



Assessment of Trajectory Tracking for Dust Storm Data and Air Quality Implications Using Satellite Imagery : A case study of Iraq

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Article Info	ABSTRACT
<p>Article type: Research Article</p> <p>Article history: Received: 17 July 2025 Revised: 12 November 2025 Accepted: 24 January 2026</p> <p>Keywords: <i>HYSPLIT</i> <i>Dust storm</i> <i>Meteosat</i> <i>CALIPSO</i> <i>Iraq</i></p>	<p>Dust storms pose significant environmental challenges in arid regions, with critical implications for human health and climate dynamics. This study investigates dust storm characteristics in Iraq during 2022, employing satellite imagery (Meteosat and CALIPSO), meteorological data, and the HYSPLIT trajectory model to analyze storm origins and atmospheric interactions. The study documented nine major dust storm events between March and July 2022, revealing storms consistently reaching 2-3 kilometers in vertical height. HYSPLIT back trajectory analysis identified multiple dust source regions, primarily in the northeastern Aljazeera area near Mosul. Particulate matter (PM_{2.5}) concentrations severely escalated to 354 PPM during dust events, a 117% increase from the annual average of 163 PPM. Air Quality Index (AQI) ratings ranged from "very unhealthy" to "hazardous". Key findings demonstrate Iraq's increasing environmental deterioration due to lack of vegetation cover, highlighting complex atmospheric dynamics and the potential long-term consequences of dust storms. The study provides critical insights into dust storm mechanisms, offering essential data for environmental management and public health strategies in climate-sensitive regions.</p>

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INTRODUCTION

The phenomenon of dust storms predominantly occurs in arid and semi-arid regions, presenting significant challenges to environmental stability, human health, and economic sustainability. According to Goudie and Middleton (2001). The majority of dust storms typically originate in regions characterized by exceptionally dry climates with an average annual rainfall of less than 100 mm. Among natural disasters, drought has severe socioeconomic repercussions worldwide, with dust storms serving as a critical indicator of environmental degradation (Bayatavrkeshi et al., 2023). Dust storms can be triggered by winds as low as 10-12 knots, which can suspend particles to altitudes up to 4.5 kilometers (Mutawa et al., 2016). The concentration and vertical distribution of atmospheric particles significantly influence mineralogical features, positioning dust storms as potential drivers of climate change (Xie et al., 2010). The increasing frequency of dust storms in Iraq in recent years necessitates comprehensive scientific investigation to analyze their genesis, propagation mechanisms, and environmental impacts. Globally, researchers have conducted extensive studies on dust storm effects, tracking, and prediction (Ekstrom et al., 2004;

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Ding et al., 2005; Gao & Han, 2010). These investigations are crucial given the multifaceted consequences of dust storms on various aspects of human and environmental systems.

The health implications of dust storms are particularly profound, especially for individuals with pre-existing respiratory conditions such as asthma and Chronic Obstructive Pulmonary Disease (COPD) (Thalib & Al-Taiar, 2012). Exposure to airborne dust particles can exacerbate these illnesses, leading to increased hospital admissions and medical expenses. Moreover, dust storms adversely affect agriculture by introducing hazardous compounds, inhibiting photosynthesis, and depositing particles on crops, thereby reducing agricultural productivity. Some recent studies even correlated COVID-19 infections with dust storms and air pollution (Alaa et al., 2025). The need for precise and early detection techniques to lessen the harm caused by dust storms is highlighted by these impacts on the environment, human health, and the economy. Recent research emphasizes the heightened dangers that areas commonly affected by dust storms face, especially respiratory conditions like asthma that are made worse by deteriorating air quality (Gupta et al., 2024).

Dust storms are typically classified into three primary types: Shamal, frontal, and convective storms (Tuhin & Pal, 2014). Each category possesses distinct characteristics that result in varying environmental and health impacts. The location, wind speed, force, and seasonal occurrence are critical factors in understanding and predicting these storms. Recent advancements in machine learning and satellite monitoring have significantly improved dust storm classification and forecasting, with techniques like support vector machines and random forests being employed in arid regions such as Saudi Arabia (Alshammari et al., 2024). Of particular concern is the long-term exposure to airborne particles. Pope and Dockery (2009) highlight that dust storms can retain air particles for extended periods, progressively worsening respiratory conditions and degrading air quality. The persistent presence of particulate matter has substantial long-term consequences for human populations and ecosystem health (Mori et al., 2003).

In the context of Iraq, dust storms have become increasingly frequent in recent years. Several research studies have been done on this phenomenon. According to satellite data such as Meteosat and CALIPSO, the wide deserts in east Syria and Saudi Arabia, as well as the western Iraqi deserts, are where those dust storms are thought to have originated (Reivandi et al., 2011; Shamsipoor & Safarrad, 2012; Azizi et al., 2012; Hashim et al., 2013; Vali et al., 2014). Furthermore, several studies have focused on using remote sensing techniques and satellite imagery to follow dust storms. The HYSPLIT model has been used in dust investigations to monitor the frequency and paths of dust transmission (Vali et al., 2014; Wang et al., 2011; McGowan & Clark, 2008).

