No2Pollution: A Guide to Analyze Air Quality via Level-2 Satellite Imagery

Abdulrahman Hameed[1], Adil Mahroof[2], Mohammed Alnuaimi[3], Areej Alamin[4], and Hamzeh Abu Qamar[1*]
[1]Dept. of Electrical and Communication Engineering, United Arab Emirates University, Al Ain 15551, UAE
[2]Dept. of Mechanical and Aerospace Engineering, United Arab Emirates University, Al Ain 15551, UAE
[3]Dept. of Political Science, United Arab Emirates University, Al Ain 15551, UAE
[4]Dept. of Biology, Chemistry, and Environmental Sciences, American University of Sharjah, Sharjah 26666, UAE
Email: {201850023; 202050174; 202002333}@uaeu.ac.ae, g00089352@aus.edu, *202050889@uaeu.ac.ae

***Abstract*—Air pollution is a global health crisis affecting all countries, contributing to 11.65% of deaths worldwide. As the impact on health and the environment intensifies, there has been a growing interest in air quality monitoring and detection. Aligned with the objectives of the UAE's National Air Quality Agenda 2031, our study provides a comprehensive guide to analyze nitrogen dioxide NO_2 emissions, a pivotal air pollution indicator, leveraging Level-2 satellite imagery. In our research, we employ advanced data analysis techniques, offering nuanced insights into the dispersion patterns of NO_2 across the UAE. This analytical approach involves processing, interpreting, and visualizing Level-2 satellite data to extract meaningful information about NO_2 concentrations. The integration of data analysis not only enhances the precision of our findings but also allows for a more in-depth understanding of the spatial and temporal dynamics of air pollution. In addition to conducting a detailed emissions analysis, we contribute an adaptable codebase that extends the applicability of our guide, especially in regions where resources for advanced monitoring technologies may be limited. This codebase facilitates the implementation of our analytical framework, enabling countries with limited technological capacities to assess and address air quality challenges effectively. Our multi-dimensional approach, combining satellite imagery analysis and sophisticated data interpretation, provides valuable information for policymakers and researchers to visually comprehend air quality metrics and formulate effective strategies.**

***Index Terms*—Air quality, data analysis, emissions, nitrogen dioxide**

I. Introduction

Air pollution is regarded as a global concern that arises from various human activities, including vehicular exhaust, industrial processes, and power generation. These activities contribute to heightened concentrations of pollutants in the atmosphere, among them Nitrogen Oxides NO_x, which poses significant risks to air quality, human health, and ecosystems. The World Health Organization (WHO) reports that air pollution is responsible for 6.7 million premature deaths annually [1].

Nitrogen Dioxide (NO_2), being the most prominent of the NO_x family, results from the incomplete combustion of fossil fuels [2]. The sources encompass vehicle emissions, industrial activities, and power plants. WHO acknowledges NO_2 as a major air pollutant by establishing clear links between its presence and respiratory issues such as asthma and chronic obstructive pulmonary diseases [1]. Studies show that 99% of the world's population live in areas where air quality guidelines levels were not met [3]. Elevated levels of NO_2 have direct implications for public health, particularly concerning respiratory ailments. Not only does NO_2 act as a primary pollutant but it also plays a pivotal role in the production of ground level Ozone (O_3), a key component of the smog seen around industrial cities around the world [4], [5]. Furthermore, NO_2 contributes to environmental problems such as acid rain and climate change, underscoring the intricate interconnectedness of air quality, human health, and ecological stability [2]. Given its pervasive nature, comprehensive monitoring and analysis are essential to discern spatial and temporal patterns [6].

