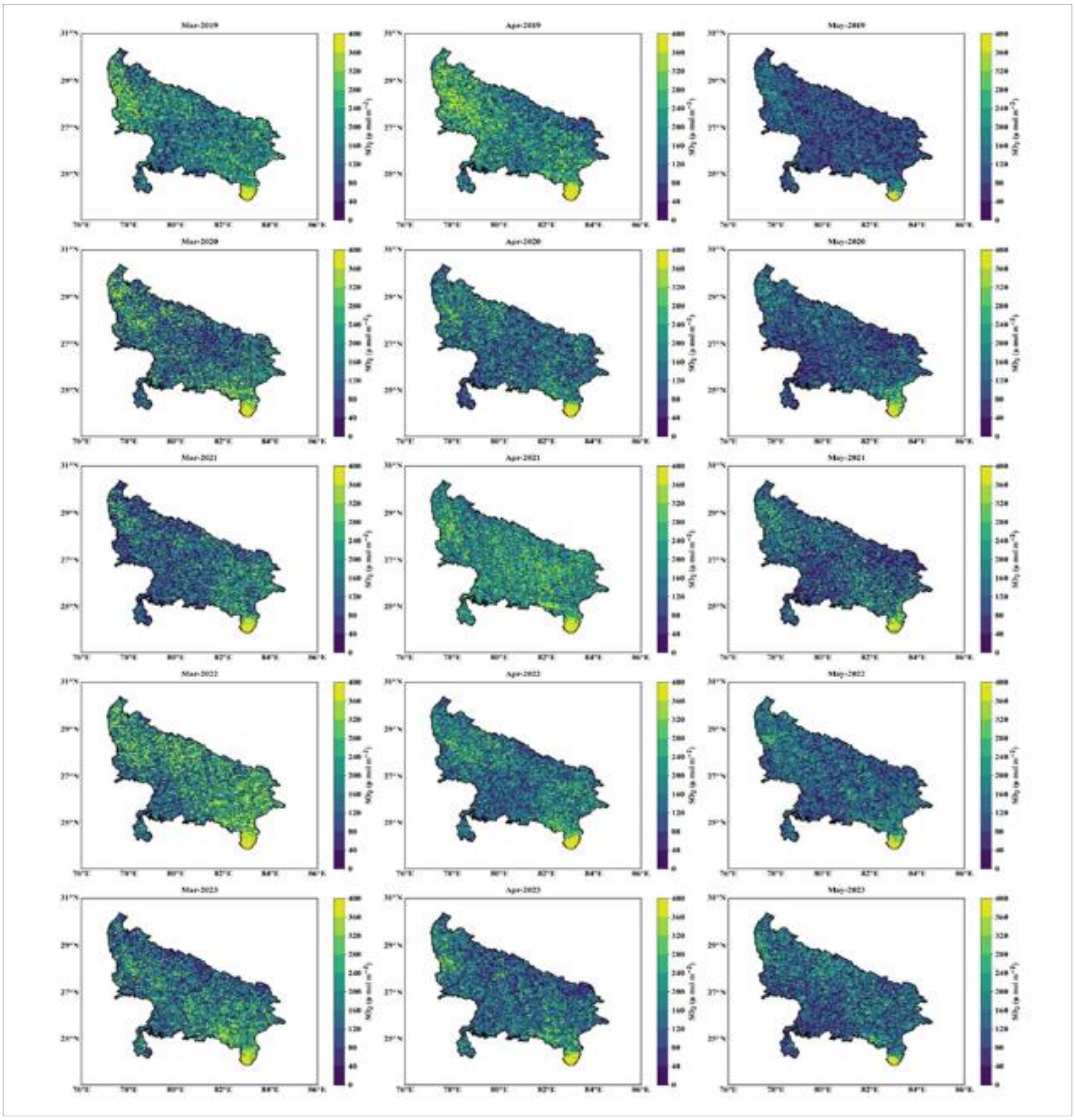
	March-2022		**April 2022**		**May 2022**	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
NO_2	41.546	21.658	49.653	25.48	44.643	20.185
SO_2	189.868	121.604	153.941	103.469	126.124	89.773
O_3	0.132093	0.000868	0.000579	0.000579	0.124812	0.001131
Aerosol	0.336755	0.079678	1.214737	1.214737	1.157519	0.306395