This study distinguishes itself through a comprehensive, multi-methodological approach to understanding dust storms in Iraq. The primary objectives are to: (i) Investigate the major dust storms in Iraq during 2022 and analyze the dust phenomenon by tracking wind flow; (ii) Trace the origins of dust storms using the HYSPLIT trajectory model and satellite images; and (iii) Analyze the environmental and climatic factors contributing to dust storms in Iraq. The study provides a more nuanced and detailed examination of dust storm dynamics than previous studies. The focus on the year 2022, a period characterized by exceptionally intense dust storm activity, offers a critical temporal snapshot of environmental changes in the region. Furthermore, this research contributes to the growing body of knowledge on climate change impacts in Iraq, which is identified as one of the top five countries most vulnerable to environmental transformations (United Nations Environment Programme, 2016). By meticulously tracking dust storm origins, vertical atmospheric distribution, and associated air quality indices, the study provides crucial insights for environmental management, public health planning, and climate adaptation strategies in increasingly arid landscapes.

MATERIALS AND METHODS

Iraq is strategically located in the southwest of the Asian continent, spanning longitudes 38.45° – 48.45° and latitudes 29.5° – 37.22° north of the equator (Figure 1). Its geographical positioning within the northern subtropical zone significantly influences its climatic characteristics, with northwest winds consistently dominating extensive parts of the year (Oliver, 2005; Ghanim et al, 2024). The region's climate is characterized by extreme temperature variations, with dramatic shifts from day to night and between winter and summer seasons. A critical feature of Iraq's climate is the prolonged drought periods, particularly during winter, fall, and spring, which result from insufficient rainfall. High solar radiation intensifies evaporation, especially during summer months, further exacerbating the arid conditions (Jassim & Goff, 2006). The topographical diversity of Iraq, ranging from desert plains to mountainous regions in the northeast, creates complex environmental conditions that contribute to dust storm formation. These geographical and climatic factors make Iraq particularly susceptible to dust storm events, positioning it as one of the top five countries vulnerable to climate change impacts (United Nations Environment Programme, 2016).

The research meticulously documented nine major dust storm events in Iraq during 2022, systematically recorded by meteorological stations in Baghdad, Mosul, and Basra. These dust storms occurred on specific dates: 13 March, 27 March, 9 April, 12 April, 16 May, 19 May, 23 May, 9 June, and 3 July. For each dust storm event, a comprehensive suite of meteorological parameters was collected and analyzed to provide a holistic understanding of atmospheric conditions. For each of these dust storm events, comprehensive meteorological measurements variables were collected, including: Relative humidity, Rainfall, Wind direction, and Wind speed. Supplementary meteorological data for Baghdad were also analyzed, including: Average