Satellites have emerged as indispensable tools for monitoring air quality on a global scale, providing a bird's-eye view of atmospheric conditions and pollutant concentrations. These orbiting platforms equipped with advanced sensors, such as spectrometers and radiometers, enable the systematic observation of various air quality parameters, including nitrogen dioxide, particulate matter, and ozone [7]. Their ability to capture data at different spatial and temporal resolutions facilitates the tracking of air pollution sources, mapping pollutant dispersion patterns, and assessing the impact on regional and global scales [8] . The integration of satellite data into air quality monitoring systems enhances our understanding of pollution dynamics. With continuous advancements in satellite technology and data analysis techniques, these orbiting observatories play a pivotal role in providing real-time, accurate, and accessible data crucial for addressing complex challenges [9]. The data satellites collect progresses through various processing levels [10]. Starting from Level-1 with raw data, it undergoes refinement in Level-2 by becoming georeferenced and calibrated. This processed information in Level-2, along with further refinement in spatially averaged Level-3 and model-ready Level-4 data, contributes to a more sophisticated understanding of air quality dynamics [10], [11]. The integration of satellite data at different processing levels enhances our ability to track pollution sources, map dispersion patterns, and assess impacts, thereby supporting effective environmental management strategies and public health interventions [11].

Due to its recent industrialization and urbanization to diversify the economy, the UAE has dramatically increased its emissions, heightening concerns for air pollution. For instance, we consider Fig. 1 which illustrates the annual emissions attributed to the UAE. The figure represents the volume of emissions released through activities, such as the combustion of fossil fuels and the production of cement [12]. As illustrated, the trajectory of the UAE's emissions marks a significant rise from the nation's union in 1971, reflecting its substantial economic development, but also its escalating environmental challenges [13]. In light of this, the UAE has ongoing research and collaborations among government and non-governmental organizations to help resolve this issue and reduce NO_2 concentrations. Ground monitoring stations have been dispersed all over the UAE and data has been collected to determine the air quality through the air quality index [14]. More recently, the UAE has launched the National Air Quality Agenda 2031, which focuses on monitoring, managing, and reducing air quality metrics [15].

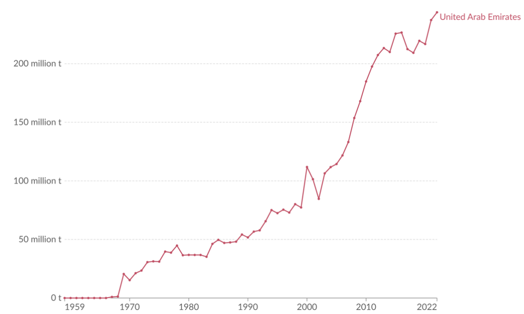

Fig. 1: Graph of emissions over time in the UAE.

The primary objective of this study is to analyze NO_2 levels in the UAE. By employing advanced data analysis techniques, we aim to discern temporal trends and spatial distribution patterns of NO_2 concentrations. This investigation seeks to provide a comprehensive understanding and address the gaps in current knowledge of air quality dynamics in the UAE, contributing valuable insights for environmental monitoring and management strategies. By focusing on NO_2, a major air pollutant, and utilizing satellite technology, we aim to offer a detailed and up-to-date assessment of the region's air quality. The outcomes of this research can inform policymakers, urban planners, and environmental authorities in implementing targeted measures to mitigate air pollution's adverse effects on public health and the environment. Additionally, the study's findings may contribute to the broader scientific understanding of air quality management in rapidly developing regions worldwide.

II. System Model

We begin with a high-level explanation of our system model as a flowchart in Fig. 2. To analyze air quality, we choose to collect Level-2 data of nitrogen dioxide concentrations. Monitoring NO_2 levels allows health authorities to identify regions with elevated concentrations [16]. This information helps target public health interventions, such as providing health advisories or implementing measures to reduce exposure for vulnerable populations. As such, monitoring facilitates regulatory enforcement. If NO_2 levels surpass established limits, regulatory bodies can take corrective actions, such as imposing emission controls on industries, implementing stricter vehicle emission standards, or introducing urban planning measures to reduce traffic-related pollution [17].

