

# Nitrogen Dioxide Monitoring with Satellite Imagery over Ankara, Turkey

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## Abstract:

Earth observation satellites are equipped with essential features that make them invaluable for environmental monitoring. These features include high-resolution imaging capabilities both temporally and spatially, broad coverage areas, multispectral imaging, and access to extensive image archives through various platforms. These characteristics allow for the regular and thorough monitoring of pollutants across the globe. Currently, weather forecasting models utilize satellite imagery to record and report pollutant levels on an hourly and daily basis. This capability enables the identification of pollution sources and the analysis of pollutant patterns over time. Remote sensing technology enhances this process by measuring not only the concentration and intensity of pollutants but also tracking their movement and changes in location. This technology has a wide range of applications in assessing air quality and supports informed decision-making and expert analysis aimed at reducing air pollution. Ultimately, this contributes to the goal of ensuring clean and healthy air on Earth. In this report, we used data from the Sentinel-5 satellite to monitor nitrogen dioxide (NO<sub>2</sub>) emissions in Ankara over a year. The data was analyzed every month to gain insights into the trends and patterns of NO<sub>2</sub> concentrations throughout the year. It will be demonstrated that advanced satellite technologies, such as those provided by Google Earth Engine, have the potential to replace traditional ground-based monitoring stations. Instead, ground stations may shift to a role focused on validating satellite data. The study highlights a significant similarity between satellite and ground-based data, especially in the context of analyzing NO<sub>2</sub> concentration and its seasonal variations. The use of advanced satellite technology like Google Earth Engine underscores the importance of leveraging both language and technology in addressing environmental challenges and working toward a sustainable future.

## 1. Introduction

Remote sensing applications in air pollution studies have been extensively explored for over three decades. The first remote sensing satellite designed for measuring pollutants was called MAPS, which used infrared bands to globally identify and monitor carbon monoxide variations between 1981 and 1999. Using this satellite, changes in carbon monoxide levels resulting from vegetation fire events were identified and monitored with an 8 to 10-day temporal resolution[1]. Since then, satellites and sensors with similar

wavelength bands and scales have been used for monitoring pollution. In addition to infrared bands, visible and ultraviolet bands have also been utilized. Currently, satellite-derived data provides the ability to measure changes and concentrations of various gases and pollutants in the Earth's atmosphere at global, national, and local levels. Notably, countries like China have adopted intelligent monitoring and control systems to combat air pollution in key regions. A key element of this strategy is the "Satellite-based Remote Sensing" network, which enables command centers in Beijing to monitor and swiftly respond to pollution events, even in remote areas. This technology allows for real-time environmental action and effective management of air quality across vast distances[2]. Remote sensing has a broad spectrum of applications across various scientific and research fields, including geology, hydrology, mining,

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fisheries, cartography, geography, biology, environmental studies, geographic information systems (GIS), meteorology, agriculture, forestry, land development, and overall land resource management. It is highly effective in monitoring periodic changes in surface phenomena, such as shifts in river courses, modifications in water bodies like lakes and oceans, and transformations in land surface morphology. This capability makes remote sensing a crucial tool for understanding and managing diverse environmental and geographical changes.

By monitoring and analyzing electromagnetic reflection differences, remote sensing accurately delineates the boundaries of various land features, including soils, rocks, plants, and a variety of agricultural products. Moreover, it plays a crucial role in weather prediction, assessing the impact of natural disasters, detecting water pollution and oil spills in the sea, and even aiding in mineral exploration. The use of remote sensing technology not only expedites research endeavors but also proves to be more cost-effective and efficient, surpassing traditional methods in terms of accuracy and resource optimization.

Remote sensing data offers unique advantages over other information collection methods, thanks to its integration, wide coverage, spectral diversity, repetitive imaging, and cost-effectiveness. Today, it is a key tool for studying the Earth's surface and its underlying factors. The digital nature of this data allows for seamless integration with computer systems, leading to the development of Geographic Information Systems (GIS) and satellite data processing platforms. These technologies capitalize on remote sensing's strengths, providing easy access to data, swift coverage of remote areas, and exceptional accuracy. These qualities make remote sensing a highly valuable resource for comprehensive environmental and geographic studies. Over 22 reputable scientific articles have leveraged the Google Earth Engine platform for a variety of applications, including vegetation cover monitoring, crop type mapping, and ecosystem assessments. This cloud-based remote sensing tool provides access to an extensive range of free satellite imagery, from instruments like Sentinel-2 and MODIS to data from other climate and environmental satellites, spanning both short- and long-term periods. Since 2018, Google Earth Engine has been prominently featured in more than 158 scientific journals globally, underscoring its value in advancing scientific research. Despite its open-source nature, it is worth noting that the use of Google Earth Engine is significantly more widespread in developed countries compared to developing ones for scientific projects, likely due to differences in technological infrastructure and research resources.