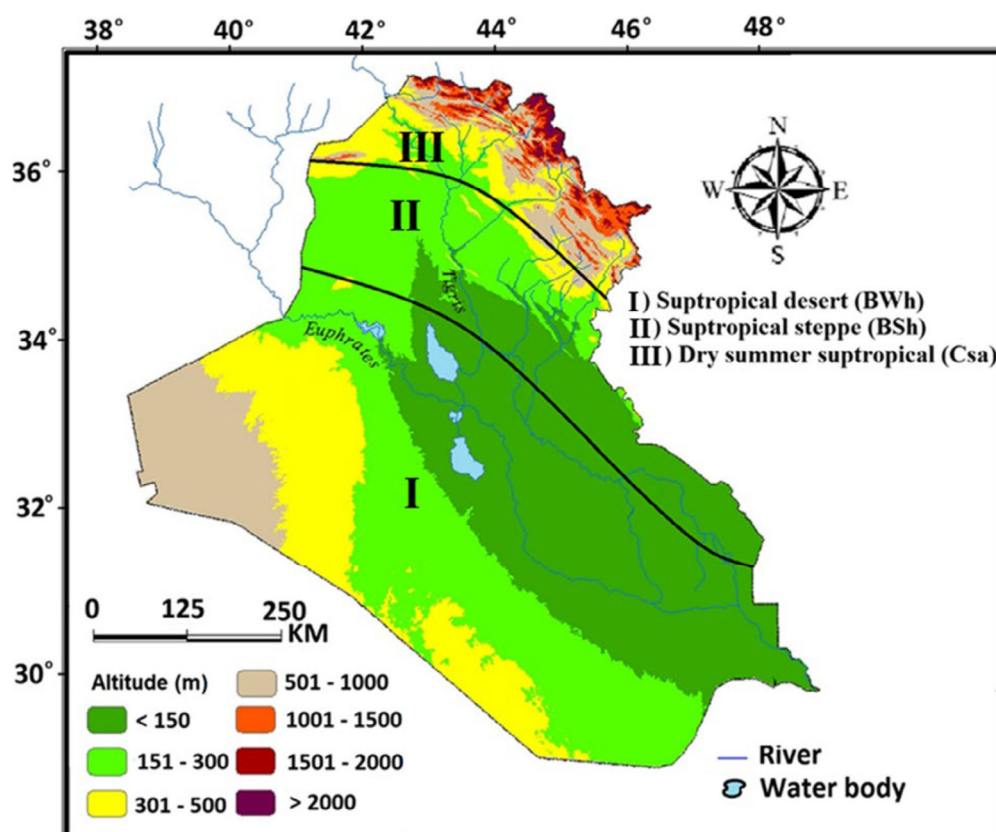


Fig. 1. Iraq's Geographic and Topographical Overview: Climate Zones and Landscape Diversity

temperature, Cloud distribution and percentage, and Atmospheric pressure patterns.

The data collection methodology adhered to World Meteorological Organization (WMO) standards, ensuring measurement precision and data reliability. Rigorous validation procedures were implemented, including cross-referencing multiple meteorological stations, satellite image corroboration, and statistical error analysis. The primary data source was the Iraqi Meteorological Organization and Seismology (IMOAS), with the collected information serving multiple research objectives. These objectives included quantifying dust storm characteristics, understanding atmospheric conditions preceding and during dust events, analyzing potential climate change impacts, and providing foundational data for predictive modeling. The significance of this detailed meteorological data collection extends beyond immediate research purposes. It contributes to a deeper understanding of regional environmental dynamics, drawing support from existing research by Jasim and Goff (2006), Oliver (2005), and the UNEP Climate Change Report (2016). These works underscore the critical importance of comprehensive meteorological data in comprehending complex atmospheric phenomena, particularly in environmentally vulnerable regions like Iraq.

The study utilized two advanced satellite systems for dust storm analysis: Meteosat 9 and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation). These remote sensing technologies provided comprehensive insights into atmospheric particulate matter during dust storm events in Iraq during 2022. The Meteosat 9 satellite employed a specialized dust detection product combining three thermal channels to generate visual representations of atmospheric conditions. This technique creates color-coded imagery where dust appears in purple to pink hues, enabling precise identification of dust storm locations, trajectories, and impacted areas across the Middle East and East Africa region. CALIPSO's Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor utilized advanced light detection and ranging (LIDAR) technology to analyze atmospheric compositions. By emitting laser pulses at 532 and 1064 nanometers, the sensor detected and characterized atmospheric aerosols, clouds, and particulate matter with exceptional vertical and spatial precision.

In this study, the CALIPSO satellite images were critically analyzed to identify dust storm locations and characteristics. The integration of Meteosat 9 and CALIPSO satellite data represents a sophisticated multi-sensor approach to dust storm analysis. By combining thermal imagery with advanced LIDAR technology, researchers could obtain a comprehensive understanding of dust storm dynamics, including spatial distribution, vertical structure, and atmospheric interaction mechanisms. These satellite-based observations were complemented by ground-based meteorological data and the HYSPLIT trajectory modeling, creating a robust, multi-dimensional analytical framework. The research methodology follows established scientific protocols outlined in previous studies by Jokar et al. (2009) and builds upon the foundational work of atmospheric remote sensing pioneers like Kovalev and William (2004) and Winker et al. (2006).

Back trajectory analysis is a critical methodological approach for understanding the origin and transport pathways of atmospheric particles, particularly in dust storm investigations. In this study, a Lagrangian approach was employed using NOAA's Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT-4) model to trace the source and path of dust storms in Iraq during 2022. The back trajectories were calculated at three distinct atmospheric layers: 500, 1000, and 1500 meters above sea level (a.s.l.). A 48-hour back trajectory was generated for each recorded dust storm date, enabling a detailed reconstruction of the dust storm's origin and propagation path. The methodology involved several key steps:

1. Utilizing online meteorological data from NOAA's archives
2. Inputting precise geographical coordinates for Iraq
3. Calculating backward trajectories at multiple atmospheric layers
4. Visualizing and analyzing the resulting trajectory maps

The back trajectory analysis was complemented by satellite image interpretation, specifically using Meteosat and CALIPSO satellite data. The procedure builds upon previous studies that have successfully employed the HySplit model for dust storm tracking, such as Wang et al. (2011) and McGowan and Clark (2008) that demonstrated the model's effectiveness in global and regional dust transport analysis.

