

Article

Dust Event Characteristics, Transport Pathways, and Source Regions over Riyadh Using AERONET, HYSPLIT, and Surface Observations (2024–2025)

Sarah Albugami 

Department of Physical Sciences-Geographic Information Systems Program, College of Science, University of Jeddah, Jeddah 21589, Saudi Arabia; saalbugami@uj.edu.sa

Abstract

Dust storms are a major environmental hazard across the Arabian Peninsula, affecting air quality, human health, transportation, and infrastructure. Despite their frequency in Riyadh, event-based studies integrating aerosol optical observations, atmospheric transport analyses, potential source-region identification, and surface validation remain limited. This study characterized dust events over Riyadh during 2024–2025 using AERONET aerosol observations, NOAA Integrated Surface Database (ISD) meteorological records, HYSPLIT backward trajectories, and potential source contribution function and concentration-weighted trajectory analyses. Dust events were identified using a dual optical criterion based on aerosol optical depth (AOD) at 500 nm ($AOD_{500} \geq 0.50$) and the 440–870 nm Ångström exponent (≤ 0.50) and were compared with co-located NOAA ISD present-weather and visibility observations. Among the 34 identified dust events, 82% occurred between March and May. The events were dominated by coarse-mode aerosols, with a mean Ångström exponent of 0.28 and a mean fine-mode fraction of 0.26. Same-day dust-related present-weather reports were recorded for 26 events (76%), while the remaining eight events (24%) were classified as elevated because no dust-related present-weather code was reported at the co-located ISD station during the corresponding event day. The trajectory and source–receptor analyses showed a consistent spatial association with the Mesopotamian Basin as a major potential source region and the northern Rub’ al-Khali as a secondary potential source region. Surface wind speed was significantly and positively associated with coarse-mode aerosol loading and dust-event severity, whereas sea-level pressure showed no statistically significant association with severity. These findings provide an updated observational characterization of dust events affecting Riyadh during 2024–2025 and demonstrate the complementary value of aerosol optical observations, co-located surface records, atmospheric transport analysis, and source–receptor methods for examining dust-event characteristics and transport over central Saudi Arabia.

Keywords: dust storms; aerosols; AERONET; HYSPLIT; PSCF; CWT; aerosol optical depth; air quality; Riyadh; Arabian Peninsula



Academic Editor: Tao Wang

Received: 8 July 2026

Revised: 12 August 2026

Accepted: 17 August 2026

Published: 20 August 2026

Copyright: © 2026 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Dust storms are among the most significant environmental hazards in arid and semi-arid regions, affecting air quality, human health, ecosystems, transportation, and infrastructure [1,2]. They are generated when strong surface winds entrain loose soil particles from sparsely vegetated drylands into the atmosphere [3–7]. Dust particles smaller than approximately 20 µm in diameter can remain suspended in the atmosphere and be transported

hundreds to thousands of kilometers from their source regions, thereby influencing regional weather and climate. During severe dust events, this long-range transport can substantially reduce horizontal visibility, often to less than 1 km, creating significant hazards for aviation and surface transportation [8]. Severe episodes can lead to near-zero visibility, posing serious risks to public safety and economic activities [2]. Dust storms have also been associated with increased respiratory and cardiovascular diseases, disruption of transportation systems, and damage to infrastructure and agricultural productivity [1,9–12].

The Arabian Peninsula is one of the world's major dust-producing regions due to its extensive deserts, arid climate, limited vegetation cover, and frequent strong winds [3,13–15]. Across central and northern Saudi Arabia, including Riyadh, annual precipitation is low, ranging from 80 to 150 mm [16], and summers are extremely hot, with mean daily maximum temperatures ranging from 35 °C to 45 °C [17]. Together with intense evaporation and sparse vegetation, these arid conditions expose large areas of loose soil that are highly susceptible to wind erosion, resulting in frequent dust emissions and long-range transport across the region [18]. In addition, Modaihsh et al. [19] reported that dust storms were the primary cause of elevated particulate matter levels in Riyadh. During the dust season, monthly mean PM_{10} concentrations reached $696 \mu g m^{-3}$, with peak daily values exceeding $2234 \mu g m^{-3}$, while $PM_{2.5}$ concentrations also increased markedly during these events [19].