In 1859, the first aerial photo was taken by Gaspard Felix from a hot air balloon, and a few decades later, in 1903, spy pigeons were used in military missions. Prepared In the last

years of World War I, aerial photographs were quickly used for reconnaissance purposes, but World War II ushered in a new era for aerial photography. In the 1960s, the United States began collecting information against Cuba and the former Soviet Union through spy satellites. In 1972, NASA launched the first earth resource assessment satellite called ERTS-1, later known as Landsat. In 1972, the first series of Landsat satellites with RBV (Return Beam Vidicon), MSS (multispectral sensor), and, TM (Thematic Mapper) cameras and sensors in four and seven bands were placed in the earth's orbit by the United States of America. Imaging went from analog to digital, a new window for image processing, and finally, their interpretation was opened to mankind. In 1986, France sent the first series of SPOT satellites into space with a resolution of 10 and 20 meters (in three bands), and sometime later, India launched the IRS (Indian Remote Sensing) series of satellites in 1988[3]. Japan also launched in 1988. In 1990, the MOS (Marine Observation Satellites) series was launched, and the European Space Agency also sent the ERS series of satellites into space. In 1991, Canada launched the Radar-sat series of satellites into Earth orbit to photograph the Earth's surface. (Radio Detection and Ranging-Satellite). A few years later in 1995, the partnership between Brazil and China to launch a satellite led to the joint design, construction, and launch of a new satellite (China-Brazil Earth Resource Satellite). In 1996, America launched the IKONOS satellite with a resolution of 1 meter and 4 meters, and in 1999 with the launch of QuickBird satellites with a resolution of 61 cm and 44.2 meters, leading to significant progress in this field. In 2003, the Indian Space Research Organization (ISRO) was researching the project of satellites that are capable of being sent into space and returned to Earth[4].

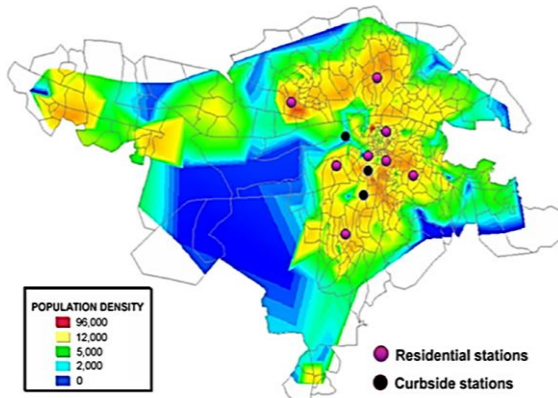
## 2. Methodology

### 2.1 Study area

Ankara, the capital of Turkey, situated in the central Anatolian region, stands as a relatively new and modern city with a population of approximately 5.6 million. Despite its modernity, the city faces challenges related to rapid population growth, unsuitable urbanization, and increasing industrialization, leading to heightened levels of air pollution, particularly during the winter months [5].

Research indicates a notable surge in the number of vehicles used in Ankara, contributing significantly to the degradation of air quality. The impact of air pollutants on the environment and human health is influenced by factors such as time, location, duration of exposure, concentration, and other characteristics. This has led to increased mortality rates from cardiovascular and respiratory diseases, along with a rise in hospital admissions due to these health issues[6].

The air quality in Ankara experiences severe deterioration, particularly during the cold months and nighttime, characterized by elevated levels of particulate matter and harmful gases. This poses challenges for the general population, particularly for vulnerable groups such as children, the elderly, and individuals with heart and respiratory conditions. Medical professionals advise these individuals to avoid venturing outdoors during late evening hours. Recognizing the severity of the issue, the Turkish government has made significant efforts in recent years to address and improve air quality in the capital. Additionally, as observed, Figure 1 shows the population distribution in the shape of Ankara. The central and eastern regions exhibit high population density, while the western and southwestern parts of the city have low population density.



**Fig. 5:** Detailed visualization of population distribution across the city of Ankara

## 2.2 Google Earth Engine Platform

Google Earth Engine is a powerful remote sensing tool specifically designed to extract valuable insights from satellite imagery. It is important to clarify that, contrary to common belief, Google Earth Engine is not the same as Google Earth. While Google Earth primarily serves as a platform for visual exploration, Google Earth Engine offers advanced functionality for viewing and analyzing areas, coverages, and land use with high spatial detail in both two and three dimensions. Its robust analytical capabilities make it an indispensable resource for conducting comprehensive remote sensing analysis, far beyond simple visualization[7]. Using this system, you will be able to perform various spectral processing on different phenomena on the Earth's surface using different satellite data. While Google Earth and Google Earth Engine have many similarities, Google Earth only provides a portion of the data and capabilities used in the Google Earth Engine system. With Google Earth Engine, you can undertake various projects from local to global scales. More specifically, Google Earth Engine enables you to perform processing with spatial resolution capabilities from 10 meters to several kilometers for various locations on the Earth's surface.