RESULTS AND DISCUSSION

During The CALIPSO images in Figure 2 provides a sophisticated vertical and spatial

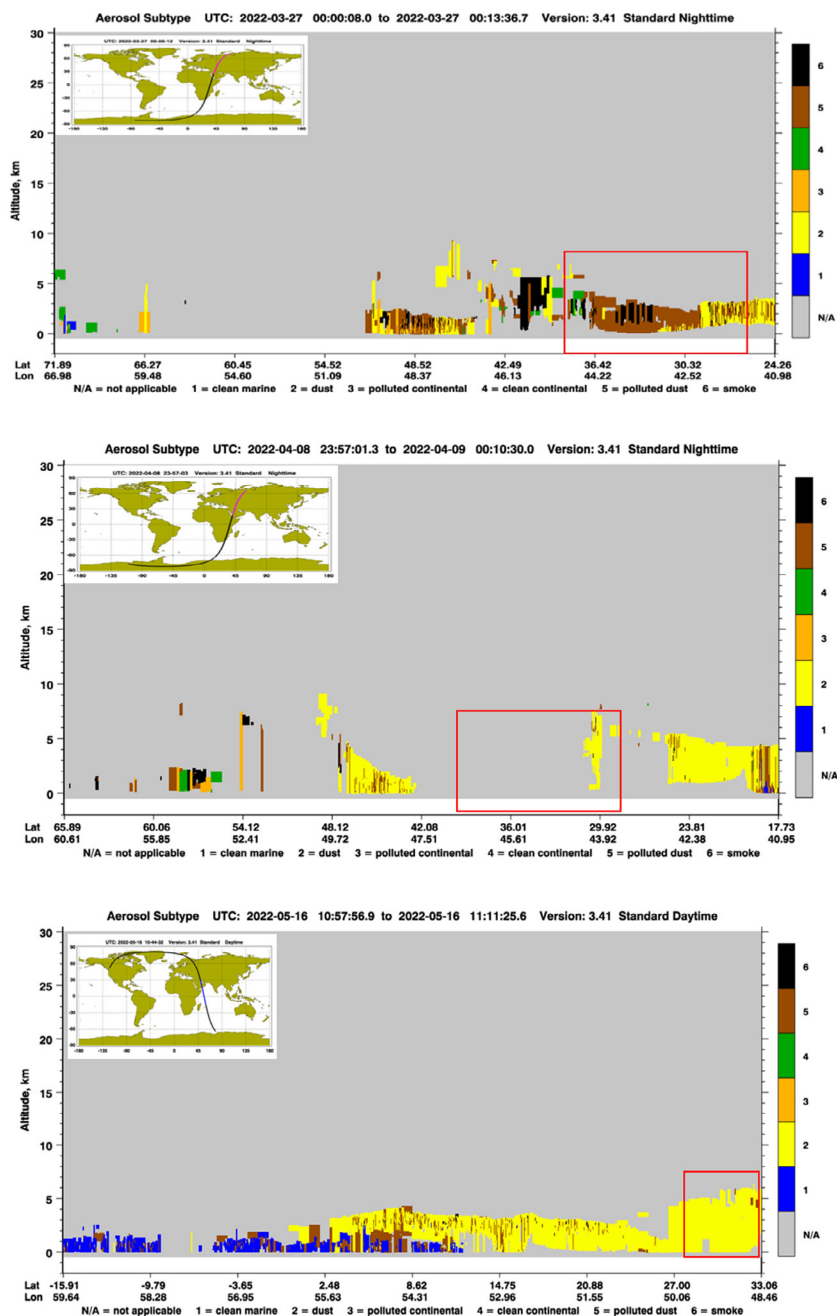
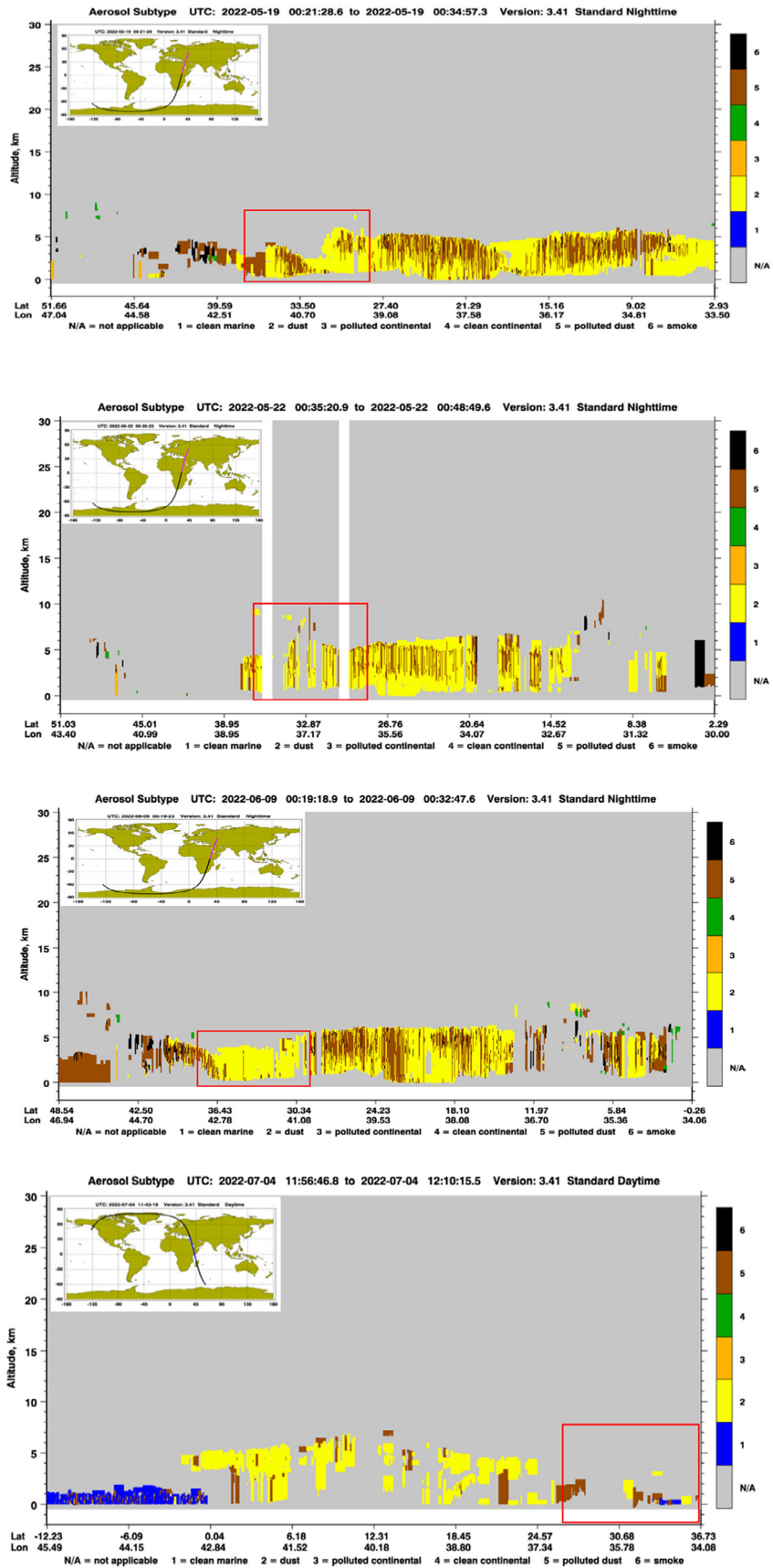