Accordingly, Riyadh, the capital of Saudi Arabia, is frequently affected by dust storms, particularly during the spring and summer months [20,21]. These events have substantial environmental, health, and socioeconomic impacts. Maghrabi et al. [22] reported that the severe dust storm of 10 March 2009 caused heavy dust deposition, near-zero visibility, airport closure, and widespread damage to infrastructure and vegetation. Meo et al. [23] found that dust storm exposure significantly increased respiratory and general health complaints, including eye irritation, cough, wheezing, headache, sleep disturbances, and asthma exacerbations. During the April 2015 dust storm, King Khalid International Airport recorded zero visibility, resulting in a seven-hour operational closure and disruption to air traffic affecting more than 164,500 passengers [24]. These studies highlight the importance of understanding the characteristics, transport pathways, and source regions of dust affecting Riyadh.

Ground-based observations from the Aerosol Robotic Network (AERONET) have substantially improved the characterization of atmospheric aerosols by providing long-term measurements of aerosol optical depth (AOD), Ångström exponent, single scattering albedo, and other aerosol optical properties [25,26]. In Saudi Arabia, long-term observations from the Solar Village AERONET station indicate increasing AOD associated with frequent dust events and expanding anthropogenic emissions [27]. Likewise, Maghrabi and Alotaibi [28] reported increasing annual and seasonal AOD trends, particularly during spring, reflecting the dominant influence of transported desert dust over the central Arabian Peninsula. Previous studies have also shown that dust events in Riyadh are characterized by high aerosol loading and coarse-mode particles, as indicated by elevated AOD and low Ångström exponent values [29].

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPPLIT) model has been widely applied to identify dust transport pathways and source regions across the Middle East. Previous studies consistently identified the Rub' al Khali, the Iraqi and Syrian deserts, and the Sahara Desert as the principal dust source regions influencing Saudi Arabia, with transport largely controlled by Shamal winds and regional synoptic circulation [30–33]. More recent studies have shown that transported dust events substantially increase $PM_{2.5}$ and PM_{10} concentrations, degrading air quality and posing significant public health risks [34].

Although previous studies have characterized aerosol optical properties using AERONET observations and identified dust transport pathways using HYSPLIT, relatively few studies have integrated aerosol optical properties, atmospheric transport pathways, potential source contribution function (PSCF) and concentration weighted trajectory (CWT) source-receptor analyses, and surface meteorological observations within a single event-based framework to investigate dust events affecting Riyadh. Integrating these complementary datasets provides a more comprehensive characterization of dust events by linking aerosol optical properties, transport pathways, probable source regions, surface observations, and dust-event severity.

Accordingly, this study investigates the characteristics, transport pathways, source regions, and severity of dust events affecting Riyadh during 2024–2025 through an integrated analysis of AERONET observations, HYSPLIT backward trajectories, PSCF/CWT source-receptor analyses, and NOAA Integrated Surface Database (ISD) observations. Specifically, the study characterizes dust events using aerosol optical properties derived from AERONET, identifies atmospheric transport pathways through HYSPLIT backward trajectory analysis, determines potential dust source regions using PSCF and CWT analyses, and evaluates the relationships between aerosol optical properties, surface meteorological conditions, and dust-event severity.

2. Materials and Methods

2.1. Study Area and Data

The study was conducted over Riyadh, Saudi Arabia (24.93° N, 46.72° E), located in the central Arabian Peninsula (Figure 1). This study is based on point observations collected at the co-located Riyadh_Airport_SDSC AERONET station and NOAA ISD station (40437099999) at King Khalid International Airport.