Some users of remote sensing systems may mistakenly believe that these tools are only suitable for international-scale projects. However, this assumption is incorrect, as remote sensing can be applied to projects ranging from a city scale to global coverage. A common inquiry revolves around the accuracy of processing within these systems. It's important to clarify that processing accuracy is inherently tied to the quality of satellite imagery. In reality, remote sensing systems allow for various processing tasks using freely available satellite images, including those from sources like Landsat, Sentinel, Hyperion, ASTER, MODIS, NAWA, and more[8]. The accuracy achieved through this system is comparable to traditional desktop processing methods, highlighting its versatility and reliability for projects of varying scales[9].

Google Earth Engine enables users to perform calculations on large volumes of data without the need for powerful computing systems. The increase in ubiquitous access to land viewing at this scale was previously unimaginable. For example, in a matter of seconds, you can call up 5,000 satellite images and perform various continuous processing on them[10].

This system supports various commonly used satellite data currently available for free. For example, all satellite images such as Landsat, Sentinel, ASTER, MODIS, etc. can be used and processed in this system. On the other hand, each user can upload and process their desired raster (TIFF format) and vector (shp format) data[11].

## 2.3 Satellite data

The mission of Sentinel-5 is to monitor the concentration of gases and particulate matter in the atmosphere, with a focus on monitoring air quality and climate protocols. This satellite captures images in the ultraviolet and infrared range. Sentinel-5P generates raw radiance and irradiance data (Level-1B) from its TROPOspheric Monitoring Instrument (TROPOMI). The radiance data corresponds to light reflected by Earth's atmosphere and surface, while irradiance data comes from direct sunlight. The Level-1B data is georeferenced, meaning the exact geographical coordinates of each pixel are determined, accounting for the satellite's position and viewing geometry[12]. This system employs the DOAS algorithm to analyze the spectral absorption features of NO<sub>2</sub> in the ultraviolet-visible (UV-Vis) spectral range. This algorithm identifies NO<sub>2</sub> by detecting its unique absorption pattern in the scattered sunlight. Also, clouds can obstruct the satellite's view of NO<sub>2</sub> concentrations near the ground. Sentinel-5P incorporates a cloud detection algorithm to estimate cloud cover. Pixels with cloud cover exceeding a certain threshold (usually around 30%) are excluded to avoid cloud interference in NO<sub>2</sub> data.

Sentinel-5P instruments are periodically calibrated using onboard and external reference measurements to maintain the accuracy of radiance and irradiance data. NO<sub>2</sub> data is validated through comparison with ground-based instruments like the Multi-Axis Differential Optical Absorption Spectroscopy (MAX-DOAS) or Pandora spectrometers. These instruments measure NO<sub>2</sub> concentrations at the surface and help refine the satellite data[13]. The following are some of the pollutants that can be measured with this satellite:

#### Carbon Monoxide:

Carbon monoxide, a highly hazardous gas primarily generated from vehicle exhaust due to the incomplete combustion of carbon, poses a severe threat to human health. Notably, this odorless and colorless gas exhibits a dangerous affinity for hemoglobin in the blood, binding approximately 200 times more strongly than oxygen. This phenomenon can lead to various toxicities and, critically, a reduction in the supply of oxygen to the brain. Utilizing Sentinel-5 satellite images, it becomes possible to monitor changes in carbon monoxide concentrations over specific areas[14]. Moreover, these images enable the creation of temporal series represented in the form of charts, graphs, or even Excel files. This advanced monitoring capability proves invaluable for assessing the impact of carbon monoxide and implementing strategies to mitigate its adverse effects on both human health and the environment[15].

#### Ozone (O<sub>3</sub>):

While ozone plays a crucial role in safeguarding life by preventing solar ultraviolet radiation from reaching the Earth's surface, its presence in lower atmospheric layers can become harmful[15]. The thinning of the ozone layer, primarily attributed to the Industrial Revolution and uncontrolled use of fossil fuels, poses a significant threat to human civilization. Monitoring ozone levels is essential, and one practical method for this is through the use of Sentinel-5 satellite images. Leveraging advanced technology, these images provide valuable insights into ozone concentrations, aiding in the assessment of environmental changes and supporting efforts to address the challenges posed by ozone depletion[16].

#### Aerosols with Sentinel-5:

One of the valuable products of Sentinel-5 is its aerosol product. With this product, you can easily monitor aerosols using the Google Earth Engine system. Aerosols are suspended particles in the air resulting from human activities or dust. These particles settle on the ground (if their diameter is larger than 100 micrometers). Monitoring these pollutants is valuable for many studies[17].

#### Methane:

After carbon dioxide, methane stands out as the second most important greenhouse gas, experiencing enhancement due to human activities. While methane has both natural and artificial sources, human-driven factors are considered the primary contributors to its increase. In the realm of remote sensing, this gas exhibits cloud-like features, encompassing characteristics such as cloud thickness, cloud amount, high cloud pressure, low cloud pressure, optical depth, and albedo[18].