Fig. 2. CALIPSO Satellite Images: Vertical Aerosol and Dust Particle Distribution During Iraqi Dust Storms in 2022



Continued Fig. 2. CALIPSO Satellite Images: Vertical Aerosol and Dust Particle Distribution During Iraqi Dust Storms in 2022

representation of dust storm characteristics across Iraq in 2022. Each image provides critical insights into the atmospheric composition, aerosol distribution, and vertical extent of dust storms during different events throughout the year. The most striking observation from these images is the consistent vertical penetration of dust particles into the atmosphere. Across multiple dust storm events, the images reveal that dust storms in Iraq reached remarkable heights, typically ranging between 2 to 3 kilometers above sea level.

The color coding in the CALIPSO images is particularly informative. The yellow tint specifically represents dust particles, while other colors indicate different types of atmospheric pollutants and aerosols. One critical insight from these images is the interconnected nature of dust storms in the region. The analysis reveals that dust storms affecting Iraq are not isolated events but are part of a broader atmospheric phenomenon spanning the Arabian Peninsula. The images suggest that the vast deserts of southern Iraq and neighboring regions serve as substantial dust reservoirs, contributing to the storm's intensity and geographical spread. This finding is supported by previous research (Hashim et al., 2013).

The vertical profile of these dust storms is especially noteworthy. The consistent 2–3-kilometer height suggests powerful atmospheric dynamics driving these events. Such vertical penetration means that dust particles are not merely surface-level phenomena but significant atmospheric components that can interact with solar radiation, potentially affecting regional climate patterns. The images corroborate the study's central argument about Iraq's increasing vulnerability to dust storms, which is linked to prolonged drought, soil degradation, and climate change. The consistent and substantial dust vertical profiles across multiple events in 2022 provide empirical evidence of these environmental transformations.

