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Comparative Analysis of NO2, SO2, CO, HCHO, and Aerosol Concentrations in Shanghai and Dubai Using Satellite Imagery from NASA's Giovanni and Sentinel-5P within Google Earth Engine

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ABSTRACT

Background and objective: Air pollution is a critical environmental issue, particularly in urban areas. This study investigates the concentrations of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and aerosols in Shanghai and Dubai from 2012 to 2021. The primary objective is to analyze the spatial and temporal variations in these pollutants, utilizing satellite data from Sentinel-5P and NASA's Giovanni.
Materials and methods: Using Google Earth Engine (GEE), we employed a robust methodological framework that integrated satellite imagery analysis with statistical modeling to assess the variations in air quality. Data was collected for both cities, focusing on seasonal patterns and pollution sources. Comparative analyses were conducted to understand the relationship between pollution levels and environmental factors.
Results and conclusion: The results revealed that Shanghai consistently exhibited higher concentrations of pollutants compared to Dubai, correlating with its extensive industrial activities. Seasonal variations were significant, with increased levels during specific months. In contrast, Dubai's air quality was more stable, although a recent rise in SO_2 levels poses concerns. The findings underscore the necessity for tailored air quality management strategies in both cities, emphasizing the importance of ongoing monitoring, regulatory frameworks, and public awareness to mitigate pollution effectively.

1. Introduction

Air pollution is a significant environmental issue that has widespread and detrimental effects on human health, ecosystems, and climate change (Chen et al., 2023). Key air pollutants, including nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and aerosols, directly and indirectly contribute to the rise in cardiovascular and respiratory diseases, as well as global warming (Cheng et al., 2024). Examining the changes in the concentration of these pollutants in major industrial cities like Shanghai and Dubai, which both face severe air quality challenges, is

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crucial.

Shanghai, one of China's largest industrial cities, experiences high levels of gas emissions such as NO_2 and CO due to heavy industries and widespread fossil fuel use (Liu et al., 2020). In contrast, Dubai, as a major commercial and construction hub in the Middle East, is impacted by aerosol particles resulting from construction activities, natural dust, and urban development (Kesti et al., 2022). These two cities, with different emission patterns, provide an excellent opportunity to study and compare the spatial and temporal variations of various pollutants.

The assessment of air pollution and its impacts on health and the environment has gained significant attention over recent decades. The use of satellite remote sensing has emerged as a powerful tool for monitoring atmospheric conditions and air quality (Dubovik et al., 2021). Various studies have utilized satellite data to analyze pollutant concentrations, identify their sources, and understand their temporal and spatial variations. This literature review synthesizes key findings from previous research related to air pollution and satellite observations.

Numerous studies have established a robust link between air pollution and adverse health effects. For instance, Pothirat et al. (2019) conducted a comprehensive review of epidemiological studies that indicate long-term exposure to particulate matter (PM) and gases like NO_2 and SO_2 is associated with increased morbidity and mortality rates, particularly for cardiovascular and respiratory diseases. Furthermore, Berlinger et al. (2024) emphasized the importance of considering both direct and indirect health impacts of air pollutants, including their role in exacerbating pre-existing conditions.

The advent of satellite technology has transformed the monitoring of air quality by providing spatially and temporally comprehensive data. Choi et al. (2014) demonstrated the capabilities of satellite instruments, such as the Aura satellite and its Ozone Monitoring Instrument (OMI), in capturing tropospheric NO_2 levels globally. Their research highlighted how satellite data can reveal urban pollution hotspots and track changes in air quality over time.

The monitoring of nitrogen dioxide is particularly important due to its role as a precursor to ground-level ozone and its contribution to respiratory illnesses. Salama et al. (2022) used satellite data from the GOME (Global Ozone Monitoring Experiment) to analyze urban NO_2 emissions, correlating the data with surface measurements to establish the reliability of satellite observations. Their findings indicated that industrial activities and vehicular traffic are major contributors to elevated NO_2 levels in urban environments.

Sulfur dioxide, primarily generated from the combustion of fossil fuels, is another critical pollutant monitored using satellite technology. Qu et al. (2019) analyzed SO_2 emissions using data from the OMI satellite and compared the results with ground-based observations in China. Their study revealed a strong correlation between satellite-derived SO_2 levels and industrial activity, illustrating the potential of remote sensing for tracking emissions from specific sources.

Carbon monoxide is a significant air pollutant with implications for both air quality and climate change. Strow et al. (2020) explored the use of satellite observations from the Atmospheric Infrared Sounder (AIRS) to assess CO levels in various regions. Their research demonstrated the ability of satellite data to capture seasonal variations in CO concentrations and correlate them with biomass burning and fossil fuel combustion activities.

The monitoring of formaldehyde is vital due to its formation as a secondary pollutant from photochemical reactions (Dai et al., 2024). Fan et al. (2021) utilized satellite data from the OMI to study HCHO levels in eastern China, highlighting its seasonal variations and the impact of anthropogenic activities on its concentration. Their findings emphasized the importance of understanding secondary pollutants in the context of urban air quality.

Aerosols significantly affect air quality and climate through direct and indirect effects on radiation (Filonchyk et al., 2024). Filonchyk et al. (2024) reviewed various satellite-based aerosol retrieval algorithms and their applications in monitoring aerosol concentrations globally. Their work highlighted the importance of combining satellite data with ground-based observations to improve the accuracy of aerosol measurements and enhance our understanding of their sources and impacts.

Comparative studies between different cities have also been conducted to assess the efficacy of satellite data in monitoring air quality. For example, Lachatre et al. (2020) compared the air quality in Beijing and Shanghai using satellite data and ground measurements, finding significant differences in pollutant levels attributed to varying industrial activities and urban planning policies. Such studies underscore the necessity of localized assessments to develop effective air quality management strategies.

The continuous advancement of satellite technologies, including the launch of missions like Sentinel-5P and its TROPOMI instrument, provides enhanced capabilities for monitoring air pollutants with greater accuracy and resolution (Kaplan & Avdan, 2020). Veefkind et al. (2012) highlighted the potential of TROPOMI in providing near-real-time data on various trace gases, paving the way for improved air quality monitoring and management.

This study aims to examine and compare the spatial and temporal changes in the concentrations of NO_2, SO_2, CO, HCHO, and aerosols in the cities of Shanghai and Dubai using satellite data from Sentinel-5P and NASA's Giovanni. The primary objectives of this research are:

Analysis of Spatial and Temporal Changes in Pollutants: To investigate and analyze the spatial and temporal patterns of these pollutants' concentrations in Shanghai and Dubai.

Comparison of Climatic and Industrial Impacts: To analyze the role of climatic differences and industrial activities in influencing the changes in pollutant concentrations.

Assessment of Satellite Data Overlap: To evaluate the capabilities and accuracy of Giovanni and Sentinel-5P data in analyzing pollutant changes and to investigate any overlaps or discrepancies between them.

The importance of this study lies in several key aspects:

Utilization of Two Reliable Satellite Data Sources: This research uniquely employs data from two reputable satellite sources (Sentinel-5P and Giovanni) to investigate and compare air pollutant changes in two cities with differing conditions.

Comparative Analysis Between Two Major Cities with Significant Differences: Shanghai and Dubai, as large industrial and economic metropolises with contrasting climates, offer a suitable context for studying and comparing various pollutant emission patterns.

Providing Recommendations for Better Air Quality Management: The findings of this research can aid environmental policymakers in both cities to adopt more effective policies for managing and reducing air pollution.

Research Questions or Hypotheses:

- Hypothesis One: The concentrations of NO_2, SO_2, CO, HCHO, and aerosols in Shanghai are higher than those in Dubai due to greater industrial development.
- Hypothesis Two: The seasonal and spatial variations of pollutant concentrations differ significantly between Shanghai and Dubai, linked to the climatic and emission source disparities in these cities.
- Hypothesis Three: The Giovanni and Sentinel-5P data exhibit minor differences in accuracy and temporal range, yet provide similar results in analyzing pollutant change patterns.

2. Materials and Methods

2.1. Study Area

The study focuses on two major urban centers Shanghai, China, and Dubai, United Arab Emirates (Fig.1). These cities have been selected for their distinct geographical, climatic, and industrial characteristics, which provide a rich context for analyzing variations in air pollution levels, particularly for nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and aerosols.

2.1.1 Shanghai, China

Shanghai is one of the largest cities in China and serves as a global financial hub. It has a population of over 24 million people and covers an area of approximately 6,340 square kilometers. The city has a humid subtropical climate, characterized by hot, humid summers and cool, damp winters (Tian et al., 2017).

Industrial and Urbanization Impact:

Shanghai's rapid industrialization has led to a significant increase in emissions from transportation, construction, and manufacturing sectors. The Yangtze River Delta, in which Shanghai is situated, is one of the most economically vibrant regions in China, further intensifying air quality challenges. The city experiences high levels of NO_2 and SO_2 due to vehicle emissions and industrial activities, making it an ideal location for studying the impact of urbanization on air pollution.

Geographical Features:

Shanghai is located at the eastern coast of China, bordered by the East China Sea to the east and the Yangtze River to the south. The city's topography is relatively flat, and its location can lead to stagnant air conditions, which may exacerbate pollution levels, particularly during the summer months when temperature inversions are more common.

2.1.2 Dubai, United Arab Emirates

Dubai is a major city within the United Arab Emirates, known for its rapid development and economic diversification. With a population exceeding 3 million people and covering approximately 4,114 square kilometers, Dubai has evolved into a leading global city and a prominent business and tourism center in the Middle East (Elessawy, 2017).

Economic Activities and Pollution Sources:

Dubai's economy relies heavily on trade, tourism, and construction, which have all contributed to increased air pollution levels. The construction boom has led to significant emissions of particulate matter (aerosols) and other pollutants. Moreover, the city's dependence on vehicles for transportation further contributes to the emissions of NO_2 and CO.

Climatic Conditions:

Dubai has a hot desert climate, characterized by extremely high temperatures during summer, mild winters, and low annual rainfall. The arid climate results in significant dust storms, contributing to aerosol levels. The atmospheric conditions in Dubai often lead to stagnant air, which can trap pollutants and exacerbate air quality issues.

2.1.3 Comparison of Study Areas

The contrasting characteristics of Shanghai and Dubai make them valuable study areas for this research. Shanghai's industrial activities and dense urban population contrast sharply with Dubai's construction-driven economy and environmental conditions. By comparing these two cities, this study aims to elucidate the factors influencing air pollution levels, providing insights that can inform air quality management strategies in both regions.

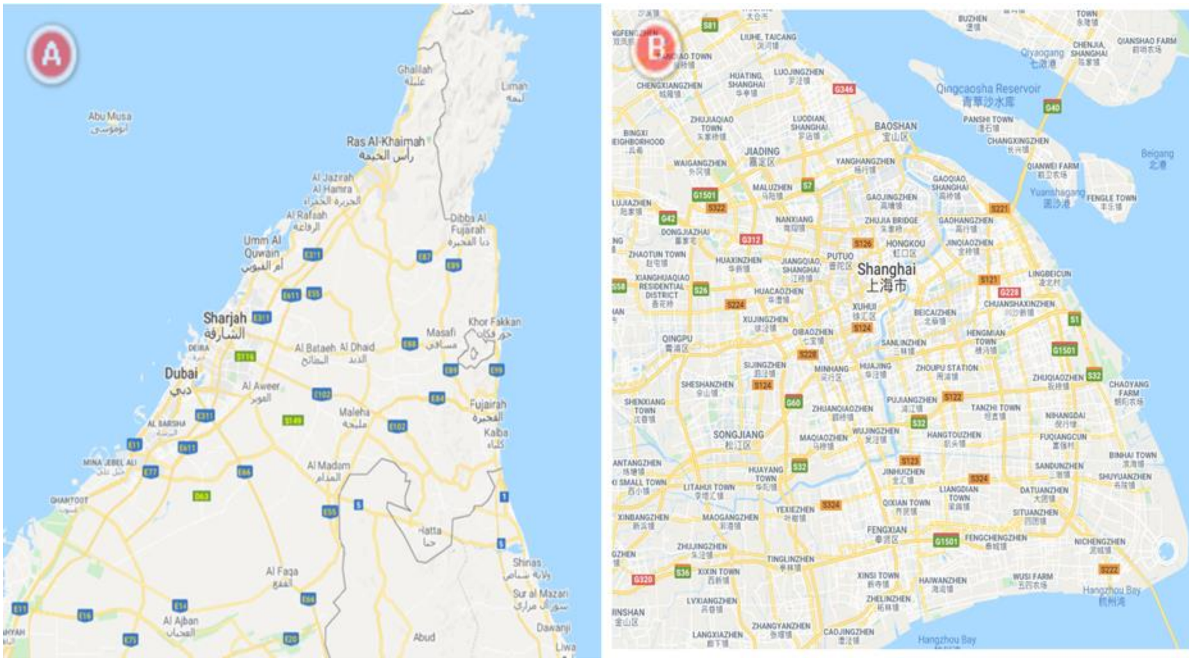

Fig. 1 - Research Study Areas: A) Dubai, United Arab Emirates; B) Shanghai, China

2.2. Methodology

This section outlines the methodology employed in this study, detailing the data sources, analytical techniques, and procedures used to assess the spatial and temporal changes of air pollutants (NO_2, SO_2, CO, HCHO, and aerosols) in the study areas of Dubai and Shanghai.