Table 5 Monthly statistics for four indicators of air quality in Uttar Pradesh, India in 2023

	March-2023		**April 2023**		**May 2023**	
Variable	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
NO_2	38.424	20.161	44.793	23.192	45.245	22.037
SO_2	151.33	113.125	136.589	102.377	122.518	95.227
O_3	0.132565	0.001754	0.130297	0.001118	0.131288	0.00051
Aerosol	-0.25101	0.093823	0.277134	0.140786	0.513292	0.165602


Mar-2019
Apr-2019
May-2019
Mar-2020
Apr-2020
May-2020
Mar-2021
Apr-2021
May-2021
Mar-2022
Apr-2022
May-2022
Mar-2023
Apr-2023
May-2023
31°N
29°N
27°N
25°N
76°E
78°E
80°E
82°E
84°E
86°E
60
54
48
42
36
30
24
18
12
6
0
NO₂ (μ mol m⁻²)

(a)NO_2


Mar-2019
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Mar-2020
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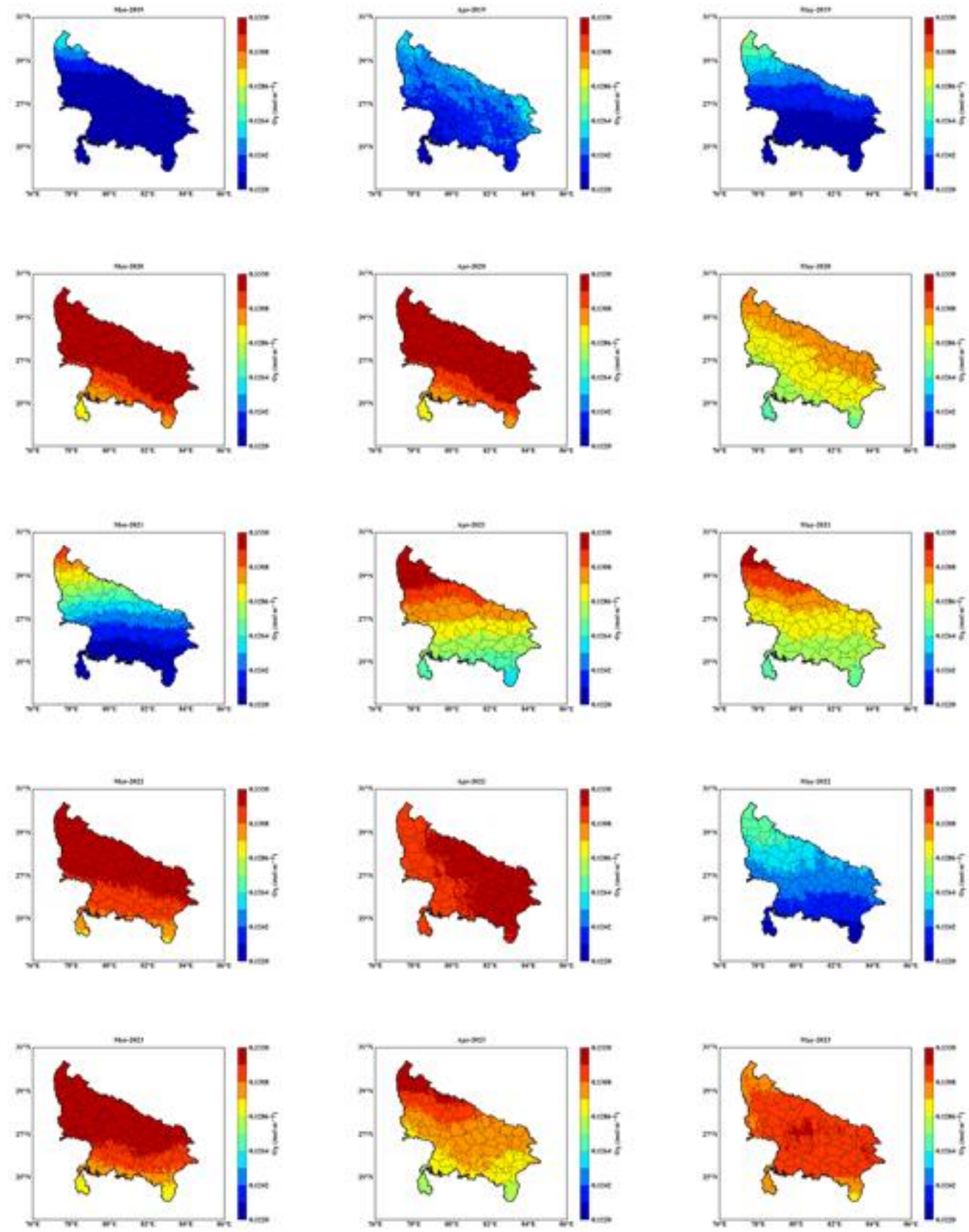
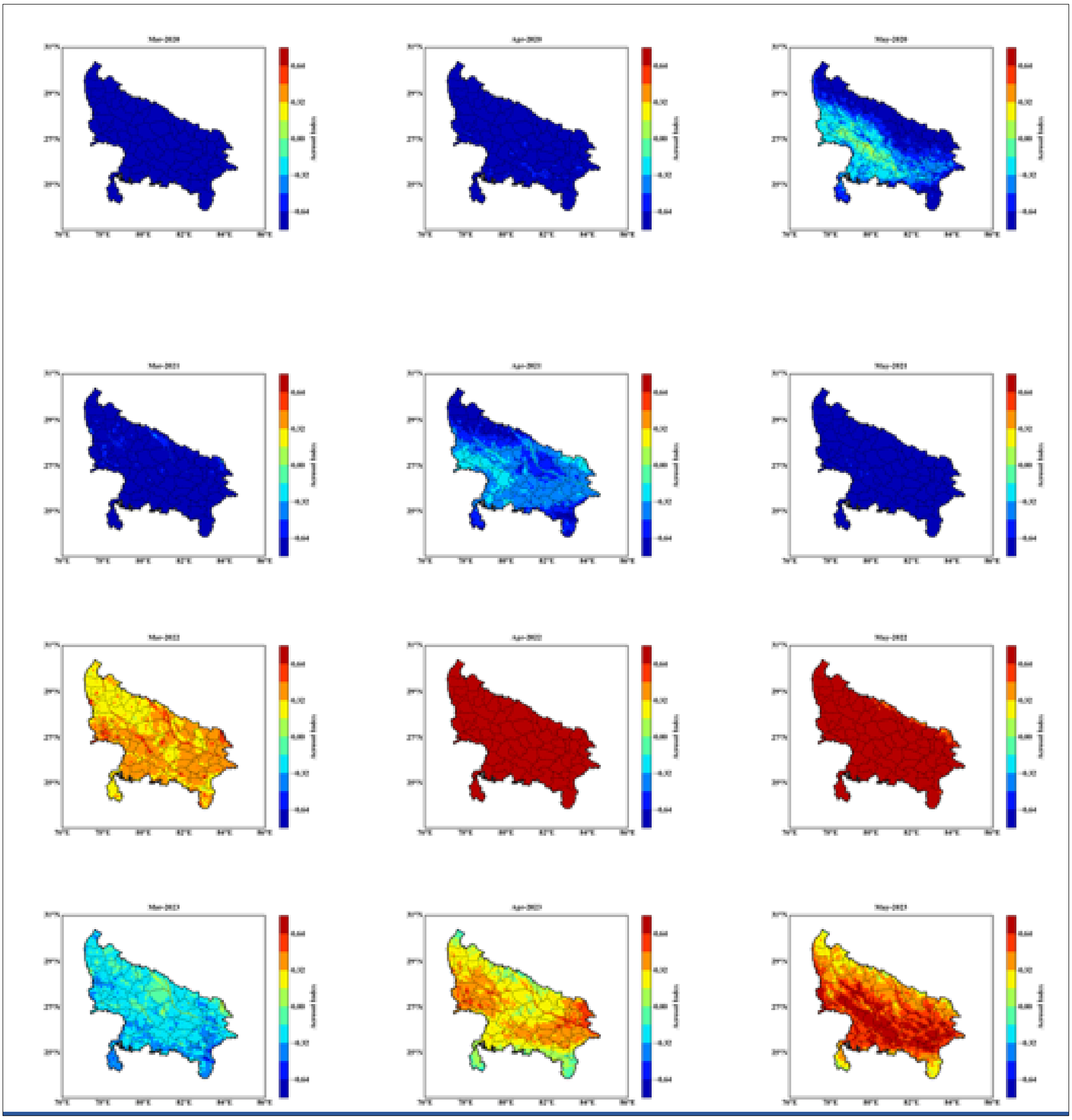
Apr-2023
May-2023
31°N
29°N
27°N
25°N
76°E
78°E
80°E
82°E
84°E
86°E
0
40
80
120
160
200
240
280
320
360
400
SO2 (μ mol m⁻²)