Figure 3 provides a visual representation of dust storm origins, trajectories, and propagation

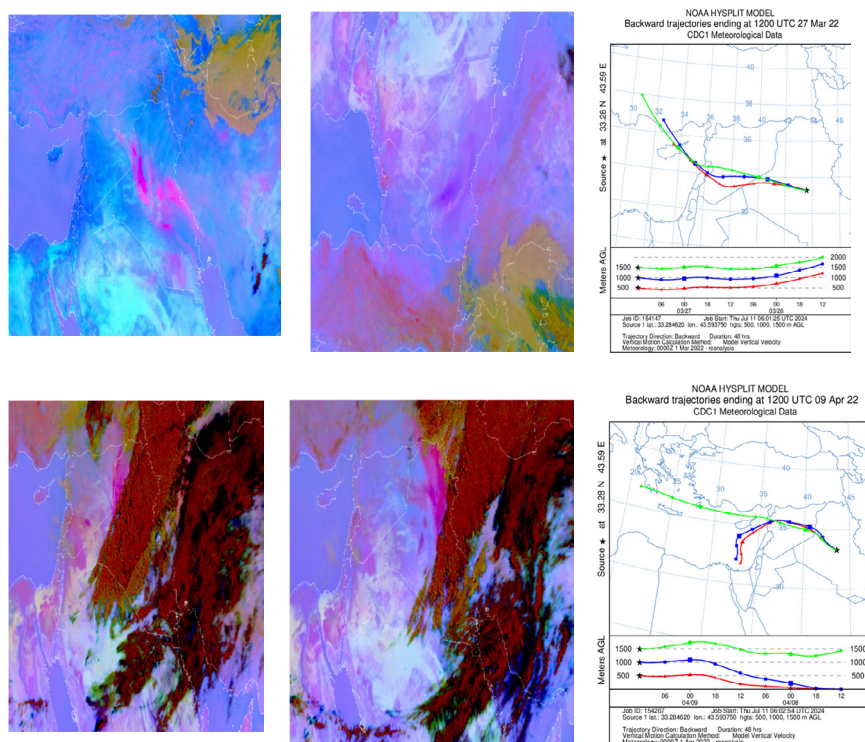
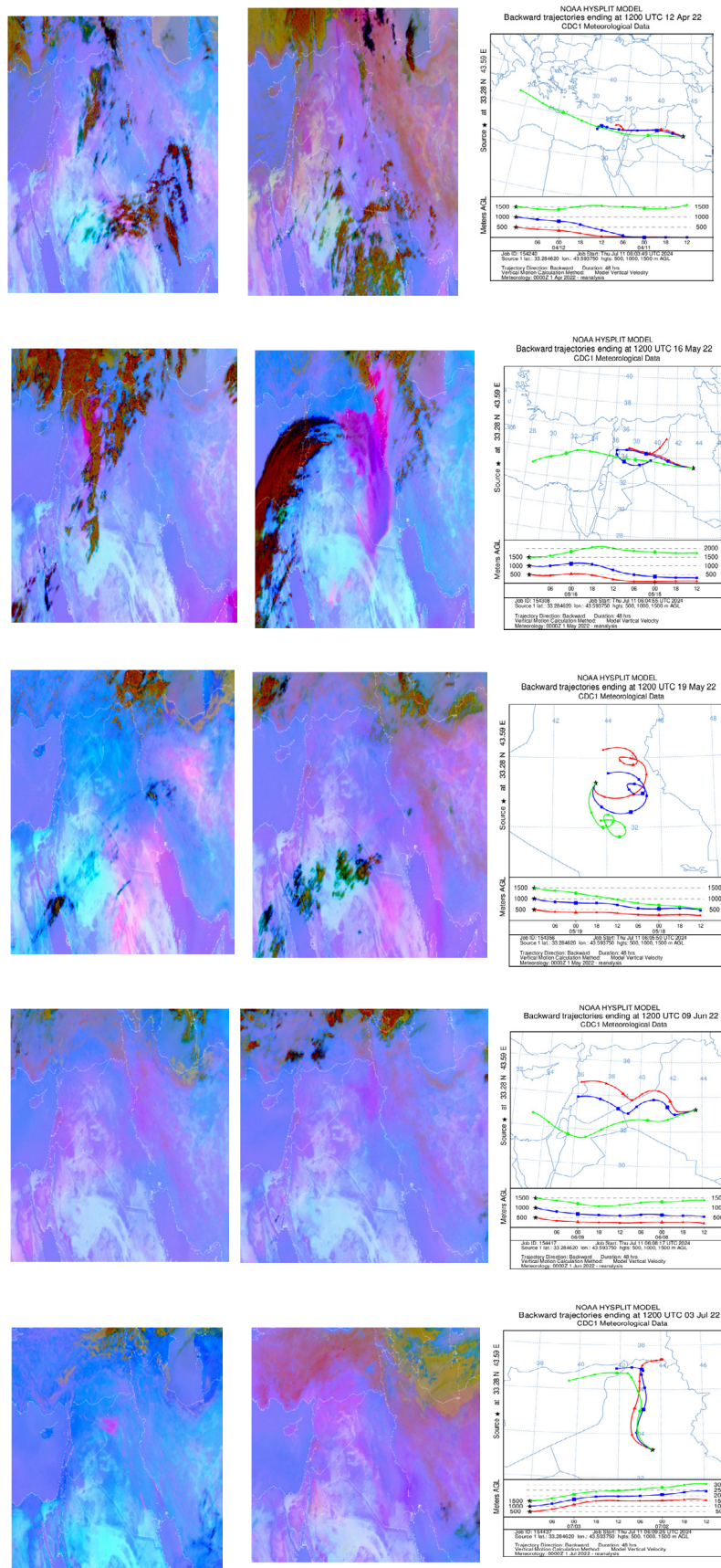