2.2.1 Data Sources

The data for this study were obtained from NASA's Giovanni platform, and Google Earth Engine (GEE). These platforms provide high-resolution satellite imagery and atmospheric data, essential for assessing air quality (Wang et al., 2022).

Sentinel-5P Data:

The Sentinel-5P satellite, launched by the European Space Agency, is equipped with the Tropospheric Monitoring Instrument (TROPOMI), which captures data on various trace gases, including NO_2, SO_2, CO, HCHO, and aerosols. The data are available at a spatial resolution of approximately 7 km x 3.5 km, allowing for detailed monitoring of pollutant concentrations over time (Cofano et al., 2021).

NASA's Giovanni Data:

Giovanni is a web-based application developed by NASA that allows users to visualize and analyze satellite data. It provides access to various datasets, including atmospheric composition and meteorological parameters (Malings et al., 2023). For this study, Giovanni's data on air quality and meteorological parameters were accessed to supplement the Sentinel-5P data, allowing for a comprehensive analysis of the pollutants in both cities.

2.2.2 Analytical Techniques

The analysis of the spatial and temporal changes in air pollutant concentrations involved several advanced techniques, particularly leveraging the capabilities of Google Earth Engine (GEE):

Geospatial Analysis with GEE:

Google Earth Engine provided a robust platform for conducting geospatial analyses of air pollutants across the study areas (Fuentes et al., 2020). Utilizing GEE's vast library of algorithms and datasets, we were able to process large volumes of satellite imagery efficiently. This included creating high-resolution spatial visualizations and heat maps to illustrate the distribution of pollutants (NO_2, SO_2, CO, HCHO, and aerosols) across Dubai and Shanghai. The ability to analyze temporal changes allowed for the visualization of pollutant trends over specific time intervals.

Time-Series Analysis:

Time-series analysis was conducted using GEE to assess changes in pollutant concentrations over the study period. By employing GEE's time-series capabilities, we analyzed monthly and seasonal variations in air quality metrics. This method enabled the identification of long-term trends and patterns, which were critical for understanding how air quality evolves in response to changes in urbanization, industrial activities, and meteorological conditions.

Statistical Analysis:

The statistical analysis included employing descriptive statistics and regression analysis to quantify relationships between pollutant concentrations and various influencing factors. GEE facilitated the integration of additional datasets, such as population density and land use patterns, which were critical for understanding the sources of emissions and the impact of urbanization on air quality.

Comparative Analysis:

A comparative framework was established within GEE to evaluate differences in pollutant levels between Dubai and Shanghai. This involved using statistical tests to determine the significance of differences observed in concentrations of air pollutants across the two cities. GEE's capabilities allowed for efficient cross-comparison, enabling a comprehensive understanding of how different urban contexts influence air quality.

Integration of Meteorological Data:

GEE also enabled the integration of meteorological data, such as temperature, humidity, and wind speed, into the air quality analysis. This integration was essential for elucidating the roles of meteorological variables in pollutant dispersion and concentration. GEE's ability to process and analyze diverse datasets in a unified environment greatly enhanced the study's analytical depth.

Visualization of Results:

The results obtained from the analyses were visualized using GEE's powerful mapping and charting tools. This allowed for clear presentations of findings, including visual representations of pollutant trends and spatial distributions. These visualizations facilitate a better understanding of air quality dynamics and support effective communication of results to stakeholders.

3. Result

3.1 Temporal Changes in NO_2 Concentration

The analysis of NO_2 concentrations from 2019 to 2021 reveals significant differences between Dubai and Shanghai (Fig.2). In Shanghai, the concentration of NO_2 is consistently high, primarily due to ongoing industrialization, the presence of numerous power plants, and heavy vehicular traffic. This elevated concentration is evident across the region, indicating that urban activities continue to contribute to poor air quality. The high levels of NO_2 not only highlight the impact of anthropogenic emissions but also serve as a marker for urban pollution in one of China's most densely populated cities.

Conversely, the NO_2 concentrations in Dubai are generally lower than those observed in Shanghai. However, it is noteworthy that the NO_2 levels are more pronounced in coastal areas. This pattern can be attributed to the high commercial ship traffic along the coast, which contributes to localized emissions. The maritime activities, coupled with the city's urbanization, play a crucial role in shaping the NO_2 distribution across Dubai.

3.2 Spatial Variations in Aerosol Concentration

The examination of aerosol concentrations from 2019 to 2021 further illustrates the distinct environmental contexts of Dubai and Shanghai. In Dubai, the aerosol levels are notably high, reflecting the region's desert landscape, characterized by limited vegetation and prevailing arid conditions. The increase in aerosol concentrations compared to previous years may indicate an exacerbation of dust storms, likely linked to this year's drought conditions. The combination of low vegetation cover and dry weather enhances the susceptibility of the region to dust events, leading to higher particulate matter levels in the atmosphere.

In contrast, Shanghai exhibits lower aerosol concentrations, which can be attributed to the relatively higher vegetation coverage in the region. The presence of green spaces and trees acts as a natural barrier, reducing the dispersion of dust and contributing to better air quality. The vegetation not only helps to mitigate dust levels but also plays a vital role in absorbing pollutants, further enhancing the overall air quality in the city.

3.3 Comparative Analysis of NO_2 and Aerosols in Dubai and Shanghai

The comparative analysis of NO_2 and aerosol concentrations between Dubai and Shanghai highlights the impact of urbanization, industrial activities, and environmental conditions on air quality. While Shanghai faces challenges related to industrial emissions, Dubai's air quality is influenced significantly by its geographical context and climatic conditions.

NO_2 Concentration: The persistent high levels of NO_2 in Shanghai underscore the need for effective air quality management strategies to mitigate pollution from industrial and vehicular sources. The contrasting lower levels in Dubai suggest that while the coastal emissions are a concern, the overall air quality may still benefit from the city's urban planning and regulation of emissions.

Aerosol Levels: The rising aerosol concentrations in Dubai point to increasing environmental vulnerabilities, particularly regarding dust storms. In comparison, Shanghai's effective green spaces play a critical role in controlling aerosol levels, suggesting that urban planning initiatives focused on increasing vegetation could be beneficial.

Overall, the results indicate a complex interplay of factors influencing air quality in both cities. Addressing these challenges requires a multifaceted approach that considers both technological interventions for reducing emissions and natural solutions such as enhancing vegetation cover.

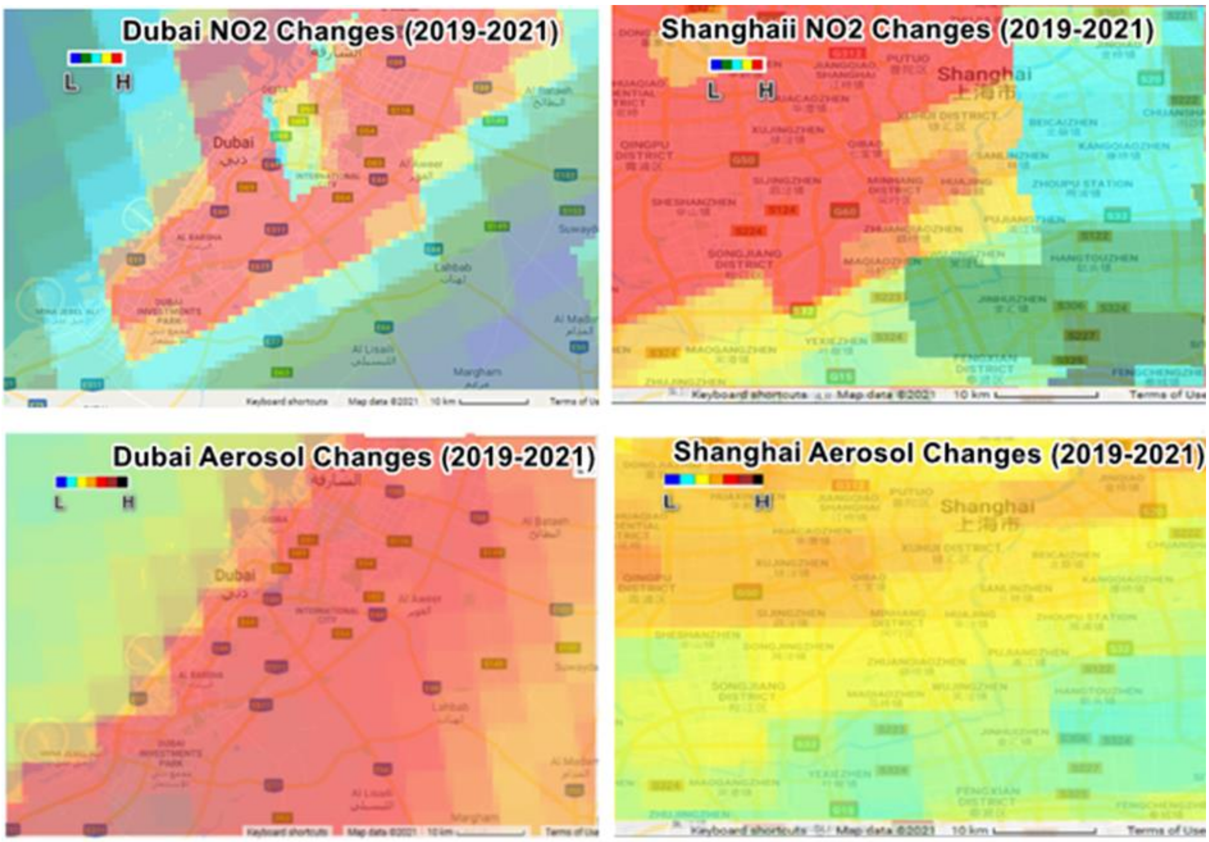

Fig. 2- Spatial Distribution of NO_2 and Aerosol Concentrations in Dubai and Shanghai (2019-2021)

3.4 Temporal Changes in CO and SO_2 Concentrations

The assessment of carbon monoxide (CO) and sulfur dioxide (SO_2) concentrations from 2019 to 2021 reveals significant spatial and temporal variations between Shanghai and Dubai, driven by urbanization, industrial activity, and transportation patterns (Fig.3).