(b) SO_2



(c) O_3



(d) Aerosol

Figure 2 Spatial variation of (a) NO_2 CND (b) SO_2 for CND (c) Ozone (O_3) CND (d) ultraviolet Aerosol Index (UVAI) over India in Uttar Pradesh during march - May for 2019-2023

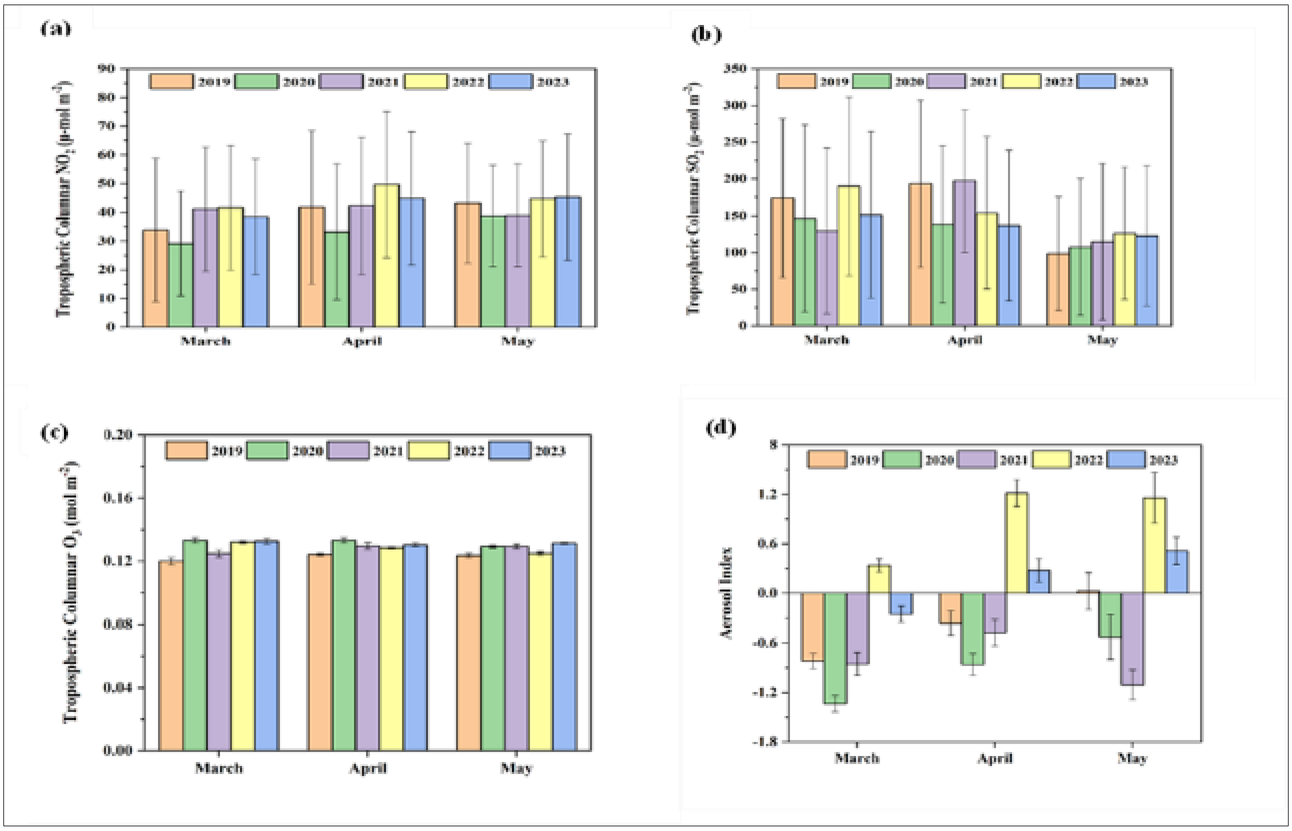


Figure 3 (a) **NO$_2$** Column Number Density over Uttar Pradesh from March to May from 2019 to 2023: Seasonal Variation. (b) For the years 2019 to 2023, the **SO$_2$** Column Number Density over UP in India from March to May. (c) Seasonal change of **O$_3$** Column Number Density over Uttar Pradesh in India from March to May for the years 2019 to 2023. (d) Seasonal variations in the UVAI Column Number Density over Uttar Pradesh, India, from March to May for the years 2019 to 2023