Fig. 3. Meteosat Satellite Imagery and HYSPLIT Back Trajectory Analysis of Dust Storm Origins and Propagation in Iraq (2022)



Continued Fig. 3. Meteosat Satellite Imagery and HYSPLIT Back Trajectory Analysis of Dust Storm Origins and Propagation in Iraq (2022)

patterns across multiple events in 2022. The figure consists of paired images for each major dust storm event, with satellite imagery alongside corresponding back trajectory maps, providing a multi-dimensional analysis of dust storm dynamics. The most striking observation from these images is the consistent northwestern origin of dust storms in Iraq. The back trajectory maps consistently demonstrate that dust particles predominantly originated from the Aljazeera region in Ninawa province, located north of Mosul near the Syrian border. This geographical consistency suggests a systematic environmental vulnerability in this specific region, likely related to prolonged drought, soil degradation, and specific topographical conditions.

Interestingly, the analysis reveals multiple dust storm sources within Iraq, challenging the simplistic notion of a single origin point. While the Aljazeera region emerges as a primary source, the back trajectory maps and satellite images also highlight dust generation from the northeastern mountainous regions of Iraq. This multiplicity of sources underscores the complex environmental dynamics driving dust storm formation in the region. The trajectory maps reveal fascinating wind patterns and particle movement. Each map shows colored lines representing the movement of air masses at different atmospheric layers (500, 1000, and 1500 meters above sea level), providing a three-dimensional understanding of dust storm propagation. The color variations in these trajectories likely represent different atmospheric conditions and particle behaviors at various altitudes.

The satellite images accompanying the trajectory maps offer visual confirmation of the dust storm formation is not just a matter of wind speed, but a complex interplay of multiple environmental factors. The images suggest that soil surface disintegration, combined with appropriate wind speeds in various Iraqi regions, contributes to dust storm generation. This observation is particularly significant in the context of climate change and ongoing environmental degradation in the region. The temporal distribution of these dust storms is also noteworthy. The figure presents multiple dust storm events across different months, suggesting a pattern of increasing frequency and intensity. This aligns with the study's broader argument about Iraq's growing vulnerability to environmental changes and dust storm occurrences (Hashim et al., 2013; Mamouri et al., 2009).

Figures 4 and 5 provide a quantitative analysis of particulate matter and air quality in Baghdad during 2022, revealing the severe environmental impact of dust storms. Figure 4 shows the PM_{2.5} concentrations throughout the year, with a striking average concentration

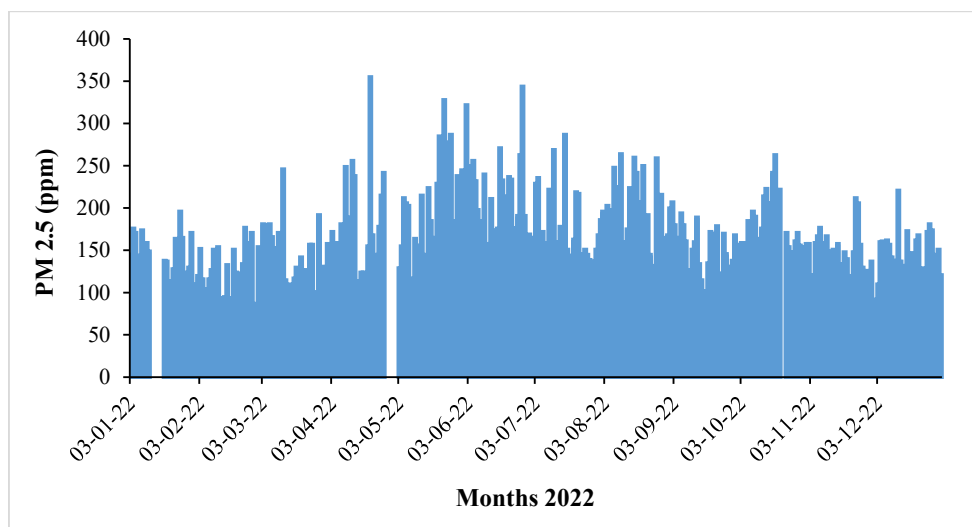


Fig. 4. PM_{2.5} Concentration Levels in Baghdad Throughout 2022, Highlighting Dust Storm Impact