#### Formaldehyde Product:

Formaldehyde is an intermediate gas that is present in almost all oxidation chains of non-methane organic compounds and eventually leads to carbon dioxide. Its sources include vegetation coverage, combustion, traffic, and industry.

#### Nitrogen Dioxide:

Nitrogen dioxide enters the atmosphere as a result of human activities such as fossil fuel combustion, and biomass burning, as well as natural processes such as microbiological processes in the soil, fires, and lightning [19].

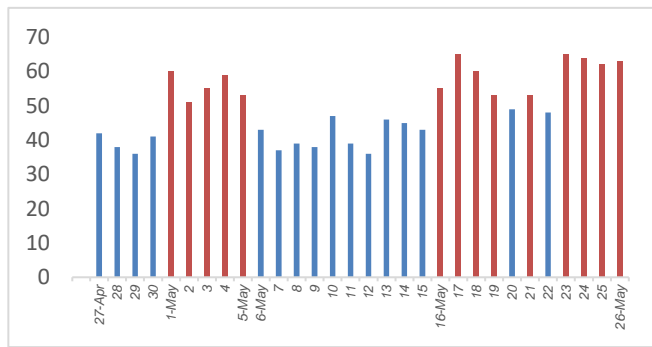
#### Sulfur Dioxide:

Sulfur dioxide (SO<sub>2</sub>) enters the atmosphere through both natural and human processes, although most of them are of anthropogenic origin. The production of greenhouse gases, SO<sub>2</sub>, has negative effects on human health and air quality and also affects water and climate through radiative forcing [20].

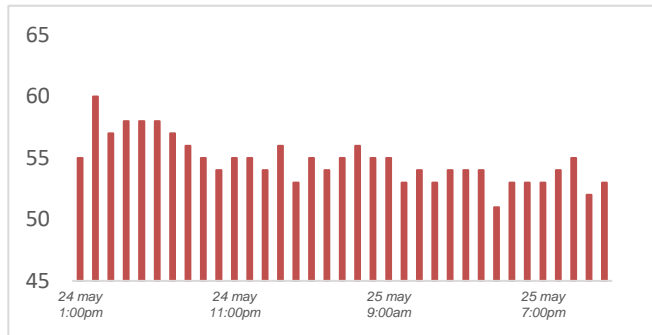
## 2. Results and discussion

Google Earth Engine was employed to measure the concentration of NO<sub>2</sub> gas, and the outcomes were extracted over a year period. The results encompass hourly, daily, and monthly concentration charts, along with concentration histogram charts for each month. As observed, Figure 2a represents the hourly air quality index (AQI), while Figure 2b represents the measured daily values. To enrich the analysis, Figure 2 depicts the Air Quality Index (AQI) and NO<sub>2</sub> levels from ground stations have also been extracted for further examination [21].

The study also incorporates monthly visualizations of gas concentration levels, represented through distinct color schemes. This approach enhances the analysis by providing a clearer understanding of air pollution patterns in the city, allowing for the identification of specific areas with varying pollution levels across different months. The inclusion of case studies based on these images further enriches the detailed examination of the data.



(a)



(b)

**Fig. 6:** (a) Daily AQI trends throughout the study period; (b) Hourly AQI variations for select days in May

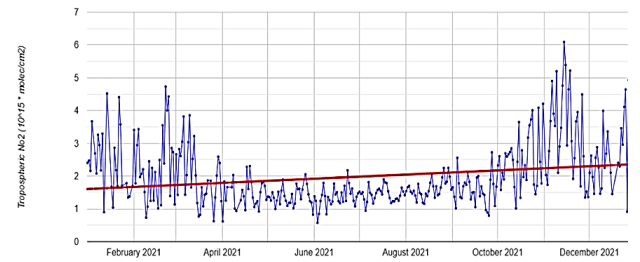
The measured AQI levels at ground stations remain relatively stable throughout the day. However, the daily concentration chart shows that on some days—particularly weekends—pollutant concentrations are lower, while they tend to be higher on working days.

A notable trend emerges, with higher hourly pollutant concentrations recorded between 7 p.m. and 5 a.m., as shown in Figure 2. This pattern can likely be attributed to increased traffic density and atmospheric stability during nighttime and early morning hours. Additionally, the charts show lower concentrations on weekends compared to weekdays, with an uptick in concentrations on days leading up to weekends. This highlights the impact of traffic patterns and human activity on air quality.