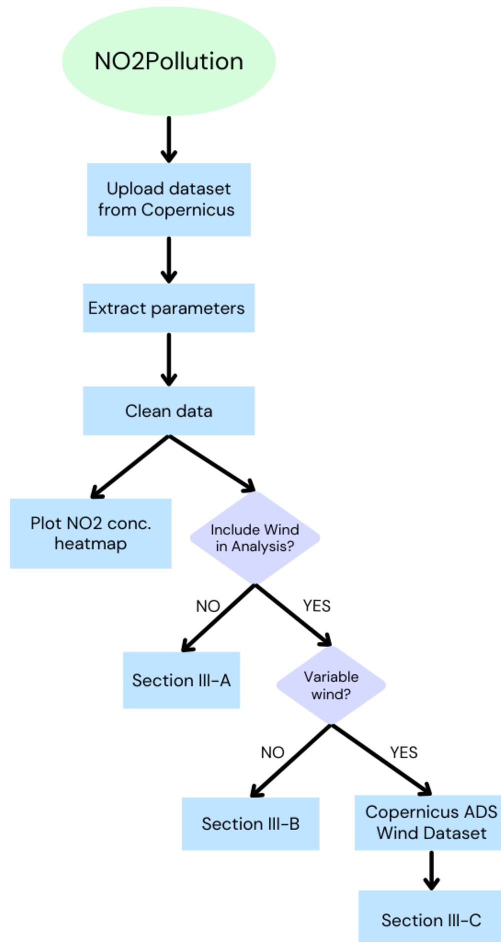

Fig. 2: Flowchart of No2Pollution.

After uploading the Level-2 satellite data obtained from Sentinel-5P Satellite using Copernicus Browser, we extract the parameters we will utilize in our data visualization [18]. These are the relevant parameters required to analyze the emissions due to nitrogen dioxide: `nitrogendioxide_tropospheric_column`, `latitude`, `longitude`, and `qa_value`, representing the nitrogen dioxide concentration, latitude, longitude, and quality of the data, respectively. Each of these variables is a function of time, scanline, and groundpixel, and hence, need to be flattened into a 1D array for processing.

To make our analysis more detailed, we focused on conducting the data visualization over the course of a week: June 1st to 7th, 2023. As shown in Fig. 3, the Level-2 satellite imagery covers a fairly large region. Inspired by the UAE National Air Quality Agenda 2031, we decided to restrict our analysis to the

United Arab Emirates by using the `geopy` library in Python. To ensure high precision and accuracy in selecting the region, we removed all data points outside our area of interest and those of quality below 50%. The coordinates of our area of interest can be found in Table I.

TABLE I: Coordinates of area of interest.

	Minimum	**Maximum**
Latitude	24.10	25.46
Longitude	54.75	56.11

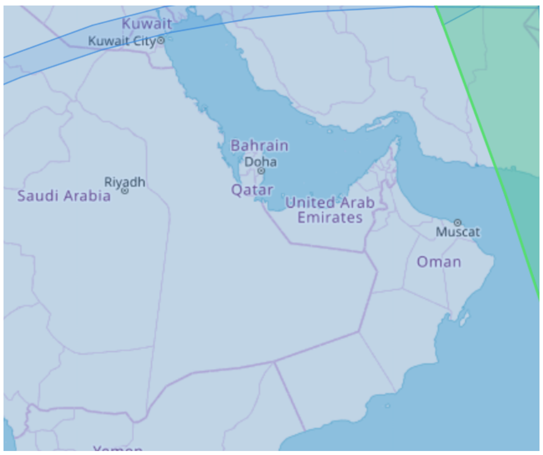

Fig. 3: Map of Level-2 Imagery from Sentinel-5P Satellite.

The final step of our system model before simulating is creating a common grid. Using the `meshgrid` library in Python, we build a common grid for all plots to maintain consistency in the spatial representation of images. Each pixel corresponds to a specific geographic location, and `meshgrid` facilitates data interpretation, especially when comparing images acquired over the same area at different conditions. Another reason it is imperative in satellite data visualization is because it promotes interoperability, allowing seamless integration of datasets from various sources.

III. Simulation Results

Proceeding to the simulation, we are now ready to process Level-3 data as a result of our efforts. Fig. 4 shows the distribution of nitrogen dioxide concentrations over the UAE region.