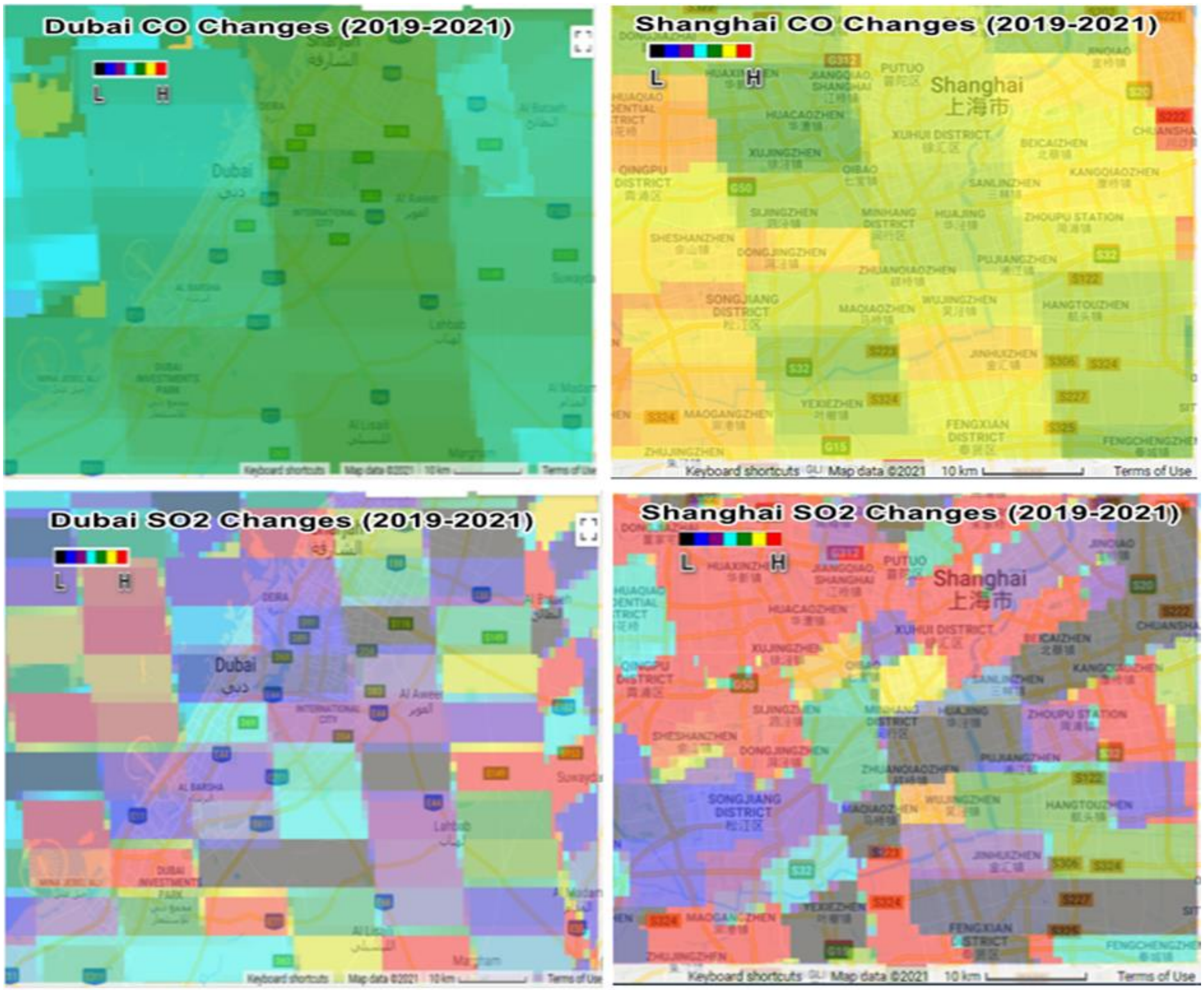

Fig. 3- Spatial Distribution of CO and SO_2 Concentrations in Dubai and Shanghai (2019-2021)

3.4.1 Spatial Variations in CO Concentration

From the spatial analysis, it is evident that Shanghai experiences notably higher CO concentrations compared to Dubai. The elevated levels of CO in Shanghai can be attributed to several factors, including high population density, extensive vehicular traffic, and a significant number of factories operating within the metropolitan area. The presence of these emission sources contributes to a persistent buildup of CO, particularly in urban centers and heavily trafficked roadways.

In contrast, the CO levels in Dubai are relatively lower. The city's urban planning, which incorporates strategies for traffic management and pollution control, likely contributes to the reduced concentrations of CO. However, localized spikes may still occur near major thoroughfares and areas with high vehicle activity, but overall, the emissions appear to be effectively managed.

3.4.2 Temporal Changes in SO_2 Concentration

Sulfur dioxide (SO_2) concentrations follow a similar pattern, with Shanghai exhibiting significantly higher levels than Dubai. The increased SO_2 emissions in Shanghai are primarily linked to industrial activities, including power generation and manufacturing processes that rely on fossil fuels. The persistent industrial output, combined with high traffic volumes, results in elevated SO_2 concentrations, particularly in proximity to factories and transport hubs.

In Dubai, SO_2 concentrations are less dense, reflecting the city's efforts to implement cleaner technologies and transition towards more sustainable energy sources. While localized emissions may still occur, especially during periods of increased industrial activity, the overall trend indicates a commitment to maintaining lower SO_2 levels through regulatory measures and investment in alternative energy.

3.4.3 Comparative Analysis of CO and SO_2 Levels in Dubai and Shanghai

The comparative analysis of CO and SO_2 concentrations from 2019 to 2021 underscores the stark differences in air quality management between the two cities:

CO Concentration: The persistent high levels of CO in Shanghai illustrate the challenges posed by urbanization and industrialization. The data indicates a pressing need for enhanced air quality measures to mitigate the effects of emissions from vehicles and factories. Conversely, Dubai's relatively lower CO levels reflect successful urban management and environmental policies that prioritize air quality.

SO_2 Concentration: The significant SO_2 emissions in Shanghai point to a reliance on fossil fuel combustion for industrial activities. In contrast, Dubai's lower SO_2 concentrations highlight the city’s transition towards cleaner energy solutions and its effectiveness in implementing policies aimed at reducing sulfur emissions.

Overall, the findings indicate that while Shanghai grapples with air quality issues driven by its dense industrial and urban activities, Dubai demonstrates a proactive approach to managing its air quality through strategic urban planning and regulation. Addressing the challenges posed by CO and SO_2 emissions will require continued efforts in both cities, focusing on sustainable practices and emissions reduction strategies.

3.5. Comprehensive Analysis of SO_2 and CO Changes with Wind Speed and Precipitation in Dubai

The provided graph consists of four major components: the SO_2 changes, CO changes, wind speed variations, and precipitation over time from early 2020 to the end of 2021 for Dubai (Fig. 4).

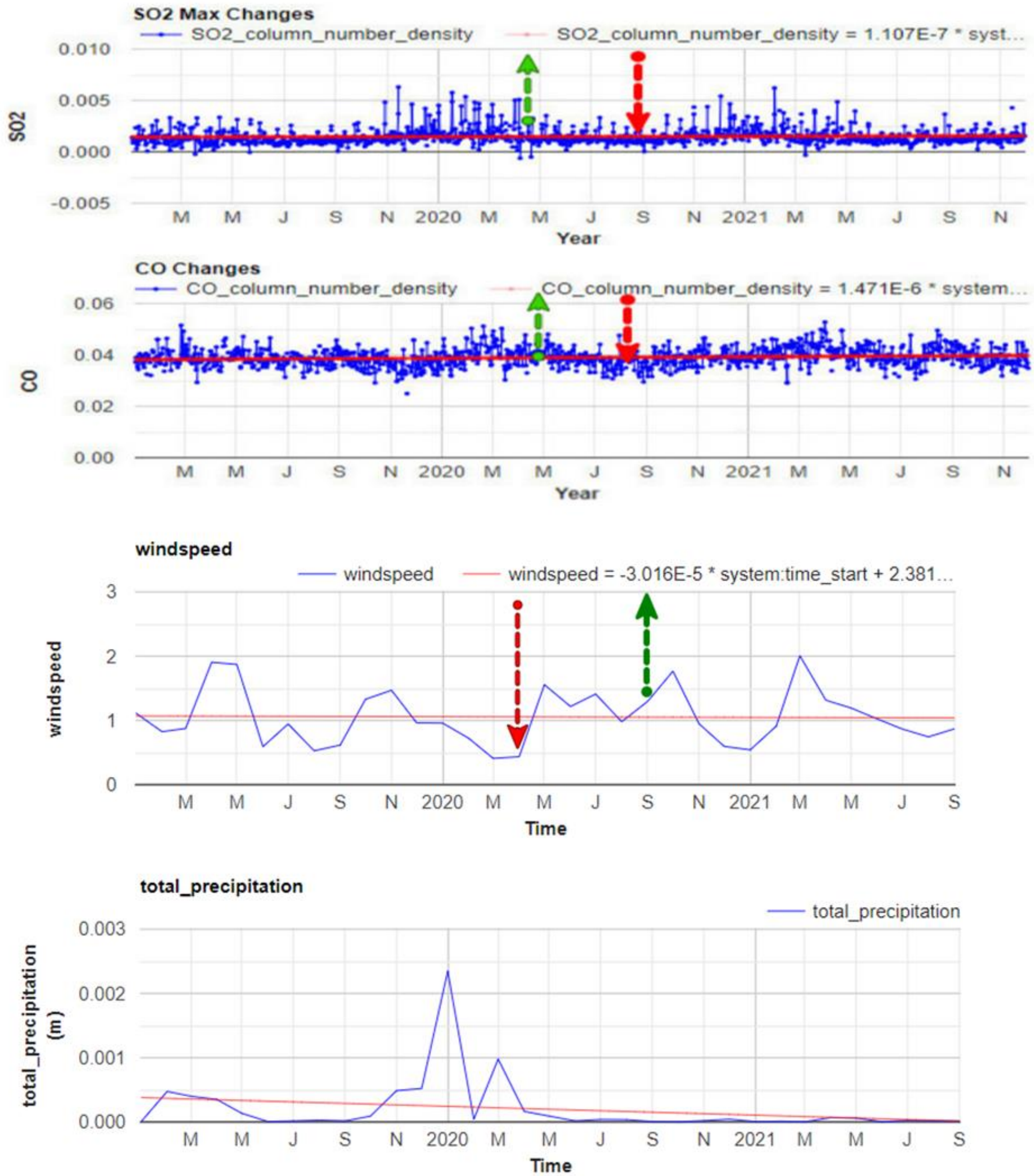

Fig.4 - Comparison of SO2 and CO Concentrations with Wind Speed and Precipitation in Dubai

1. SO_2 and CO Concentration Changes (2020-2021)

The first two plots showcase the changes in SO_2 (Sulfur Dioxide) and CO (Carbon Monoxid) concentrations over time. The blue lines with fluctuations represent the daily changes in the atmospheric concentrations, while the horizontal red lines indicate the trend lines for the respective gases.

SO_2:

The SO_2 concentrations remain relatively low throughout the period, with some noticeable spikes around March 2020 and August 2020, indicated by green and red arrows.

March 2020 (red arrow) shows a significant increase in SO_2 levels, which may correlate with industrial activities or reduced wind speeds, as seen in the wind speed graph.

August 2020 (green arrow) marks another spike, which could potentially be due to weather changes or fluctuations in industrial output.

CO:

The CO concentration follows a similar trend to SO_2 but has generally higher values, which is expected due to Dubai's high traffic and urban activity.

The two distinct spikes—around March 2020 and August 2020—match those in the SO_2 graph, indicating a possible common cause such as weather conditions or a shared source of pollution.

2. Wind Speed (2020-2021)

Wind speed plays a crucial role in the dispersion of pollutants. The third plot depicts the wind speed variations across the same period:

The wind speed appears to drop significantly in March 2020 (red arrow), which correlates with the SO_2 and CO concentration spikes. This decrease in wind speed likely caused the pollutants to accumulate in the atmosphere, resulting in higher concentrations.

In August 2020 (green arrow), there’s a noticeable increase in wind speed, which aligns with a decrease in the concentration spikes for both gases, suggesting that higher wind speeds helped disperse the pollutants more effectively.

Overall, the analysis suggests that lower wind speeds contribute to the accumulation of SO_2 and CO, while higher wind speeds promote the dispersion of these pollutants.

3. Precipitation (2020-2021)

Precipitation also plays a critical role in cleansing the atmosphere by removing pollutants. The fourth plot shows the total precipitation levels:

There’s a significant spike in precipitation around March 2020, which coincides with the spike in SO_2 and CO. However, despite this increase in rainfall, the concentrations of pollutants also increased, indicating that the precipitation alone was insufficient to offset the effects of reduced wind speed during that period.

Later in August 2020, despite the increase in wind speed, the lack of precipitation may have allowed some pollutants to remain in the air, albeit at reduced concentrations due to the wind's dispersive effect.