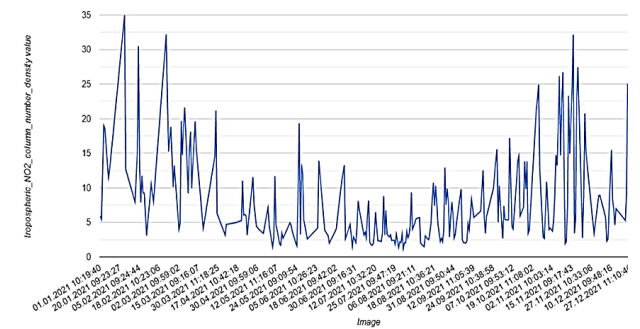
In Figure 3, the measured values from ground stations are shown. Figure 3.a presents the measured values of tropospheric nitrogen dioxide for all days of the month. Figure 3.b shows the nitrogen dioxide concentration levels for specific days of the month. Figure 3.c displays the monthly tropospheric nitrogen dioxide levels. It is worth mentioning that the values in Figures 3.a and 3.c are expressed in molecules per square centimeter( $\text{mole}/\text{cm}^2$ ).

As can be observed, there is a significant decrease in the measured values from April to October, while these values show a notable increase in the early and late months of the

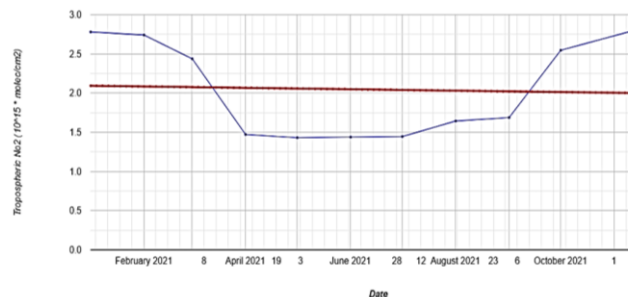
year. Figure 4 and figure 5 illustrates the concentration levels of nitrogen dioxide from January to November.



(a)



(b)



(c)

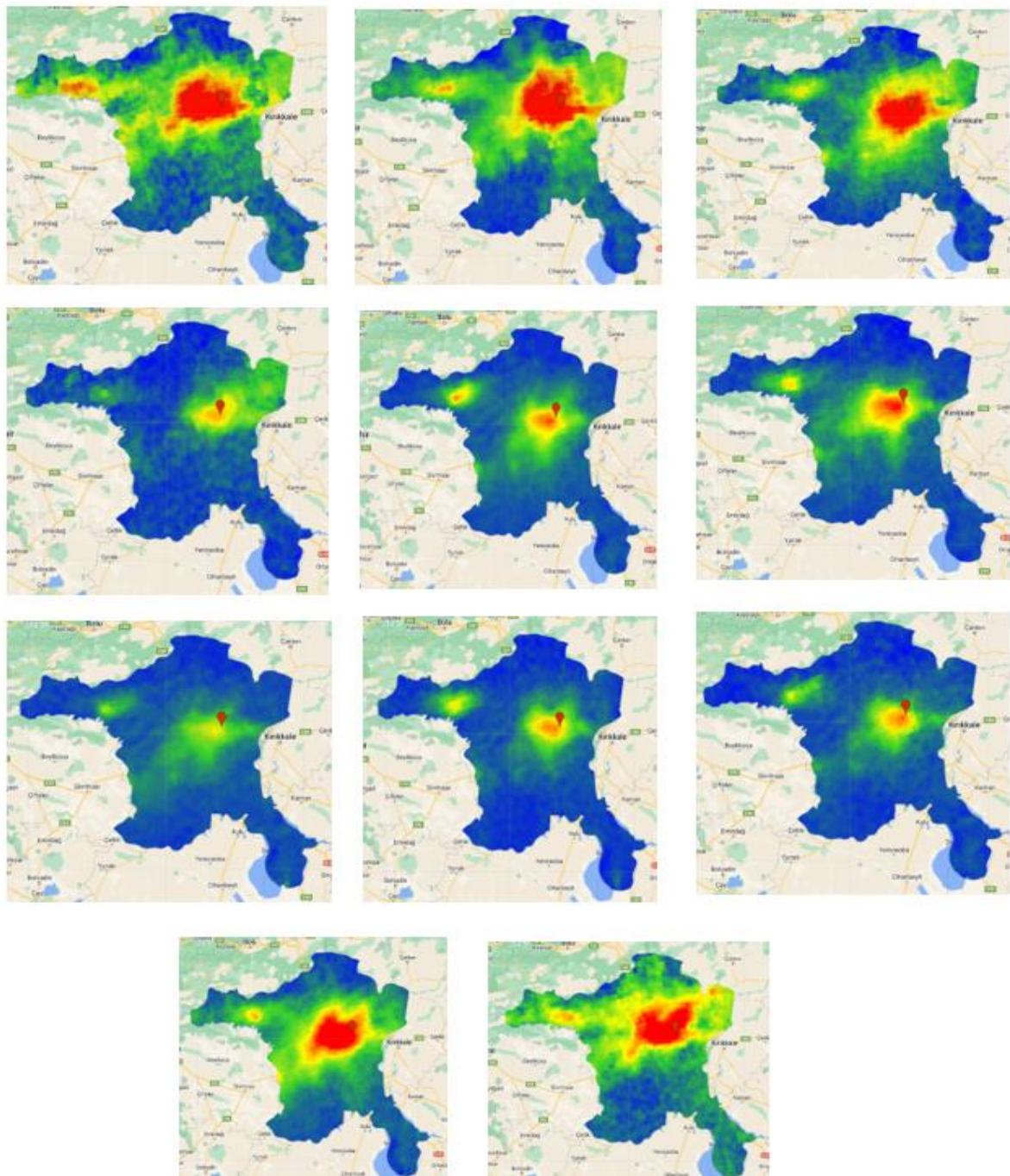
**Fig. 7:** (a) daily tropospheric nitrogen dioxide levels(value based on  $10^{15}$  multiplied by molecules per  $\text{cm}^2$ ); (b) tropospheric nitrogen dioxide levels at specific times; (c) monthly Nitrogen oxide concentration. (value based on  $10^{15}$  multiplied by molecules per  $\text{cm}^2$ )(data derived from station grounds)