We take it a step further and process Level-4 data by studying the correlation between wind vectors and NO_2. Assuming NO_2 sinks are dominated by the chemical loss due to the reactions of NO_2 with OH, we can calculate emissions E as follows:

$$E = \frac{Ln}{t} + \nabla(Lnw) \tag{1}$$

where L = 1.23 is the constant ratio of NO_x to NO_2, n refers to the vector associated with NO_2 concentrations, t is the period we performed our analysis throughout and, in this case, is 4 hours, w is the wind vector (zonal wind, meridional wind), and ∇ is the divergence vector. We will analyze different cases for w, and in turn, extract emissions in different weather conditions.

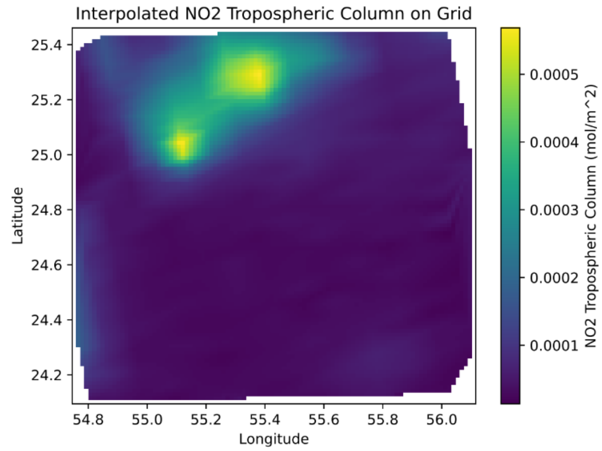

Fig. 4: Heatmap of NO_2 concentration in the UAE.

A. No Wind

Our first case is ideal: no wind (w = 0).

$$E_{\text{no wind}} = \frac{Ln}{t} \propto n \tag{2}$$

In other words, $E_{\text{no wind}}$ will be directly proportional to the tropospheric column vector n as L and t are constants. Hence, we expect that the heatmap will be exactly the same as Fig. 4 only with a change in magnitude.

Simplifying (1) yields:

$$E = E_{\text{no wind}} + L \cdot \nabla(nw) \tag{3}$$

Also, we know that

$$\nabla(A) = \nabla_{\text{x}}(A) + \nabla_{\text{y}}(A) \tag{4}$$

B. Constant Wind

Now, we consider a more practical, however still unrealistic case: constant wind vector. Since w is a constant,

$$E = E_{\text{no wind}} + Lw \cdot \nabla(n) \tag{5}$$

Using (4)

$$E = E_{\text{no wind}} + Lw \cdot [\nabla_{\text{x}}(n) + \nabla_{\text{y}}(n)] \tag{6}$$

To simplify our calculation, we consider

$$\nabla_x(n) = \frac{n[i+1] - n[i]}{long[i+1] - long[i]} \tag{7}$$

$$\nabla_y(n) = \frac{n[i+1] - n[i]}{lat[i+1] - lat[i]} \tag{8}$$

where lat and $long$ are the vectors of the latitudes and longitudes of the common grid, respectively. The plot of the emissions due to constant wind is shown in Fig. 5.

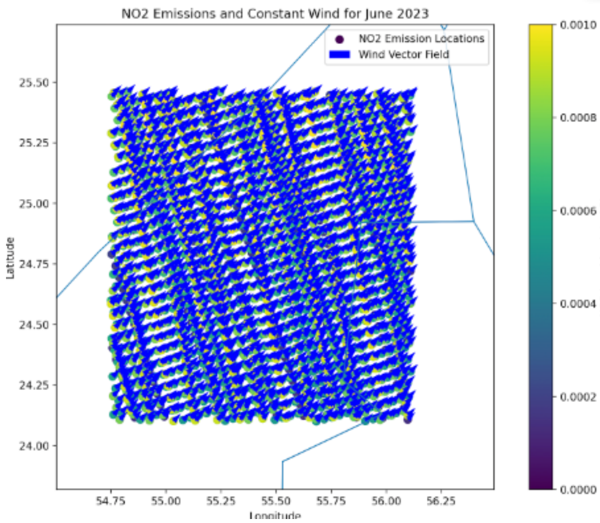

Fig. 5: Emissions at Constant Wind Speed.