4. Comparative Analysis and Conclusions

SO_2 and CO Relationship: The fluctuations in both gases are closely aligned, suggesting common sources such as traffic emissions or industrial activities. The simultaneous peaks and troughs reinforce the idea that both gases respond similarly to external influences like wind and precipitation.

Wind Speed and Pollutant Levels: There’s a clear inverse relationship between wind speed and pollutant concentrations. Lower wind speeds lead to higher pollutant accumulation (as seen in March 2020), while higher wind speeds facilitate dispersion (as seen in August 2020). This finding highlights the importance of wind in maintaining air quality in urban areas like Dubai.

Precipitation Impact: The effect of precipitation appears more nuanced. While precipitation events (like in March 2020) can help cleanse the air, their effect is less pronounced when wind speeds are low. This suggests that precipitation, in isolation, may not be enough to significantly reduce pollutant concentrations without the aiding factor of wind.

March 2020: The spike in both SO_2 and CO concentrations is associated with low wind speeds and a significant amount of precipitation. This implies that despite the rainfall, the lack of wind allowed pollutants to accumulate in the atmosphere.

August 2020: Higher wind speeds resulted in a decrease in pollutant concentrations, despite lower levels of precipitation, indicating that wind plays a more critical role in pollutant dispersion than rainfall in Dubai's arid climate.

The interaction between these environmental factors—wind speed, precipitation, and pollutant concentrations—provides important insights into how natural phenomena affect air quality in Dubai, particularly in an urban setting with considerable industrial and vehicular activity.

3.6. Comprehensive Analysis of SO_2 and CO Variations with Wind Speed and Precipitation in Shanghai (2020-2021)

The provided graph presents the SO_2 (Sulfur Dioxide) and CO (Carbon Monoxide) concentration changes in Shanghai from 2020 to 2021, alongside the corresponding variations in wind speed and precipitation (Fig. 5).

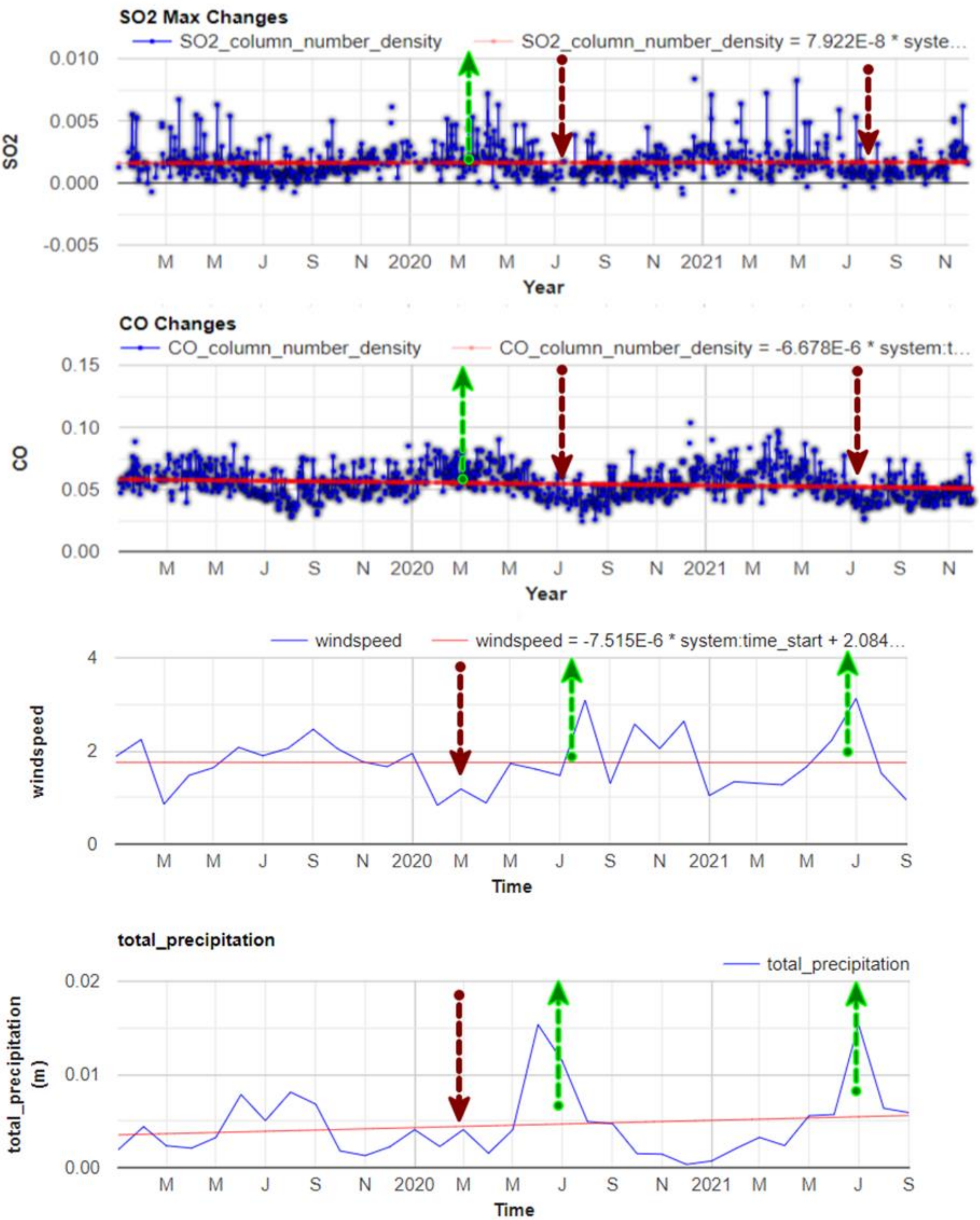

Fig.5 - Comparison of SO2 and CO Concentrations with Wind Speed and Precipitation in Shanghai

1. SO_2 and CO Concentration Changes

The first two plots depict the daily fluctuations in SO_2 and CO concentrations. The blue lines represent the number density changes over time, while the horizontal red lines serve as trend lines.

SO_2 Concentration

March 2020 (red arrow): There is a notable spike in SO_2 concentrations during this period. This peak is likely due to industrial activity combined with unfavorable meteorological conditions, such as reduced wind speeds. The spike reflects higher emissions that failed to disperse efficiently.

August 2020 (green arrow): Another peak in SO_2 levels is observed, coinciding with slightly higher wind speeds and increased precipitation. This could indicate a temporary increase in emissions, possibly from factories or increased traffic.

Overall, the SO_2 levels show some degree of fluctuation, but the spikes in March and August suggest that localized meteorological and industrial factors are at play.

CO Concentration

March 2020 (red arrow): Similar to SO_2, CO concentrations also spike significantly in March 2020. This reflects the effect of both industrial emissions and the low wind speed, which prevented the CO from dispersing.

August 2020 (green arrow): CO levels also rise slightly, mirroring the trend seen in SO_2. The presence of more emissions combined with relatively higher wind speed and precipitation likely resulted in a slower dissipation process, maintaining elevated CO levels.

Throughout the year, CO concentrations remain slightly higher than SO_2, reflecting more continuous emissions from traffic, factories, and other anthropogenic sources.

2. Wind Speed

The third plot represents the changes in wind speed throughout the period. Wind speed has a critical role in dispersing air pollutants like SO_2 and CO.

March 2020 (red arrow): A noticeable drop in wind speed is observed around March 2020. This coincides with the sharp increase in SO_2 and CO concentrations, suggesting that the lower wind speeds allowed pollutants to accumulate in the atmosphere.

August 2020 (green arrow): Wind speed slightly increases in August 2020. While this helps disperse some of the pollutants, the simultaneous increase in precipitation (discussed below) and emissions may have counteracted its effect, leading to persistent higher pollutant levels.

Generally, lower wind speeds correlate with higher pollution concentrations, while higher wind speeds promote pollutant dispersion, contributing to better air quality.

3. Precipitation

Precipitation can cleanse the atmosphere by removing particles and gases through wet deposition.

March 2020 (red arrow): Precipitation levels are relatively low during this time, coinciding with high pollutant concentrations. The combination of low precipitation and wind speed creates conditions that allow pollutants to remain trapped near the surface, leading to poor air quality.

August 2020 (green arrow): There is a sharp increase in precipitation during this period, which might have helped reduce some airborne pollutants. However, the simultaneous increase in emissions due to industrial activities and the higher wind speeds indicates that the effect of precipitation alone may have been insufficient to offset pollution.

Overall, the influence of precipitation appears moderate. While it can aid in reducing pollutant concentrations during heavy rain events, its effect is less significant when wind speeds are low, and emissions remain high.

4. Comparative Analysis and Interactions

SO_2 and CO Relationship: The fluctuations in SO_2 and CO concentrations are quite similar, indicating shared emission sources, such as factories, vehicles, and industrial activity. Both pollutants spike around the same periods, showing their susceptibility to the same meteorological conditions.

Wind Speed and Pollutant Levels: There is a clear inverse relationship between wind speed and the concentrations of SO_2 and CO. When wind speed drops (as in March 2020), pollutants accumulate, resulting in higher levels of air pollution. Conversely, higher wind speeds (as in August 2020) aid in dispersing pollutants, though elevated emissions during this time can mitigate this effect.

Precipitation Impact: Precipitation plays a secondary role in pollutant removal. Its impact is most evident when combined with favorable wind conditions. When precipitation increases, as seen in August 2020, pollutant levels do decrease slightly, but the interaction between emissions, wind speed, and precipitation complicates the overall effect. The lack of sufficient wind in March 2020, despite some rainfall, allowed pollutants to persist.

The graphs provide valuable insights into the complex interactions between pollutants (SO_2 and CO), wind speed, and precipitation in Shanghai from 2020 to 2021:

March 2020 saw a sharp increase in pollutant concentrations due to low wind speeds and limited precipitation, allowing emissions from industrial activities to accumulate.

August 2020 experienced higher precipitation and increased wind speed, contributing to a slight reduction in pollutant concentrations. However, the increase in emissions during this period mitigated the cleansing effect of wind and rain.

The overall trend demonstrates that wind speed is the most critical factor in determining air quality, with precipitation playing a supportive but less dominant role.

By understanding these dynamics, policymakers and environmental agencies can better predict air quality patterns and take measures to mitigate pollution in cities like Shanghai.

3.7. Temporal and Spatial Analysis of NO2, Aerosol, Wind Speed, and Precipitation Interactions in Dubai (2019-2021)

Based on the provided graphs for NO2, Aerosol, wind speed, and precipitation changes in Dubai, we can analyze and interpret the relationships between these variables comprehensively (Fig. 6).

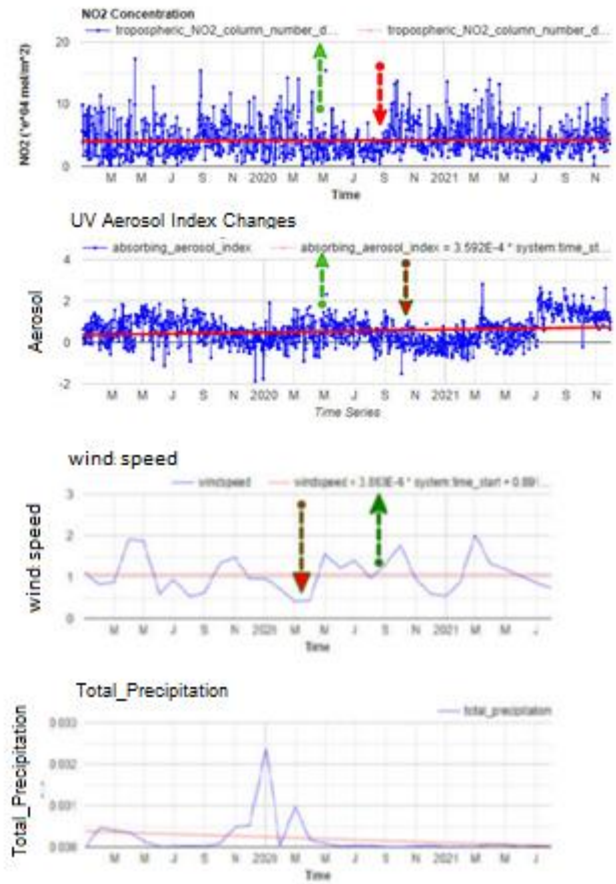

Fig.6 - Temporal Analysis of NO2 Concentration, Aerosol Index, Wind Speed, and Total Precipitation in Dubai (2019-2021)

1. NO2 Changes:

Temporal Trend: The NO2 data from 2019 to 2021 shows significant fluctuations in the concentration of this gas. There is a notable peak in mid-2020 (indicated by the red arrow), which could be associated with reduced wind speed and poor air ventilation.