As can be inferred, the overall pollutant concentration is higher during the colder months of the year. Additionally, throughout the year, concentrations are higher in densely populated areas, including the central and eastern parts of the city. Figure 6 also includes a histogram of nitrogen dioxide concentrations for the mentioned months.

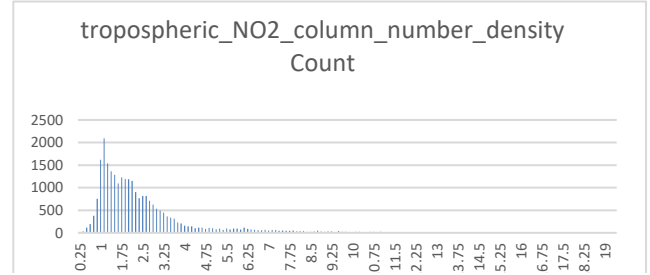
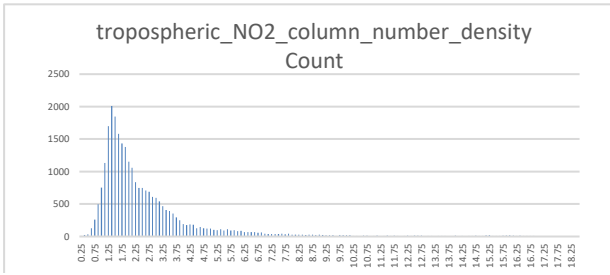
A detailed comparison between satellite and ground station data reveals a strong correlation coefficient of 0.71 and a low RMSE of 0.34, underscoring the reliability of the data alignment. Upon examining Figures 4 and 5 a clear pattern emerges, showing a decline in pollutant concentrations from

March to August, reaching their lowest levels during this period. However, starting in October, a noticeable rise is observed, peaking in December and January. This seasonal fluctuation is primarily attributed to colder temperatures and a higher likelihood of atmospheric inversion during the early months of the year, which leads to elevated pollutant concentrations. Conversely, as temperatures warm from March to September, improving dispersion conditions, pollutant levels tend to decrease. This connection between seasonal weather variations and pollutant concentrations underscores the importance of considering meteorological factors in addressing air quality

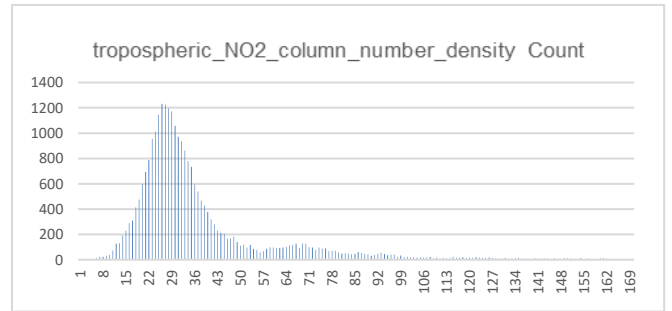
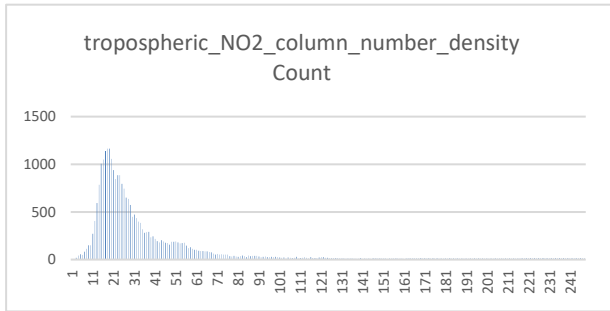
issues. Further analysis of the figure shows a clear trend of higher NO<sub>2</sub> concentrations during the first and last three months of the year, which coincides with colder weather and atmospheric inversion, particularly in the northeastern part of the city. This localized increase is likely due to higher population density, leading to more vehicles in this area. Additionally, the presence of electronic and chemical industries, along with the production of food and hygiene products, contributes to the overall pollutant levels in this region. These industrial activities shape the spatial distribution of NO<sub>2</sub> concentrations, highlighting the multifaceted factors affecting urban air quality.