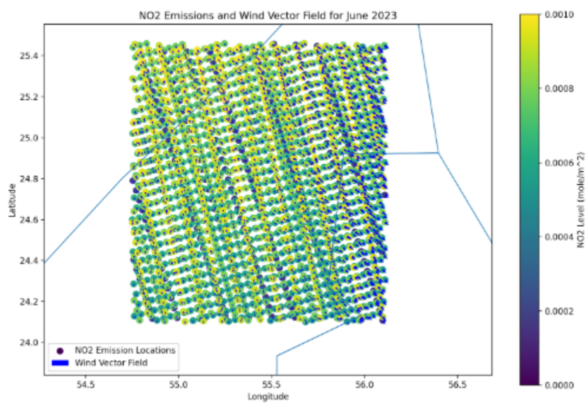

Fig. 6: Emissions and Wind Vector Field.

C. Variable Wind

Finally, we consider wind as a variable vector. For this case, we will resort to data obtained from the Copernicus Climate Data Store [19]. Since w is a 2D vector, we select "multi-level variable" as shown in (9), and pressure levels between 925 and 950 hPa. It is also important to make sure this dataset overlaps with that acquired for the NO_2 emissions to ensure consistency. By inserting the set of coordinates in Table I, the system automatically generates wind data in `grib` format, and it uses API to do so by running a generated code using the `cdsapi` library in Python.

$$w = u\boldsymbol{i} + v\boldsymbol{j} \tag{9}$$

Incorporating wind into the emission calculations is important because wind plays a crucial role in the dispersion and transport of air pollutants, including NO_2. The movement of pollutants in the atmosphere is strongly influenced by wind patterns, and considering wind in emission calculations provides a more accurate representation of pollutant concentrations and their spatial distribution.

To simplify our calculations as we did in Section III-B:

$$\nabla_x(nw) = \frac{u[i+1]\cdot n[i+1] - u[i]\cdot n[i]}{long[i+1] - long[i]} \tag{10}$$

$$\nabla_y(nw) = \frac{v[i+1]\cdot n[i+1] - v[i]\cdot n[i]}{lat[i+1] - lat[i]} \tag{11}$$

The plot of the interpolated heatmap due to variable wind is shown in Fig. 6.

D. Discussion

As depicted in the figures, the concentrations of nitrogen dioxide are prominently concentrated in urban city regions. Notably, large cities such as the capital, Abu Dhabi, and the global hub, Dubai, exhibit significantly higher nitrogen dioxide levels compared to smaller Emirates like Ajman and Ras Al Khaimah. While multiple factors may contribute to these disparities, our research suggests that fossil fuel usage is the primary contributor to these elevated concentrations. According to our assumptions, approximately two-thirds of all emissions in the region stem from energy-related activities involving fossil fuel production [20]. These toxic emissions pose a potential threat to public health, with the capacity to cause diseases and, in severe cases, even mortalities.

Examining Fig. 5, all wind vectors point in the same direction (North-East), in contrast to Fig. 6, where wind vectors indicate multiple orientations. Fig. 4, lacking wind vectors, reveals spikes in NO_2 emissions in two Emirates—Abu Dhabi and Dubai. However, Fig. 6 illustrates even more substantial emissions. Consequently, we can infer that, ideally (without wind), the air quality in rural areas of the UAE is five times cleaner than in urban cities. Realistically, wind can disperse nitrogen dioxide across different parts of the country, evident in the impact of emissions on regions with less industrial activity. Another intriguing finding is that emissions due to wind in rural areas surpass emissions without wind in the most industrialized locations in the UAE.

IV. Simulator

To facilitate the scalability of our approach, we have developed an algorithm named SatEmissionsSim. This algorithm can analyze emissions for any given dataset and set of coordinates. A screenshot of the SatEmissionsSim graphical user interface (GUI) is depicted in Fig. 7. Users can calculate NO_2 concentrations, plot emissions, and visualize corresponding vectors by uploading the datasets from Copernicus Browser and Climate Data Store, and choosing the required coordinates. Initial parameters utilized in our study are detailed in Table I. The complete codebase and SatEmissionsSim can be accessed through our dedicated GitHub repository [21]. This repository serves as a valuable resource for reproducibility and encourages ongoing enhancements in addressing critical air quality issues globally.