Relationship with Wind Speed: When wind speed decreases (shown by the red vertical lines in the wind and NO2 graphs), the concentration of NO2 tends to increase. This correlation suggests that wind helps in dispersing pollutants, and during low wind periods, pollutants accumulate near the ground.

Relationship with Precipitation: The graph shows that during rainfall events (such as early 2020), there is a temporary decrease in NO2 concentration. This reduction could be due to the "washout effect" where rain cleanses the atmosphere of pollutants.

2. Aerosol Changes:

Temporal Trend: The aerosol concentration in Dubai also exhibits significant fluctuations. A peak in aerosol concentration is observed in late 2020 (red arrow), which might be attributed to dry conditions, dust, and reduced vegetation cover.

Relationship with Wind Speed: Similar to NO2, the aerosol concentration increases when wind speed is low. During low wind conditions, dust particles and aerosols remain suspended in the air, leading to higher concentrations.

Relationship with Precipitation: During rainfall events (early 2020), aerosol concentrations drop, which is likely due to the removal of dust and aerosols by precipitation.

3. Wind Speed Changes:

Temporal Trend: Wind speed in Dubai shows variations throughout the year. During periods of higher wind speed (green arrows), the concentration of pollutants, particularly NO2 and aerosols, decreases. This indicates the role of natural ventilation in clearing the air.

Impact on Pollutants: When wind is stronger (as shown by the green arrows in the wind graph), both NO2 and aerosol concentrations decrease. This demonstrates the ability of wind to disperse and dilute airborne pollutants.

4. Precipitation Changes:

Temporal Trend: Precipitation in Dubai is very sparse and scattered, with only a few noticeable rainfall events, such as in early 2020.

Impact on Pollutants: During rainfall events, there is a clear reduction in pollutant concentrations. This is due to the natural washing effect of rain, which removes pollutants from the atmosphere.

This analysis shows a clear relationship between wind speed, precipitation, and the concentration of pollutants like NO2 and aerosols. In general, increased wind and rainfall lead to a reduction in pollutant concentrations, while reduced wind speed and dry conditions result in higher pollutant accumulation in the atmosphere.

3.8. Temporal and Spatial Analysis of NO2, Aerosol, Wind Speed, and Precipitation Interactions in Shanghai (2019-2021)

The graph provided illustrates the temporal interactions between NO2 concentration, aerosol index, wind speed, and precipitation in Shanghai from 2019 to 2021 (Fig. 7). Each of these variables plays a significant role in air quality and environmental dynamics in the city. Below is a detailed analysis of the patterns and interactions for each of these factors:

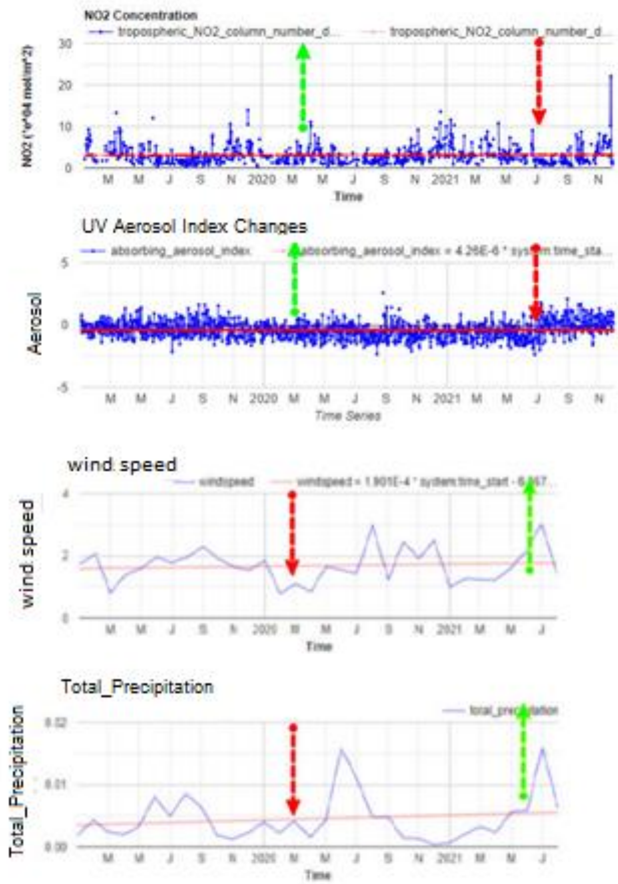

Fig. 7 - Temporal Analysis of NO2 Concentration, Aerosol Index, Wind Speed, and Total Precipitation in Shanghai (2019-2021)

1. NO2 Concentration (Top Panel)

Trends and Peaks: The NO2 concentration shows several peaks, with a distinct rise around mid-2020 (green arrow) and early 2021 (red arrow). These spikes could be attributed to increased industrial activity or traffic during these periods.

Seasonal Variation: While there are fluctuations, the concentration is relatively stable, except for notable increases during colder months, possibly due to heating emissions and reduced atmospheric dispersion.

Impact of Wind and Precipitation: The inverse correlation between NO2 spikes and wind speed, especially in early 2021 (green arrow), suggests that higher wind speeds help disperse NO2, leading to lower concentrations. Conversely, low wind speed in early 2020 (red arrow) may have contributed to higher NO2 levels.

2. Aerosol Index (Second Panel)

Stability with Occasional Spikes: The aerosol index remains mostly stable, with minor fluctuations throughout the period. However, similar to NO2, there are noticeable spikes during the same periods as NO2 peaks, especially in mid-2020 (green arrow) and early 2021 (red arrow). This indicates a possible link between industrial emissions and aerosol formation.

Correlation with Precipitation: Aerosol levels tend to decrease slightly after precipitation events, as seen after the spike in precipitation in early 2021. Rain can remove particles from the atmosphere, reducing aerosol concentration temporarily.

3. Wind Speed (Third Panel)

Patterns and Influence: Wind speed shows some variability, with notable peaks in early 2021 (green arrow) and low speeds in early 2020 (red arrow). Wind speed plays a crucial role in dispersing pollutants like NO2 and aerosols, as evident from the opposite trends seen in NO2 concentration during high wind periods.

Low Wind Speed and Pollution: During periods of low wind speed, such as early 2020, the air becomes more stagnant, leading to higher concentrations of pollutants. This relationship is critical for understanding the buildup of NO2 and aerosols in urban environments like Shanghai.

4. Precipitation (Bottom Panel)

Significant Precipitation Events: The graph indicates a significant spike in precipitation in early 2021 (green arrow), which likely contributed to the reduction of NO2 and aerosol levels by washing pollutants out of the atmosphere.

Precipitation-Pollutant Relationship: The interaction between precipitation and air pollution is well documented. In this case, the substantial rainfall in early 2021 coincides with a decrease in both NO2 and aerosol levels, demonstrating precipitation's role in temporarily cleaning the air.

Comparative and Interaction Analysis

Wind Speed and NO2/Aerosol: The inverse relationship between wind speed and pollutant levels is evident, especially in early 2021. High wind speeds help in the dispersion of pollutants, while low wind speeds contribute to their accumulation.

Precipitation's Impact: Precipitation events, particularly the one in early 2021, have a noticeable cleansing effect, reducing both NO2 and aerosol concentrations. This effect is more pronounced after heavy rainfall.

Seasonal Patterns: Both NO2 and aerosol levels tend to rise during colder months (mid-2020 and early 2021), likely due to increased heating-related emissions and reduced dispersion. Wind speed and precipitation, on the other hand, show less clear seasonal trends but play a critical role in short-term fluctuations of pollutant levels.

3.9. Comparative Seasonal Analysis of Aerosol Changes in Shanghai and Dubai from 2012 to 2021

Fig. 8 illustrates the seasonal variations in aerosol concentrations for the cities of Shanghai and Dubai from 2012 to 2021, highlighting the contrasting trends observed in each city during the months of January, April, July, and October.

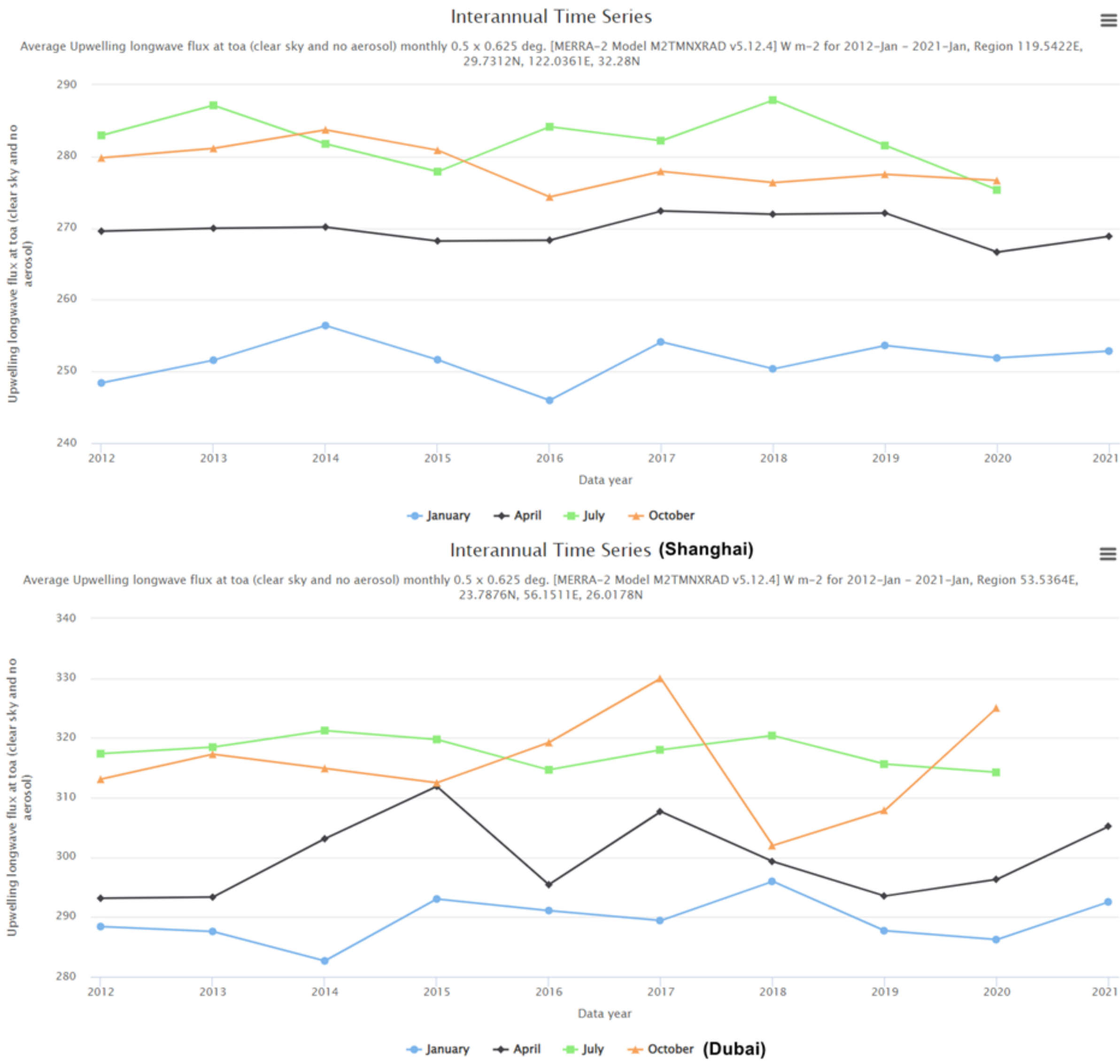

Fig. 8 - Aerosol Changes in Shanghai and Dubai from 2012 to 2021

3.9.1. Analysis of Aerosol Changes in Shanghai and Dubai (2012-2021)

Shanghai: Declining Trend

In Shanghai, the analysis of aerosol concentration from 2012 to 2021 reveals a noticeable declining trend. This suggests that air quality has improved over time in terms of particulate matter. The following key observations can be made for specific months:

January (Winter): January exhibits the lowest levels of aerosol concentration, with the most significant drop observed in January 2016. Winter months generally see reduced particulate matter due to lower temperatures and less dust circulation, which could explain this dip.