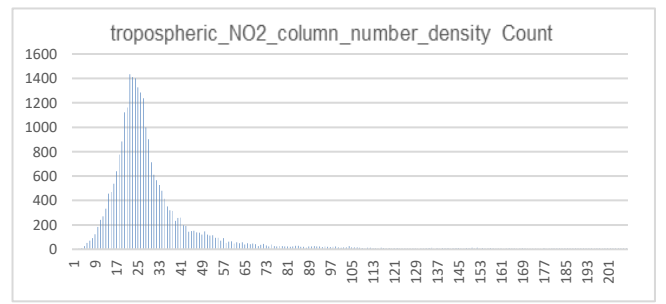
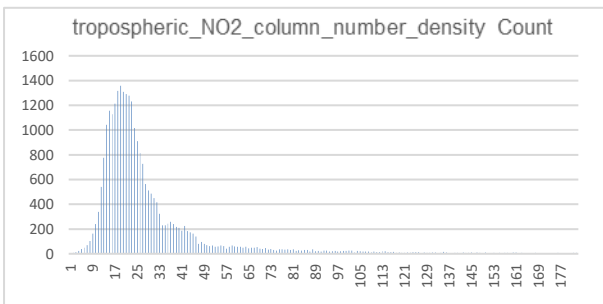
**Fig. 4:** Refined satellite-derived imagery showcasing NO<sub>2</sub> concentrations across the study area .from january (top left) to november(down right)



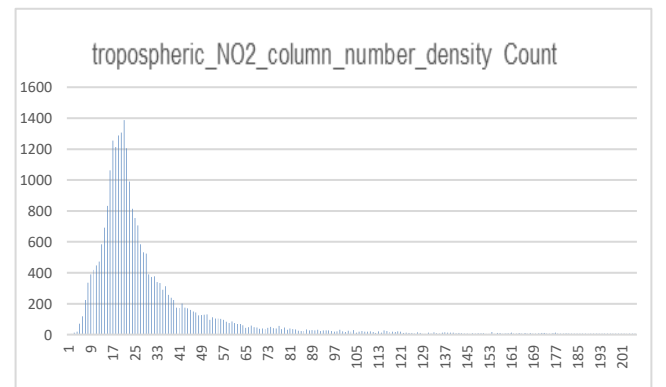
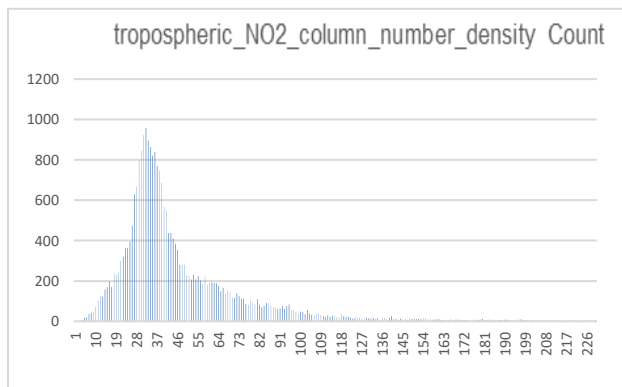
(5a)



(5b)



(5c)



(5d)