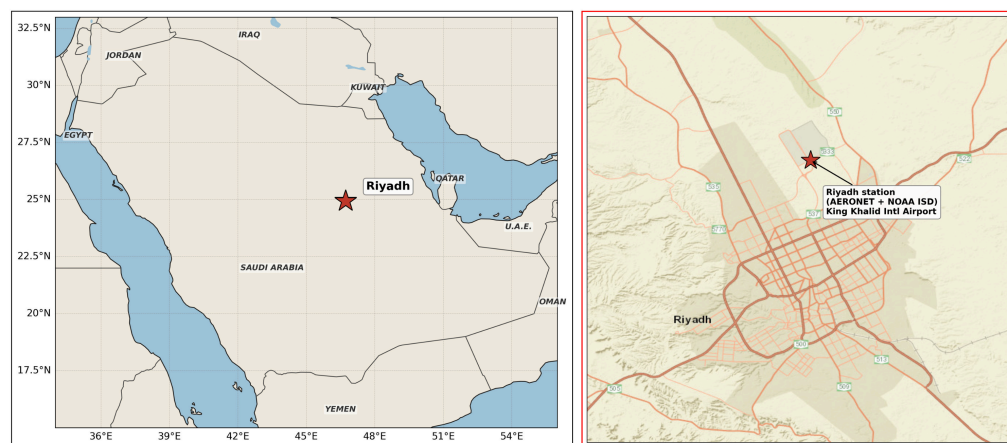


Figure 1. Study area. **(Left)** Location of Riyadh within central Saudi Arabia and neighboring countries. **(Right)** The Riyadh station (AERONET and NOAA ISD) at King Khalid International Airport (base map: Esri World Street Map).

Aerosol optical observations were obtained from the Riyadh_Airport_SDSC station of AERONET, a global ground-based sun-photometer network for aerosol monitoring [35]. Version 3 Level 1.5 cloud-screened direct-sun observations were used for the period from January 2024 to December 2025 [36]. Level 1.5 data were used because Level 2.0 requires final post-deployment calibration, which has not been completed for this recently established site, so Level 2.0 data are unavailable in the AERONET data portal. Level 1.5 observations are automatically cloud-screened and quality-controlled, and their use is standard practice for characterizing recently established AERONET sites. The variables extracted included

AOD at 500 nm; the Ångström exponent (440–870 nm); and coarse-mode aerosol optical depth, fine-mode aerosol optical depth, and fine-mode fraction (FMF) derived from the AERONET spectral deconvolution algorithm (SDA).

The NOAA ISD station serves as the synoptic and METAR reporting station used for surface observations in this study. Its spatial co-location with the Riyadh_Airport_SDSC AERONET site allows direct temporal comparison between the column-integrated aerosol observations and surface meteorological records from the same observation location. Present-weather observations and horizontal visibility measurements are reported in accordance with World Meteorological Organization observing standards and undergo automated and manual quality-control procedures implemented by the NOAA National Centers for Environmental Information (Figure 1). The datasets used in this study and their respective roles in the analysis are summarized in (Table 1).

Table 1. Datasets used in this study and their role in the analysis.

Dataset	Description and Role
AERONET direct-sun observations (Version 3, Level 1.5)	Cloud-screened direct-sun observations of AOD at 500 nm and the 440–870 nm Ångström exponent (α). Used to identify dust events and quantify aerosol optical properties.
AERONET SDA (Version 3, Level 1.5)	SDA products, including coarse-mode AOD, fine-mode AOD, and FMF at 500 nm. Used for aerosol characterization and as the weighting variable in the CWT analysis.
NOAA ISD, station 40437099999	Hourly observations of present weather, horizontal visibility, wind speed, wind direction, air temperature, dew-point temperature, and sea-level pressure. Used for surface validation, event classification, and statistical analyses.
NOAA HYSPLIT/GDAS1	Seventy-two-hour backward air-mass trajectories calculated using the HYSPLIT model driven by GDAS1 meteorological fields. Used for transport-pathway clustering and PSCF/CWT source-region analyses.

Furthermore, surface observations used for event validation were obtained from the NOAA ISD station. Its co-location with the Riyadh_Airport_SDSC AERONET site at King Khalid International Airport allowed the AERONET observations to be compared with present-weather and visibility records from the same observation location. No additional surface stations were included in the validation analysis, so the surface validation and dust-event classification represent conditions recorded at the co-located airport station. Events classified as “elevated” indicate that no dust-related present-weather code was reported at this station during the corresponding event day.

An overview of the data-processing and analytical workflow used in this study is presented in Figure 2.

2.2. Dust Event Identification and Classification

Dust events were identified using a dual optical criterion based on AERONET observations. A day was classified as a dust event when the daily mean AOD at 500 nm was ≥ 0.50 and the daily mean Ångström exponent (440–870 nm) was ≤ 0.50 [37]. Daily mean values were calculated from all available AERONET observations for each day. For each identified event, peak total AOD, peak coarse-mode AOD, mean coarse-mode AOD, mean fine-mode AOD, and FMF were extracted to characterize the aerosol conditions.