April (Spring): In April, moderate aerosol concentrations are observed as seasonal winds start to pick up. These winds may influence dust and particulate distribution, but the overall trend remains lower compared to summer months.

July (Summer): The highest aerosol concentration was observed in July 2018, likely due to increased industrial activity, higher temperatures, and reduced rainfall, which could cause more dust and particles to remain suspended in the air.

October (Autumn): Aerosol levels typically remain stable, though the overall trend is still part of the general decrease observed in the city.

This declining trend in aerosol may be attributed to improved environmental regulations, advancements in pollution control technologies, or changes in industrial practices in Shanghai.

Dubai: Increasing Trend

Contrary to Shanghai, Dubai shows an increasing trend in aerosol concentration over the same period (2012-2021). This can be linked to several environmental and climatic factors such as desertification, sandstorms, and construction activities. Key monthly observations include:

January (Winter): The lowest aerosol concentration is recorded in January 2014, likely due to milder winter conditions, where lower wind speeds and cooler temperatures prevent dust circulation.

April (Spring): Aerosol levels begin to increase as temperatures rise, which might lead to more dust and particles in the air, especially in desert regions. The increasing trend starts to become more evident during this time.

July (Summer): Dubai experiences higher temperatures and drier conditions during July, but the overall increase is moderate compared to later months. Sandstorms and desert winds could explain some of the aerosol spikes during this period.

October (Autumn): The peak aerosol concentration was observed in October 2017, possibly due to extreme heat and drier conditions. The lack of precipitation and high winds contribute to a significant rise in dust and particulate matter during this time.

This increase in aerosol concentration in Dubai could be attributed to a combination of climate change, urban expansion, and desertification, which all contribute to the elevated levels of airborne particles.

While Shanghai demonstrates a positive trend with decreasing aerosol concentrations, likely due to advancements in air quality management, Dubai shows an opposite trend, with increasing levels primarily driven by environmental and climatic factors. This contrast highlights the different challenges each city faces concerning air pollution control, industrial development, and geographical influences.

3.10. Seasonal and Temporal Variations of SO2 Levels in Shanghai and Dubai (2012-2021)

Fig. 9 illustrates the seasonal variations in SO2 concentrations for the cities of Shanghai and Dubai from 2012 to 2021, highlighting the contrasting trends observed in each city during the months of January, April, July, and October.

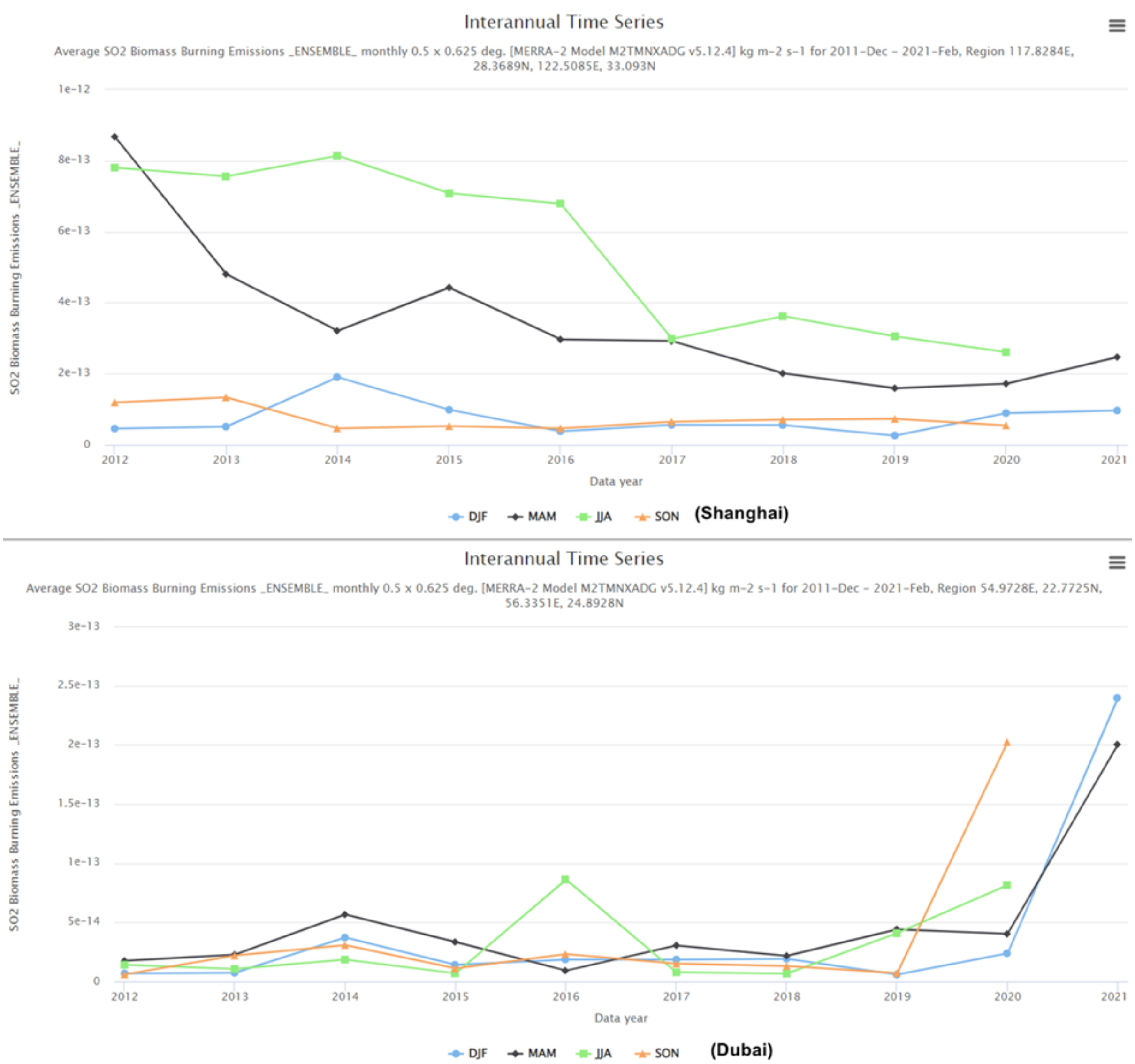

Fig. 9- SO2 Changes in Shanghai and Dubai from 2012 to 2021

3.10.1. Analysis and Interpretation of SO2 Variations:

Shanghai:

Between 2012 and 2021, Shanghai showed a general decreasing trend in SO2 concentrations, indicating gradual improvement in air quality, likely due to stricter environmental regulations and cleaner energy initiatives. The lowest SO2 concentration was observed in January 2019, suggesting significant control over emissions during the winter season. In contrast, peak SO2 levels were recorded in April 2012 and July 2014, possibly driven by increased industrial activity or higher energy consumption during these periods, reflecting seasonal energy demand and industrial operations.

Dubai:

In Dubai, the trend of SO2 concentration differs significantly. Initially, SO2 levels were relatively controlled, indicating stable air quality management. However, from around 2020 onward, there is a sharp upward trend in SO2 levels. This rapid increase culminates in the highest concentrations observed in January and April 2021, suggesting a potential surge in industrial activities, fossil fuel use, or other emission sources during this period. This rise may also correspond with increased energy demands and industrial expansion in the region, possibly due to changing economic and infrastructural developments.

Shanghai has successfully reduced SO2 levels over time, particularly in the winter months, aligning with broader pollution control policies.

Dubai, on the other hand, shows a concerning increase in SO2 concentrations, particularly in the early 2020s, requiring more focused emission control efforts.

These contrasting trends reflect differing environmental strategies, industrial growth, and energy consumption patterns in the two cities.

3.11. Comparison of Runoff Trends in Shanghai and Dubai (2000-2021)

Understanding the runoff patterns in different geographic regions is crucial for effective water resource management. Runoff, the water flow that occurs when soil is saturated or impervious, varies significantly between regions depending on climatic conditions and urbanization. In arid regions like Dubai, where precipitation is limited, the amount of runoff is naturally minimal. Conversely, cities like Shanghai, with a more humid climate, experience much higher levels of runoff, particularly during seasonal rain events.

In this section, Fig. 10 illustrates the differences in runoff volume between Dubai and Shanghai from 2000 to 2021, providing a comparative overview of how geographical and climatic factors shape these trends. The analysis that follows will delve deeper into these dynamics, highlighting the implications of these runoff patterns for water management in both cities.

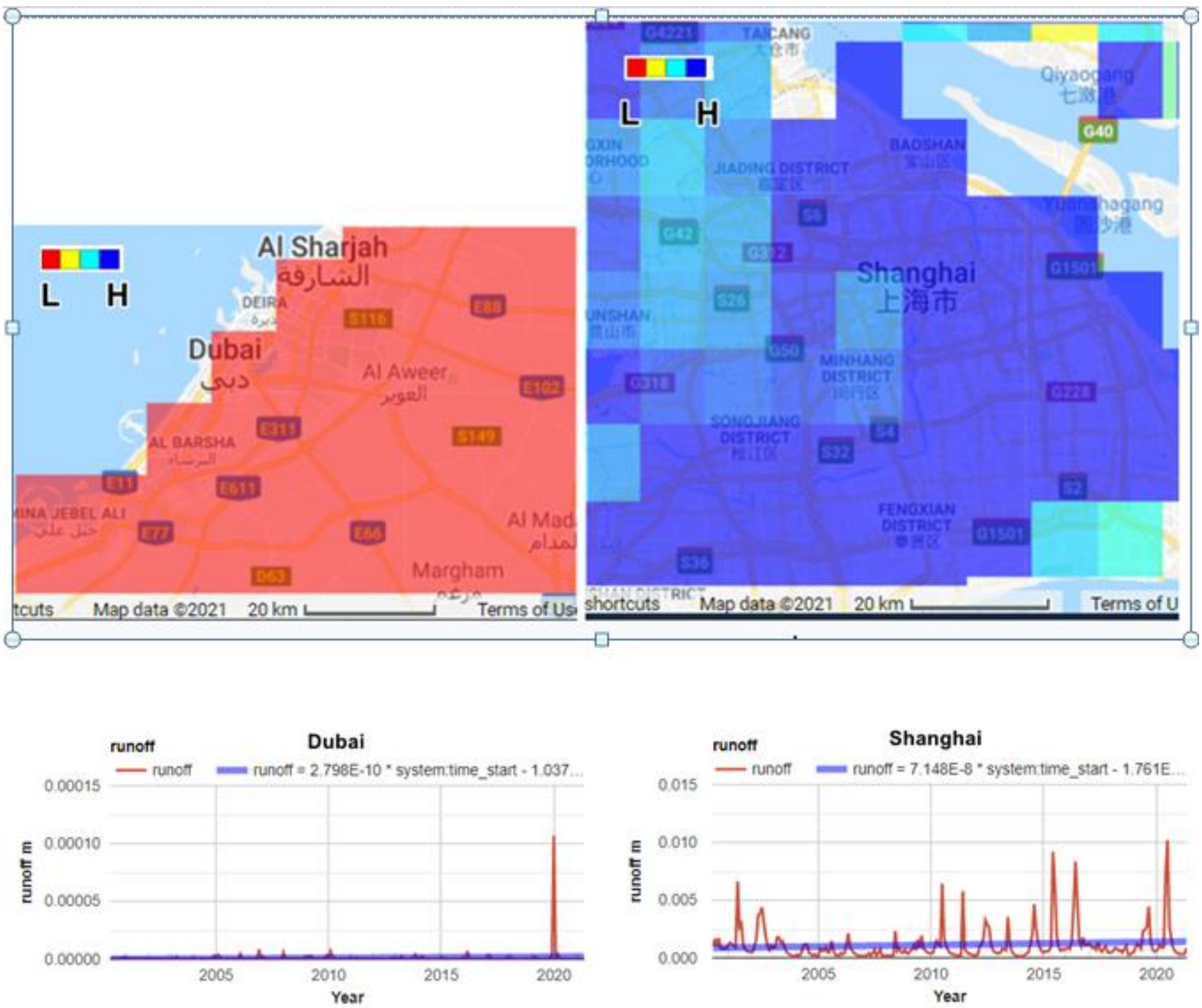

Fig. 10 - Comparative Analysis of Runoff Volume in Shanghai and Dubai (2000-2021)

3.11.1. Analysis and Interpretation of Runoff Changes:

Dubai:

Due to its hot and arid climate, Dubai experiences very limited runoff throughout the years. The city is situated in a region with low precipitation, and high evaporation rates further reduce any potential runoff. Consequently, the overall runoff volume remains minimal, with little variation over the observed time frame (2000-2021). This reflects Dubai's natural desert environment, where surface water is scarce, and rainfall events are infrequent and sporadic. Infrastructure developments in the city are likely focused on water conservation and artificial means of water management due to this inherent limitation.