3.1. NO$_2$

The trends in the NO$_2$ CND concentration levels between 2019 and 2023 were interesting. The concentration standard was set at 33.84 µ mole/m^2 during the month of March 2019. A substantial reduction to 29.095 µ mole/m^2 or a drop of almost 14.05% arose as 2020 rolled around. The levels rose to 41.068 µ mole/m^2, a significant increase of 41.21% from the year before, in the next year, 2021, but this was followed by a rebound. The concentration was pushed to 41.546 in 2 µ mole/m^2 022, a slight increase of 1.16%, thanks to the increasing trend that persisted into that year, albeit at a slower rate. The levels dropped to 38.424 µ mole/m^2 in 2023, a reversal that corresponded to a 7.52% contraction from 2022, although by that time, the trend had reversed.

When discussing April, 2019, which had a concentration of 41.685 µ mole/m^2, served as our reference. As levels fell to 33.173 µ mole/m^2 in 2020, a 20.42% decrease, the winds of change brought about a fall. In contrast, the concentration increased significantly in 2021, rising to 42.192 µ mole/m^2, a significant increase of 27.17% from the year before. As the trend continued into 2022, the levels reached a peak of 49.653 µ mole/m^2, an increase of 17.68%. In contrast, the concentration dropped to 44.793 µ mole/m^2 in 2023, a 9.79% decrease, as though the tide had begun to retreat a little.

The levels for 2019 were at 43.141 µ mole/m^2 in May when we turned our attention there. A decrease of 38.692 µ mole/m^2 (or 10.30% less) was seen in the following year, 2020. A very slight fall to 38.935 µ mole/m^2, or a dip of 0.63%, was recorded in 2021, practically maintaining current level. However, the concentration increased to 44.643 µ mole/m^2 in 2022, a 14.66% increase, signaling a period of recovery. The levels slowly increased to 45.245 µ mole/m^2, an increase of 1.35%, continuing this growth pattern into 2023 despite the reduced rate.

3.2. SO$_2$

The 2019 reading placed the starting point at 173.89 µ mole/m^2 in March. In contrast, the following year saw a dip, with 2020's concentration falling to 146.244 µ mol/m^2, an approximately 15.93% decrease. This negative trend persisted into 2021, hitting 129.217 μ mole/m², which is a decline of 11.66% from the previous year. In stark contrast to this fall, levels in 2022 experienced a stunning upsurge as they climbed to 189.868 μ mole/m², representing an increase of about 46.99% from the year before. However, 2023 attempted to undo some of this progress, settling at 151.33 μ mole/m², which is a 20.30% decline from 2022.

In 2019, April set out on its trip with a concentration of 193.277 μ mole/m². By 2020, the levels had fallen significantly, to 138.048 μ mole/m², a 28.55% decrease. But in 2021, the wind shifted, raising the concentration to 197.157 μ mole/m², a considerable increase of 42.81% from the year before. However, this ascension was fleeting. The figures decreased to 153.941 μ mole/m² in 2022, a 21.91% decline. This downward trend persisted into 2023, with levels falling even lower to 136.589 μ mole/m², a decline of 11.26% year-over-year.

The May narrative began at 98.394 μ mole/m² in 2019. The story changed for the better in 2020, when the concentration increased by around 9.08% to 107.322 μ mole/m². The increasing trajectory maintained into 2021, albeit at a reduced rate, pushing the levels up to 114.434 μ mole/m², a gain of 6.62%. This development trajectory was repeated in 2022, when the concentration increased by 10.20% to 126.124 μ mole/m². However, as 2023 approached, a tiny decline was noticed, bringing the figures down to 122.518 μ mole/m², which amounts to a slight 2.86% decline.

3.3. O_3

The year 2019 witnessed a concentration level of 173.89 mole/m² for March. In 2020, this decreased by over 15.93%, reaching a value of 146.244 mole/m². This downward trend persisted in 2021, when there was a new low of 129.217 mole/m², a further decline of 11.66% from the year before. But 2022 reversed this pattern, rising dramatically by 46.99% to a concentration of 189.868 mole/m². The next year, 2023, had a slight decline to 151.33 mole/m², a 20.30% drop from 2022.