V. Conclusion

Our comprehensive study has significantly advanced our knowledge of nitrogen dioxide (NO_2) concentrations across the United Arab Emirates (UAE) through the utilization of Level-2 satellite imagery. The meticulous analysis undertaken

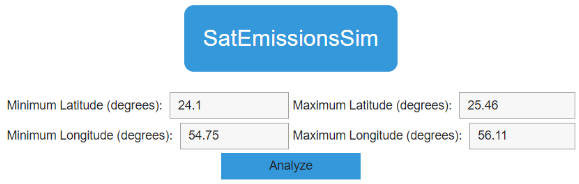

Fig. 7: SatEmissionsSim Graphical User Interface.

has not only allowed us to quantify emissions under various scenarios but has also provided invaluable insights into the intricate dynamics of air quality within the region. The calculated emissions, derived from our rigorous analysis, serve as a foundational dataset for understanding the existing state of air quality and contribute to the development of effective strategies for environmental management. Our findings hold particular significance in the context of the UAE, where rapid urbanization and industrialization necessitate a thorough understanding of pollutant concentrations and their potential impact on public health and the environment. One of the key strengths of our study lies in the elucidation of the spatial distribution of NO_2 concentrations. This knowledge allows us to pinpoint areas with elevated pollution levels, enabling a more targeted approach to environmental interventions and policies. Additionally, our exploration of various emission scenarios has identified crucial factors influencing NO_2 levels, with a specific emphasis on the role of wind conditions in shaping pollution patterns. Looking ahead, our future endeavors aim to integrate the developed simulator seamlessly with the Copernicus Browser. This integration not only promises to refine our understanding of NO_2 emissions but also opens avenues for incorporating Level-4 data for other gases. By leveraging such advanced tools and technologies, we aspire to provide even more comprehensive insights into air quality dynamics, thus laying the groundwork for informed and effective policy decisions. The significance of bridging the gap between research and real-time environmental management cannot be overstated. Our study sets the stage for proactive interventions, as the integration of our simulator with the Copernicus Browser will enable policymakers to access timely and accurate information. This real-time capability is essential for adapting strategies to changing environmental conditions, ensuring a more resilient and sustainable approach to environmental management in the UAE.

References

[1] (2024, January 24) Types of pollutants. World Health Organization. Accessed on Jan 24, 2024. [Online]. Available: https://www.who.int/teams/environment-climate-change-and-health/air-quality-and-health/health-impacts/types-of-pollutants

[2] U. EPA. (2023) Basic information about NO_2. Accessed on July 25, 2023. [Online]. Available: https://www.epa.gov/no2-pollution/basic-information-about-no2

[3] World Health Organization: WHO. (2022, December 19) Ambient (outdoor) air pollution. Accessed on Jan 24, 2024. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health

[4] US EPA. (2023, June 2) Ground-level ozone basics. Accessed on Jan 24, 2024. [Online]. Available: https://www.epa.gov/ground-level-ozone-pollution/ground-level-ozone-basics

[5] A. Pinho-Gomes, E. Roaf, G. W. Fuller, D. Fowler, A. C. Lewis, H. ApSimon, C. Noakes, P. Johnstone, and S. T. Holgate, "Air pollution and climate change," *The Lancet Planetary Health*, vol. 7, no. 9, pp. e727–e728, 2023. [Online]. Available: https://doi.org/10.1016/s2542-5196(23)00189-4

[6] (2023, January 1) Tropospheric no_2: Explorative analyses of spatial variability and impact factors. ResearchGate. Accessed on [Date]. [Online]. Available: https://www.researchgate.net/publication/357353714

[7] A. Rowley and O. Karakuş, "Predicting air quality via multimodal ai and satellite imagery," *Remote Sensing of Environment*, vol. 293, p. 113609, 2023. [Online]. Available: https://doi.org/10.1016/j.rse.2023.113609