Shanghai:

In contrast, Shanghai exhibits a significantly higher runoff volume. The city is located in a region with a humid subtropical climate, characterized by frequent rainfall and seasonal variations. The amount of runoff in Shanghai is heavily influenced by seasonal rain events, including the summer monsoon, which results in peaks in runoff during the summer months. Over the years, the runoff in Shanghai shows fluctuations corresponding to both natural rainfall variability and potential urban development impacts, such as the increase of impermeable surfaces which could lead to higher runoff.

Overall Comparison:

Dubai's low runoff is a result of its arid climate and lack of significant rainfall, with minor variations over time.

Shanghai's higher runoff is due to its wet climate, with variations influenced by seasonal rainfall patterns and potentially urbanization.

These differences highlight the contrasting environmental conditions and water management challenges faced by the two cities. Shanghai must deal with significant runoff during certain seasons, while Dubai's challenges revolve around water scarcity and the management of minimal surface water resources.

3.12. Analysis of Vegetation Cover in Shanghai and Dubai (2000-2021)

Based on NDVI (Normalized Difference Vegetation Index) data from 2000 to 2021, it is clear that the vegetation cover in the cities of Shanghai and Dubai is vastly different (Fig. 11). Shanghai, being located in a region with more favorable climatic conditions, boasts strong and dense vegetation. The city benefits from ample rainfall, a temperate climate, and fertile soils, leading to a consistently high NDVI value throughout the years. In contrast, Dubai, situated in an arid desert environment, shows significantly weaker vegetation cover, with extremely low NDVI values due to minimal precipitation and harsh climatic conditions.

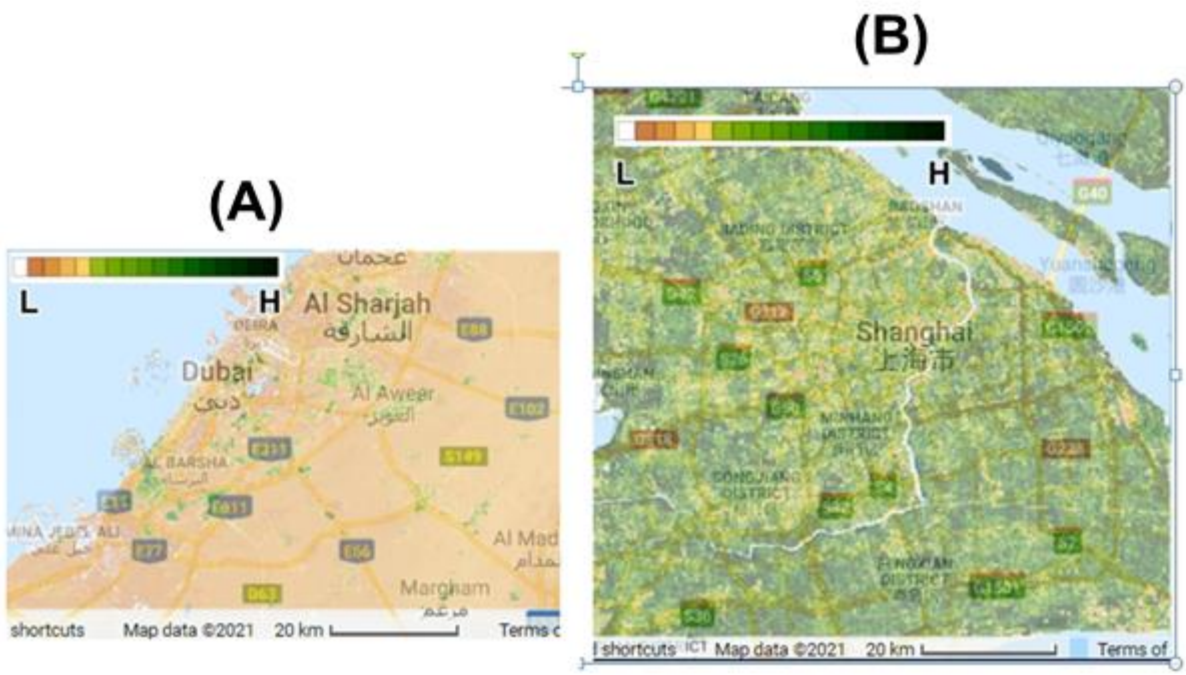

Fig. 11- NDVI-Based Vegetation Cover Comparison in Dubai (A) and Shanghai (B) (2000-2021)

Shanghai:

Over the study period, the NDVI for Shanghai demonstrates a relatively stable and high level of vegetation cover. Seasonal fluctuations are observed, but overall, the vegetation remains robust, especially in the city's surrounding areas, which feature parks, forests, and agricultural lands. The presence of consistent precipitation and moderate temperatures supports this strong vegetative growth.

Dubai:

On the other hand, Dubai’s NDVI values are very low throughout the period. This is reflective of its desert location, where vegetation is sparse, and any significant greenery is mostly confined to irrigated urban landscapes or artificial green spaces. Despite some efforts at urban greening, Dubai’s NDVI trends show only minimal improvement over the years, with the harsh desert environment limiting the potential for natural vegetation growth.

3.13. Analysis of Land Cover in Shanghai and Dubai

The comparison of land cover between Dubai and Shanghai, as illustrated in Fig. 12, reveals the striking differences in urbanization and environmental conditions between these two cities. This analysis is based on satellite imagery, highlighting various land cover types such as urban areas, vegetation, water bodies, and exposed soil.

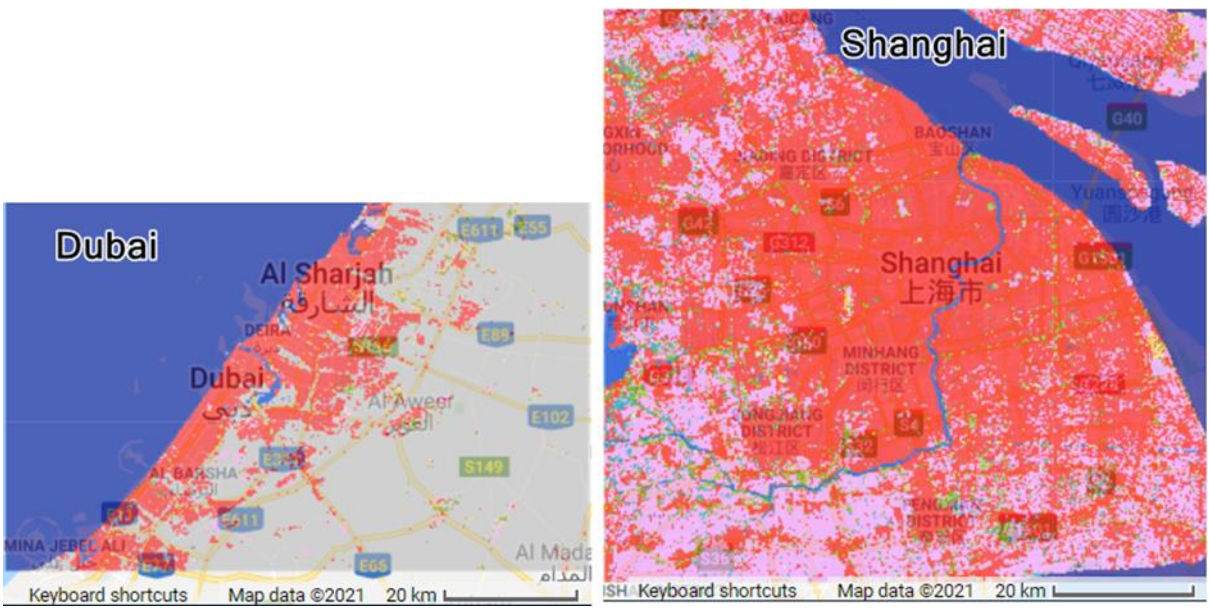

Fig. 12- Land Cover Classification of Dubai and Shanghai: Urban, Vegetation, and Exposed Soil Analysis (2021)

Dubai:

Urban/Built-Up Areas (Red Zones):

A significant portion of Dubai’s land cover is dominated by urban and built-up areas. These are marked in red, primarily representing the city’s extensive infrastructure, commercial zones, and residential developments. Dubai’s rapid urbanization is evident in the dense red areas along the coastline and in major city centers.

Exposed Soil, Sand, or Rocks (White Zones):

Large white areas surrounding the urban centers signify desert landscapes, where vegetation is nearly absent. This desert terrain is characteristic of Dubai’s geographic location, where the climate is arid, and natural vegetation rarely exceeds 10% of cover throughout the year.

Water Bodies (Blue Zones):

The blue areas on the map represent the Arabian Gulf, an essential feature of Dubai's geography. These saltwater bodies provide a crucial environmental contrast to the surrounding desert, influencing the city's coastal development and marine activities.

Shanghai:

Urban/Built-Up Areas (Red Zones):

Similar to Dubai, Shanghai has significant urban areas, marked in red. However, the distribution of these areas is more balanced with surrounding vegetation, reflecting Shanghai's approach to urban planning that incorporates green spaces. These built-up areas are largely concentrated in the city center and along the river.

Cultivated and Managed Vegetation (Light Red Zones):

One of the key differences in Shanghai's land cover is the presence of extensive cultivated and managed vegetation areas, shown in light red. These zones reflect agricultural lands, parks, and managed green spaces that are integrated into the urban environment. Shanghai's ability to balance urban growth with vegetation is a notable feature of its land use strategy.

Water Bodies (Blue Zones): The proximity to the Yangtze River and other water bodies is a defining characteristic of Shanghai's geography. These blue areas contribute to the city's economic activities, particularly trade and transportation, while also supporting the surrounding ecosystems.

Comparative Analysis:

Urban Expansion: Both cities exhibit extensive urban development, but Dubai's land cover is more dominated by artificial structures, while Shanghai balances its urban areas with managed vegetation and agricultural lands.

Natural Landscape:

Dubai's natural landscape is characterized by exposed desert soils, with very limited vegetation. In contrast, Shanghai's natural landscape includes both water bodies and large areas of cultivated vegetation, reflecting a more temperate and fertile environment.

Water Proximity:

While both cities are coastal, Shanghai's integration of its rivers into the city layout contrasts with Dubai's more isolated approach, where the majority of urban development is concentrated away from the coastline, except for commercial and tourism-focused areas.

3.14. Comparative Analysis of Wind Patterns for Dubai and Shanghai Based on Windrose Diagrams (A and B)

The provided windrose diagrams (Fig. 13A for Dubai and Fig.13B for Shanghai) visually depict the wind speed distribution and directional frequency for the two cities. These diagrams help to understand the wind characteristics in both locations, which are crucial for assessing environmental factors like air pollution dispersion, urban planning, and renewable energy potential.