In 2019, April's tale was completed with 193.277 mole/m². The following year, this story took a negative turn, with the concentration falling to 138.048 mole/m², a considerable decrease of 28.55%. However, 2021 overturned this with a stunning increase to 197.157 mole/m², a growth of 42.81% from 2020. This increase was moderated by 2022, when a value of 153.941 mole/m² was recorded, a decrease of 21.91%. This slowdown continued until 2023, when the concentration stabilized at 136.589 mole/m², a further drop of 11.26% annually.

With regard to May, the year 2019 got off to a lowly start of 98.394 mole/m². This value increased by 9.08% the following year, 2020, to reach 107.322 mole/m². In 2021, the number increased to 114.434 mole/m², a 6.62% increase, continuing the growing trend, but at a slower rate. The ascent became steeper in 2022, reaching 126.124 mole/m², an increase of 10.20% from the year before. 2023, representing a 2.86% decrease, was pulled back somewhat to 122.518 mole/m².

3.4. Aerosol

The data from March tells a compelling story. The benchmark for 2019 was an index value of -0.817529229. When we go ahead to 2020, we see a sharp decline to -1.335219082, which represents a considerable drop of around 63.24% from the initial 2019 figure. The narrative changed again in 2021 when the index increased to -0.855315114, a 35.64% improvement over 2020 but still in the negative range. In 2022, the index reversed to the positive side and registered at 0.336754543, breaking this downward trend. The index's reversion back to -0.251007458 in 2023, a significant 174.58% decline from the upward swing of 2022, served as a reminder of the index's volatility, nonetheless.

An index of -0.360452674 for April 2019 was recorded. However, in 2020, the value further dropped to -0.861229668, representing a 138.85% steep loss. The index increased to -0.476924529 in 2021, a modest shift in gears that resulted in a 44.62% improvement. The index saw a significant transformation in 2022 and registered a strong positive of 1.214737068. The momentum persisted in 2023. However, the value began to decline by 2023 and peaked at 0.277143034, a 77.21% decline from the high.

The story of May is just as interesting, if not more so. A meagre positive of 0.025634619 was provided by 2019. This brief moment of optimism was short-lived, however, as 2020 caused the index to plunge sharply to a dismal -0.528067188, a startling 2158.16% decline. With an index of -1.106815731 and a further 109.67% decline, 2021 plunged even farther into the red. The index triumphantly returned to positivity in 2022, at 1.157518812, giving rise to new hopes. In spite of this, the story was once more altered in 2023, settling at a more subdued positive of 0.51329204, a drop of 55.64% from 2022.

4. Conclusion

The COVID-19 pandemic's beginning in late 2019 and early 2020 had an impact on various industries around the world, with environmental measures being particularly affected. In 2020, emissions will decline, which will be reflected in the slowdown in the economy. But the reappearance of some pollutants in 2021 denotes an economic recovery, as seen by the restart of traffic and industrial activities.

In 2020, NO_2 levels decreased in every month, most likely as a result of the consequences of global lockdowns. However, as limitations loosened and activity picked back up, levels started rising in 2021 and fluctuated in 2022 and 2023. Similar to NO_2, SO_2 concentrations fell in 2020, indicating a drop-in industrial activity at the time of the pandemic's peak. The variable levels in the following years imply various rates of industry recovery and perhaps additional regulatory actions. The trends for O_3 are a little more intricate. O_3 can result from NO_2, under sunlight as a secondary pollutant, however there are several variables that can affect its concentration. The impact of the epidemic may still be to blame for the decline in 2020. The sudden shifts in aerosol levels demonstrate both the immediate effects of less human activity in 2020 and the following recovery. The large variations point to influences other than human action.

The years 2019 to 2023, particularly 2020, mark a singular time in modern history where human activity was significantly limited as a result of a global epidemic. The COVID-19 effect can be seen in the decreases in pollution levels in 2020. The planet's reaction to human activities picking back up in the years that followed highlights how important our contribution to environmental changes has been. This time frame can serve as a reminder of the instant effects that human behaviour on the environment can have, both for good and bad.

Compliance with ethical standards

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Disclosure of conflict of interest

No conflict of interest to be disclosed.

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