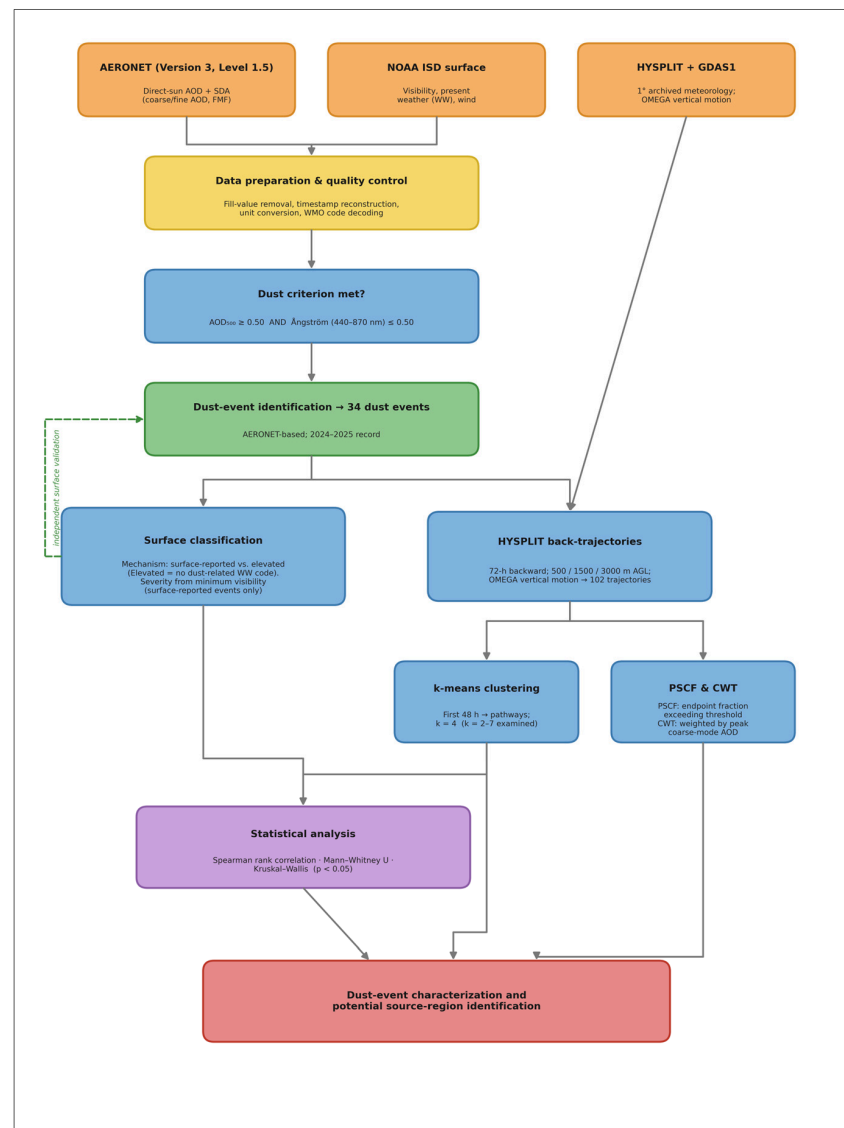


Figure 2. Workflow of the data processing and analysis framework used for dust-event identification and characterization over Riyadh, including AERONET and NOAA ISD observations, HYSPLIT back-ward trajectories, transport-pathway clustering, PSCF/CWT source–receptor analysis, and statistical analysis. Colors indicate the main workflow stages, and arrows show the analytical sequence.

The corresponding NOAA ISD present-weather (ww) observations and horizontal visibility records were then examined for each identified event day. Surface confirmation was based on the occurrence of at least one dust-related ww code during that day. The dust-related ww codes included 06 (suspended dust), 07 (dust or sand raised by wind at or near the station), 08 (dust whirls), 09 (dust or sandstorm), and 30–35 (dust or sandstorm codes). The number of dust-related present-weather observations recorded during each event day was counted as the surface dust observation count. An event with at least one such observation was considered surface-confirmed, whereas an event with no dust-related ww code recorded during the available observations ($ndust = 0$) was classified as elevated (aloft) dust. Thus, the elevated classification was based on the absence of a reported surface dust code rather than on a specific visibility threshold.

For surface-confirmed events, dust-event severity was classified using the minimum horizontal visibility recorded during the event day. Events with minimum visibility <1 km were classified as dust storms, those with visibility ≥1 and <5 km as dense dust, and those with visibility ≥5 km as moderate dust. These thresholds were applied only after confirming

the presence of at least one surface dust report. Consequently, minimum visibility was not used to determine the elevated category.