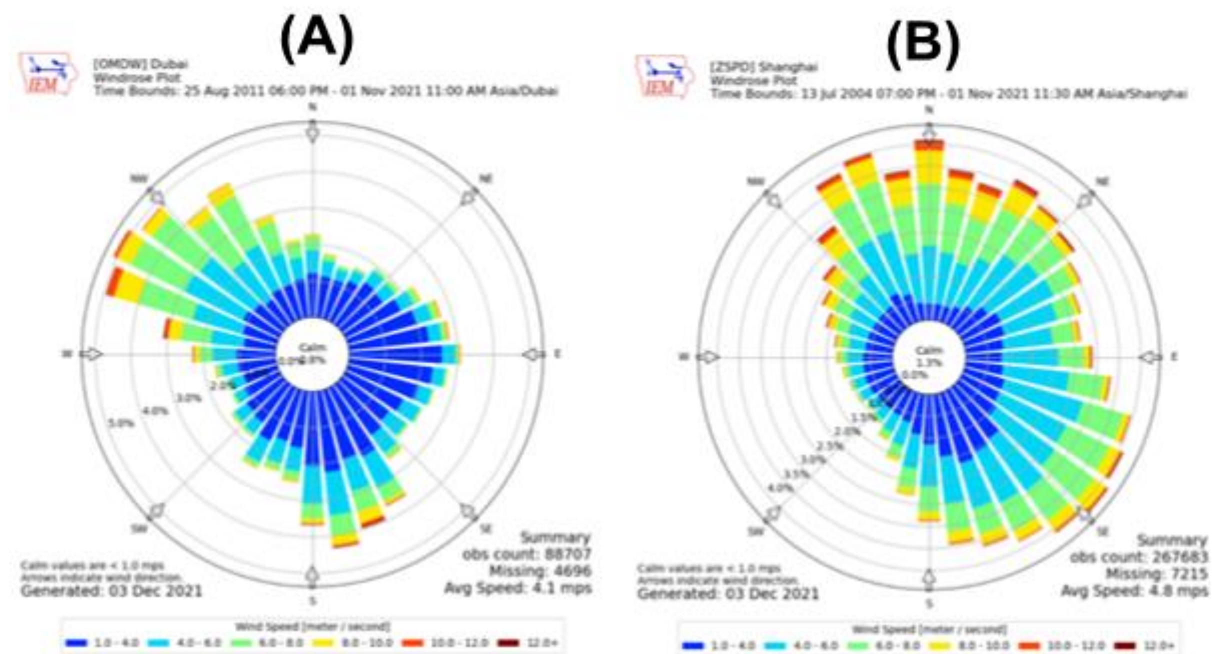

Fig. 14- Windrose Diagrams Depicting Wind Speed and Directional Frequency for Dubai (A) and Shanghai (B)

1. Wind Patterns in Dubai (A)

Average Wind Speed: The average wind speed in Dubai is approximately 4.1 m/s, with most winds blowing from the northwest (NW), followed by significant contributions from the north-northwest (NNW) and west-northwest (WNW) directions.

Wind Speed Distribution: The wind speeds are primarily in the range of 1.0-4.0 m/s (blue), but a considerable portion of winds also fall in the 4.0-8.0 m/s range (green). The percentage of calm conditions (wind speeds less than 1.0 m/s) is very low at only 0.19%, indicating consistent wind activity throughout the period.

Wind Directions: Winds predominantly come from the NW quadrant, with lesser, though still notable, frequencies from the NNE and N directions. This suggests that Dubai's geographical position and local meteorological conditions, such as proximity to the Persian Gulf, likely contribute to this pattern.

Implications: The consistent NW wind pattern plays a critical role in urban cooling and pollutant dispersion. However, it could also transport dust from desert areas into the city. Wind energy potential is moderate due to the wind speed range.

2. Wind Patterns in Shanghai (B)

Average Wind Speed: Shanghai exhibits a higher average wind speed of 4.8 m/s compared to Dubai. The dominant wind directions are from the east-northeast (ENE), northeast (NE), and east (E) directions.

Wind Speed Distribution: Similar to Dubai, most wind speeds are in the 1.0-4.0 m/s (blue) and 4.0-8.0 m/s (green) ranges. However, Shanghai experiences a higher percentage of stronger winds in the 8.0-12.0 m/s range (yellow), suggesting more frequent gusts and stronger winds overall. The calm conditions are slightly more common than in Dubai, at 1.21%, but still relatively low, indicating active wind movement.

Wind Directions: Winds primarily flow from the ENE and NE directions, which can be explained by the city's coastal position and the influence of seasonal monsoons. The consistent strong winds from these directions are likely influenced by the nearby East China Sea.

Implications: The stronger winds and more diverse directional spread in Shanghai indicate better conditions for wind-based energy generation and pollutant dispersion. However, stronger winds can also intensify storm impacts or air quality issues by spreading pollutants from industrial regions.

3. Comparison Between Dubai and Shanghai

Wind Speed: Shanghai has slightly higher average wind speeds (4.8 m/s) compared to Dubai (4.1 m/s). This indicates that Shanghai is subject to stronger winds overall, which could be due to its coastal location and the influence of monsoon winds.

Wind Direction: Both cities experience winds predominantly from the northern and eastern sectors, but Shanghai has a wider directional distribution. In contrast, Dubai's winds are more concentrated from the northwest, possibly due to its desert climate and proximity to the Persian Gulf.

Calm Conditions: Both cities experience very low calm conditions, with Shanghai having slightly more calm periods than Dubai. However, both cities benefit from active wind conditions, which aid in ventilation and pollution control.

Environmental and Urban Impact: Dubai's winds from the NW are likely influenced by the Persian Gulf and nearby desert regions, potentially bringing dust storms or humidity into the city. Shanghai, with its stronger winds from the ENE, benefits from marine breezes, which help mitigate pollution but could also contribute to storm surges or typhoon impacts during extreme weather events.

The wind patterns of Dubai and Shanghai, as represented in the windrose diagrams, show both similarities and differences. Dubai's wind is steady, with most of its wind energy concentrated from the northwest, while Shanghai experiences more variability in both direction and intensity, with stronger winds from the ENE and NE. Understanding these wind dynamics is essential for environmental planning, pollution control, and sustainable urban development in both cities.

4. Discussion

This study aimed to analyze the spatial and temporal changes in concentrations of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and aerosols in Shanghai and Dubai from 2012 to 2021, utilizing satellite data from Sentinel-5P and NASA's Giovanni through GEE. The findings provide crucial insights into the air quality dynamics in these two distinct urban environments, shaped by their unique climatic, industrial, and regulatory contexts.

The results of this research affirm our first hypothesis, which posited that pollutant concentrations in Shanghai are higher than in Dubai due to greater industrial development. The data indicated that Shanghai, characterized by its extensive industrial base and urbanization, consistently exhibited elevated levels of NO_2 and SO_2, particularly during peak industrial periods. For instance, the substantial spikes in SO_2 concentrations during April 2012 and July 2014 correlate strongly with increased industrial activity, highlighting the relationship between industrial emissions and air quality.

Conversely, Dubai's lower concentrations of NO_2 and SO_2 reflect its relatively stable air quality management strategies. However, the alarming uptick in SO_2 levels observed from 2020 onward challenges the notion that existing measures are sufficient. This trend emphasizes the need for enhanced emission control measures in the region.

These results are consistent with previous studies, such as Yan et al. (2019), which found similar correlations between industrial activity and air pollution levels in Shanghai. However, our findings diverge from those of Jung et al. (2022), who reported relatively stable pollutant levels in Dubai, suggesting a potential shift in pollution dynamics that warrants further investigation.

Our second hypothesis suggested significant differences in seasonal and spatial variations of pollutant concentrations between the two cities, attributed to climatic factors and emission sources. The findings corroborate this hypothesis, demonstrating that Shanghai's humid subtropical climate contributes to higher runoff volumes and pollutant dispersion during the summer monsoon season, coinciding with elevated pollutant concentrations.

Conversely, Dubai's arid climate results in minimal runoff, limiting the natural cleansing of pollutants. This underscores the necessity of continuous monitoring and reevaluation of air quality strategies in Dubai.

The analysis of the data overlap and discrepancies between Giovanni and Sentinel-5P yielded interesting results, supporting our third hypothesis regarding the minor differences in accuracy and temporal range of the two datasets. Both satellite sources provided reliable data for monitoring changes in air quality; however, discrepancies in specific pollutant readings were noted, particularly concerning CO and HCHO levels. These findings underscore the importance of utilizing multiple satellite sources to achieve a more comprehensive understanding of atmospheric conditions.

The contrasting trends in pollutant concentrations underscore the varied environmental strategies employed by Shanghai and Dubai. Shanghai's successful reduction of SO_2 levels over time highlights the effectiveness of stringent pollution control policies and cleaner energy initiatives, corroborating the findings of Liu et al. (2020), which emphasized the need for proactive regulatory measures. This trend serves as a model for cities facing similar industrial challenges, advocating for robust regulatory frameworks and proactive measures to mitigate air pollution.

On the other hand, Dubai's alarming rise in SO_2 levels necessitates immediate attention and policy interventions to ensure sustainable urban development. This could involve investing in cleaner technologies, enhancing regulatory measures, and promoting public awareness campaigns to reduce emissions from transportation and industry. These findings align with those of Adanma and Ogunbiyi et al. (2024), who noted that developing cities face unique challenges in balancing economic growth with environmental sustainability.

This study's findings provide essential insights into the air quality dynamics of Shanghai and Dubai, emphasizing the need for tailored environmental strategies that consider each city's unique climatic, industrial, and regulatory contexts. The evidence suggests that while significant progress has been made in improving air quality in Shanghai, Dubai faces new challenges that require urgent attention. Future research should continue to explore these dynamics, particularly focusing on the long-term impacts of climate change and urbanization on air quality.

5. Conclusion

This study has provided a comprehensive analysis of the spatial and temporal variations in concentrations of nitrogen dioxide (NO_2), sulfur dioxide (SO_2), carbon monoxide (CO), formaldehyde (HCHO), and aerosols in Shanghai and Dubai from 2012 to 2021, utilizing satellite data from Sentinel-5P and NASA's Giovanni. The results reveal distinct patterns of air quality influenced by industrial activity, climatic conditions, and urbanization processes in both cities.

The research confirmed our initial hypotheses that Shanghai experiences higher pollutant concentrations compared to Dubai, primarily due to its extensive industrial base and urbanization. Notably, the analysis indicated significant seasonal fluctuations, with higher concentrations of pollutants during specific periods tied to industrial activity and meteorological conditions. In contrast, Dubai's relatively stable air quality reflects effective management strategies, though recent increases in SO_2 levels raise concerns regarding the sustainability of these practices.

This study highlights the importance of continuous monitoring and assessment of air quality, particularly in rapidly developing urban areas. The evidence suggests that while substantial progress has been made in managing air pollution in Shanghai, urgent measures are needed in Dubai to address emerging pollution challenges.

Based on the findings, several recommendations can be made for policymakers and urban planners in both Shanghai and Dubai:

Enhanced Monitoring Systems: Establish integrated air quality monitoring systems that utilize data from multiple satellite sources to provide real-time insights into pollutant levels and trends. This can facilitate timely interventions and policy adjustments.

Strengthening Regulatory Frameworks: For Shanghai, continue to enforce and strengthen existing pollution control regulations to maintain the downward trend in pollutant concentrations. For Dubai, implement stricter emission standards, particularly for industries and transportation, to address the recent increase in SO_2 levels.

Investment in Clean Technologies: Encourage the adoption of cleaner technologies and practices in industrial sectors. Incentives for businesses to invest in low-emission technologies can play a crucial role in reducing overall pollution levels.

Public Awareness Campaigns: Promote public awareness initiatives to educate citizens about the sources and effects of air pollution. Engaging the public can enhance community support for air quality management strategies and encourage individual actions to reduce emissions.

Collaborative Research Initiatives: Foster collaboration between academic institutions, government agencies, and private sectors to conduct further research on the impacts of air quality on public health and the environment. This can help in developing targeted strategies and policies for pollution reduction.

Long-term Urban Planning: Integrate air quality considerations into long-term urban planning processes. Developing green spaces, promoting public transportation, and implementing smart city initiatives can mitigate the effects of urbanization on air quality.

In conclusion, the findings of this study underscore the need for tailored approaches to air quality management that consider the unique challenges faced by urban areas like Shanghai and Dubai. By implementing the recommended strategies, both cities can work towards achieving sustainable urban environments with improved air quality for their residents.

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Conflict of Interest /Competing interests (None)

Availability of Data and Material (Data are available when requested)

Consent to Publish (The author consents to the publication of this manuscript)

Authors Contributions (Authors contributed equally to the data collection, analysis, and interpretation. Authors critically reviewed, refined, and approved the manuscript.)

Code availability (Not applicable)

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