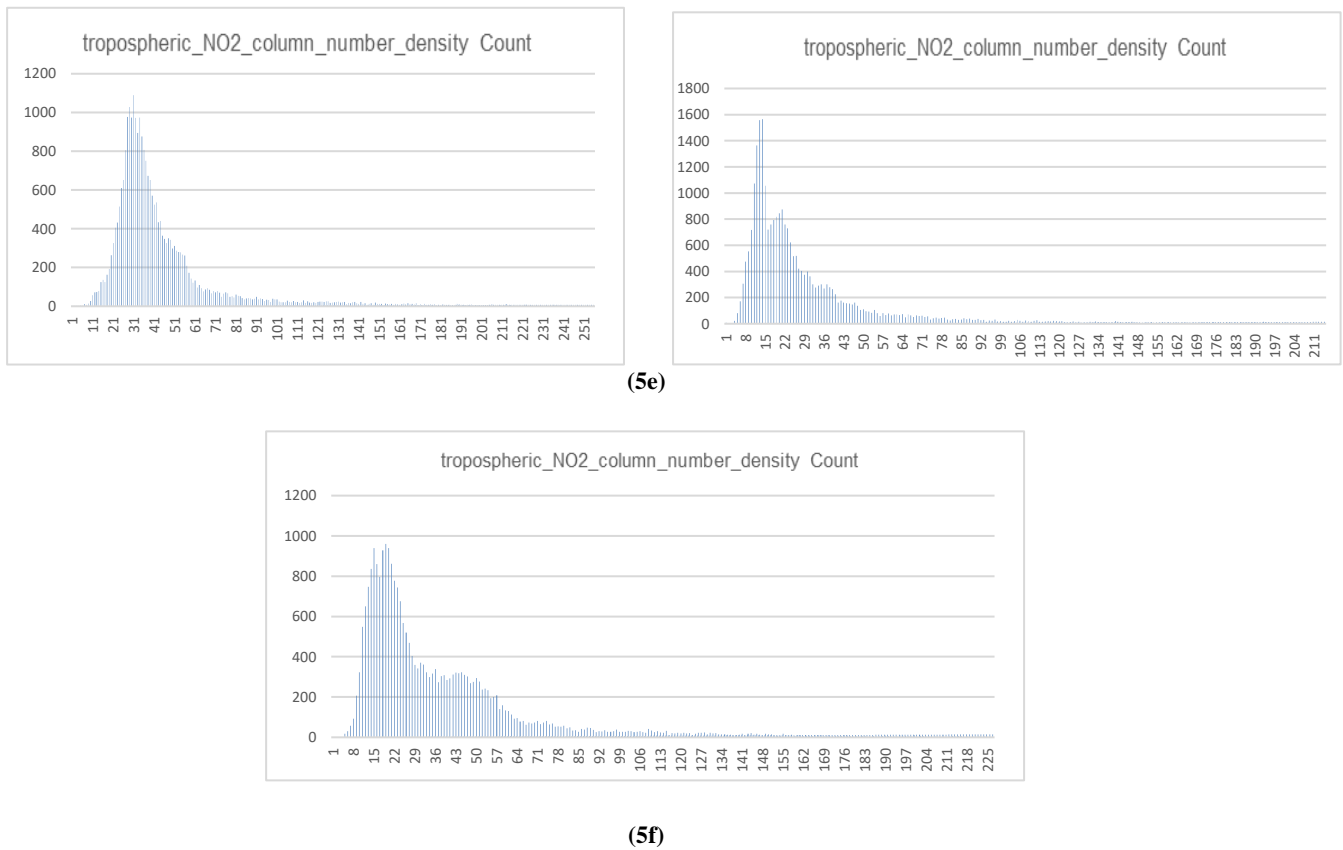


Fig. 5: Monthly histograms from January (top-left) to November 2021 (down-right), derived from satellite data

#### 4. Conclusion

The adoption of Google Earth Engine in conjunction with advanced remote sensing technologies is poised to revolutionize environmental monitoring by potentially replacing traditional ground stations. This shift would reposition ground stations primarily as tools for validating and ensuring the accuracy of satellite-derived data. Our study reveals a striking correlation between ground-based measurements and satellite data, highlighting their high degree of agreement. Through detailed analysis using satellite imagery and associated charts, the research delved into the intricate relationship between nitrogen dioxide (NO<sub>2</sub>) levels and seasonal variations. Moreover, the study investigated the influence of atmospheric inversion during the colder months, uncovering its significant role in exacerbating NO<sub>2</sub> concentrations. This comprehensive approach underscores the transformative potential of integrating cutting-edge satellite technology with remote sensing to enhance air quality monitoring and analysis. The capability to explore and analyze environmental data using advanced satellite technologies and platforms like Google Earth Engine offers crucial insights into air quality while highlighting the powerful role of language and technology in tackling environmental challenges. By

leveraging language as a medium for communication and collaboration, we can enhance awareness, inspire action, and contribute meaningfully to creating a more sustainable future for our planet. This fusion of data-driven technology and effective communication paves the way for informed decision-making and collective efforts toward environmental stewardship. While remote sensing holds significant potential and could reduce dependence on ground stations, several challenges and limitations make a full replacement unlikely in the future. These challenges include issues with data accuracy, the need for continuous validation, limitations in temporal resolution, and the ongoing reliance on ground-based data for satellite calibration. In conclusion, while remote sensing offers valuable advancements in terms of spatial coverage and can enhance air quality monitoring, it faces considerable obstacles in fully replacing traditional ground stations. A hybrid approach, integrating both technologies, is likely to remain essential for the foreseeable future, ensuring that each method's strengths are utilized to provide a more complete and reliable understanding of air quality. Hence, ground-based monitoring of air quality data is significant and serves as the foundation for analysis and modeling worldwide. The use of satellite data allows for enhancing the spatial resolution of ground data with high accuracy,

facilitating research on exposure to pollutants. Therefore, this study examines the accuracy of the model in increasing the spatial resolution of pollutant concentrations. Another application of the study's results is in the placement of ground stations and the identification of reliable data, which can be distinguished using remote sensing data.

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Additionally, the fitted model can be applied to locations with fewer stations, with lower uncertainty, like its application in Ankara.

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