[8] B. N. Duncan, A. I. Prados, L. N. Lamsal, Y. Liu, D. G. Streets, P. Gupta, E. Hilsenrath, R. A. Kahn, J. E. Nielsen, A. J. Beyersdorf, S. P. Burton, A. M. Fiore, J. Fishman, D. K. Henze, C. A. Hostetler, N. A. Krotkov, P. Lee, M. Lin, S. Pawson, and L. D. Ziemba, "Satellite data of atmospheric pollution for u.s. air quality applications: Examples of applications, summary of data end-user resources, answers to faqs, and common mistakes to avoid," *Atmospheric Environment*, vol. 94, pp. 647–662, 2014. [Online]. Available: https://doi.org/10.1016/j.atmosenv.2014.05.061

[9] A. A. Shehhi and R. E. Welsch, "Artificial intelligence for improving nitrogen dioxide forecasting of abu dhabi environment agency ground-based stations," *Journal of Big Data*, vol. 10, no. 1, 2023. [Online]. Available: https://doi.org/10.1186/s40537-023-00754-z

[10] M. Sorek–Hamer, M. Von Pohle, A. Sahasrabhojanee, A. A. Asanjan, E. Deardorff, E. Süel, V. Lingenfelter, K. Das, N. C. Oza, M. Ezzati, and M. Bräuer, "A deep learning approach for meter-scale air quality estimation in urban environments using very high-spatial-resolution satellite imagery," *Atmosphere*, vol. 13, no. 5, p. 696, 2022. [Online]. Available: https://doi.org/10.3390/atmos13050696

[11] F. Karagulian, M. Temimi, D. Ghebreyesus, M. Weston, K. N. Kumar, V. K. Valappil, A. Aldababesh, A. Lyapustin, N. Chaouch, F. A. Hammadi, and A. A. Abdooli, "Analysis of a severe dust storm and its impact on air quality conditions using WRF-Chem modeling, satellite imagery, and ground observations," *Air Quality, Atmosphere & Health*, vol. 12, no. 4, pp. 453–470, 2019. [Online]. Available: https://doi.org/10.1007/s11869-019-00674-z

[12] Climate science investigations south florida - causes of climate change. Florida Atlantic University. Accessed on Jan 24, 2024. [Online]. Available: https://www.ces.fau.edu/nasa/module-4/causes/sources-carbon-dioxide.php

[13] R. M. . R. P. Ritchie, H. (2023, December 28) CO_2 and Greenhouse Gas Emissions. Our World in Data. Accessed on [Date]. [Online]. Available: https://ourworldindata.org/co2-and-greenhouse-gas-emissions

[14] Air quality — knowledge — uae ministry of climate change and environment. UAE Ministry of Climate Change and Environment. Accessed on Jan 24, 2024. [Online]. Available: https://www.moccae.gov.ae/en/knowledge-and-statistics/air-quality.aspx?DisableResponsive=1

[15] S. Zaman. (2022, September 11) Uae launches national air quality agenda 2031 to tackle pollution. Gulf News. Accessed on Jan 24, 2024. [Online]. Available: https://gulfnews.com/uae/uae-launches-national-air-quality-agenda-2031-to-tackle-pollution-1.90398659

[16] H. Canada. (2016, May 13) Human health risk assessment for ambient nitrogen dioxide. [Online]. Available: https://www.canada.ca/en/health-canada/services/publications/healthy-living/human-health-risk-assessment-ambient-nitrogen-dioxide.html

[17] US EPA. (2023, July 25) Applying or implementing nitrogen dioxide standards. [Online]. Available: https://www.epa.gov/no2-pollution/applying-or-implementing-nitrogen-dioxide-standardsdesignations

[18] "Copernicus browser," https://dataspace.copernicus.eu/browser/, accessed 14 Jan. 2024.

[19] "Copernicus Climate Data Store," https://ads.atmosphere.copernicus.eu/cdsapp, accessed 14 Jan. 2024.

[20] D. Gielen, F. Boshell, D. Saygin, M. Bazilian, N. Wagner, and R. Gorini, "The role of renewable energy in the global energy transformation," *Energy Strategy Reviews*, vol. 24, pp. 38–50, 2019.

[21] H. Qamar, K. Mohammed, R. A. Khalil, and N. Saeed, "Satnet spacesim: A platform for performance analysis of small satellites megaconstellations," https://github.com/hamzehaq7/SatNetSpaceSim, 2023.