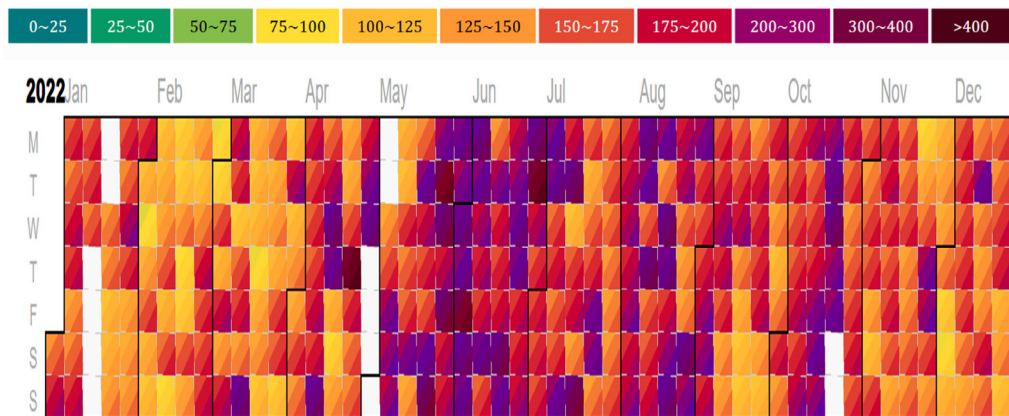


Fig. 5. Air Quality Index (AQI) in Baghdad During 2022, Showing Severity During Dust Storm Periods

of 163 PPM. During the April dust storms, this concentration dramatically escalated to 354 PPM - more than double the annual average. This significant spike demonstrates the extreme atmospheric pollution associated with dust storm events, representing a 117% increase from the annual mean. This observation is supported by other similar studies in the same region (Diana et al., 2023). Figure 5 complements this data by presenting the Air Quality Index (AQI), which categorizes the air quality severity. During dust storm periods, the AQI ranged between 201-500, classified as “very unhealthy” (AQI between 201-300) to “hazardous” (AQI between 301-500) according to World Health Organization standards (World Health Organization, 2021). This classification indicates extreme health risks for the population, with potential severe respiratory and cardiovascular implications. The correlation between $PM_{2.5}$ concentrations and dust storm occurrences is particularly noteworthy. The data substantiates the study’s broader argument about Iraq’s increasing environmental vulnerability. The massive particulate matter increases during dust storms represent more than just atmospheric phenomena - they signify profound environmental transformation and potential long-term health consequences for the population. The quantitative evidence in these figures provides concrete scientific documentation of the environmental challenges facing Iraq. The dramatic particulate matter increases during dust storms underscore the urgent need for comprehensive environmental management strategies and public health interventions in the region.

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CONCLUSION

This thorough study of dust storms in Iraq during 2022 reveals critical insights into the complex atmospheric dynamics and environmental challenges facing the region. Through a multi-methodological approach combining satellite imagery, meteorological data, and advanced trajectory modeling, several key findings emerge:

1. The year 2022 was marked by exceptionally severe and frequent dust storms in Iraq,

with the most intense events occurring between March and July. The analysis demonstrated that these dust storms were not isolated phenomena but part of a broader atmospheric process involving multiple source regions.

2. The study identified multiple dust storm sources within Iraq. While the northeastern regions, including the Aljazeera area near Mosul, emerged as a primary origin point, the study revealed that dust generation is a complex interplay of environmental factors such as soil surface disintegration and wind dynamics.

3. CALIPSO satellite images consistently showed dust storms reaching remarkable vertical heights of 2-3 kilometers above sea level. This vertical penetration underscores the significant atmospheric interaction and potential climate implications of these events.

4. The particulate matter analysis revealed alarming air quality metrics. During dust storm periods, PM_{2.5} concentrations dramatically escalated to 354 PPM, more than double the annual average, with Air Quality Index (AQI) ratings ranging from “very unhealthy” to “hazardous”.

The consistent dust storm patterns observed in 2022 substantiate Iraq’s increasing vulnerability to environmental transformations, particularly in the context of climate change. These meteorological events are indicators of profound environmental shifts, including prolonged drought, soil degradation, and changing atmospheric conditions. The dramatic increases in particulate matter during dust storms highlight the urgent need for comprehensive environmental interventions and robust public health preparedness in the region. Future research should continue to monitor these trends, further investigate the underlying environmental mechanisms driving dust storm formation, and develop targeted mitigation strategies to address the growing environmental challenges in Iraq.

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The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, and redundancy has been completely observed by the authors.

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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