The dust-raising mechanism was classified separately using the NOAA ISD ww codes. Events containing code 06 were classified as transported (suspended) dust, whereas events containing code 07 were classified as locally raised dust. Events in which both suspended and locally raised dust were reported during the same event day were classified as mixed. Events without any reported dust-related ww code were retained as elevated (aloft). Dust-related codes 08, 09, and 30–35 were included in the surface-confirmation procedure.

2.3. HYSPLIT Trajectory Analysis

Backward air-mass trajectories were calculated using the NOAA HYSPLIT model with meteorological fields from the Global Data Assimilation System (GDAS1). For each identified dust event, 72 h backward trajectories were initialized at the Riyadh receptor site (24.93° N, 46.72° E) at arrival heights of 500, 1500, and 3000 m above ground level. The hour corresponding to the peak AOD of each event was used as the trajectory arrival time. The HYSPLIT calculations used the OMEGA vertical-motion method. Trajectories were calculated at the three arrival heights to examine air-mass transport at different vertical levels.

A total of 102 trajectories were generated for the 34 identified dust events, corresponding to three trajectories per event. For transport-pathway classification, the first 48 h of each trajectory were used. Each trajectory was represented by its latitude and longitude coordinates over this period, and the complete set of 102 trajectories was analyzed using *k*-means clustering. Candidate solutions with *k*-values from 2 to 7 were examined using the within-cluster sum of squares. Four clusters were selected based on the resulting spatial grouping and the geographic distinction among the transport pathways. The final *k*-means analysis was performed with *k* = 4, *n*_init = 10, and random_state = 0.

For event-level analyses, each dust event was assigned to the cluster containing the majority of its three trajectories at 500, 1500, and 3000 m. When the three trajectories were assigned to three different clusters, the cluster assigned to the 500 m trajectory was used for the event-level classification.

2.4. PSCF and CWT Analysis

Potential dust source regions were investigated using the PSCF and CWT methods based on the complete set of backward trajectories. Peak coarse-mode aerosol optical depth was used as the weighting variable for the CWT analysis. PSCF was used to identify grid cells frequently associated with dust-event trajectories, whereas CWT calculated the average coarse-mode aerosol loading associated with trajectories crossing each grid cell. The resulting PSCF and CWT fields were used to identify the principal source regions associated with the identified dust events.

Both analyses were computed on a 1° × 1° grid over the domain 10–40° N, 30–60° E. For the PSCF, each grid cell (*i*, *j*) was assigned $PSCF_{ij} = m_{ij}/n_{ij}$, where *n*_{*ij*} is the total number of trajectory endpoints in the cell, and *m*_{*ij*} is the number of endpoints associated with dust events whose peak coarse-mode AOD exceeded the event-mean peak coarse-mode AOD. To reduce the influence of cells sampled by few trajectories, the PSCF values were multiplied by an empirical weight function that down-weights sparsely sampled cells, following the general approach of Polissar et al. [38]; cells were assigned weights of 1.00, 0.70, 0.42, and 0.17 when their endpoint count exceeded 3.0, 1.5, and 1.0 times the mean cell count, or fell below it, respectively. For the CWT, each cell was assigned $CWT_{ij} = (1/n_{ij}) \sum C_l$, the mean peak coarse-mode AOD over all trajectory endpoints

l passing through the cell. Cells containing fewer than three trajectory endpoints were masked in both fields.

2.5. Statistical Analysis

The 34 identified dust events were statistically analyzed using Python 3.13. Spearman rank-correlation analysis was used to examine relationships between peak coarse-mode AOD, mean and maximum surface wind speed, minimum surface visibility, sea-level pressure, and dust-event severity. Dust-event severity was treated as an ordinal variable, coded as elevated = 0, moderate = 1, dense = 2, and dust storm = 3, consistent with the event-classification scheme described in Section 2.2. Differences in mean surface wind speed between locally raised and transported dust events were evaluated using the Mann–Whitney U test. The Kruskal–Wallis H test was used to compare peak coarse-mode AOD among the four transport-pathway clusters and maximum surface wind speed among the dust-event severity classes. Statistical significance was defined as $p < 0.05$.

3. Results

3.1. Dust Climatology and Event Frequency

Application of the dual optical criterion to the 2024–2025 dataset identified 34 dust events over Riyadh. Dust activity exhibited a marked seasonal cycle, with events concentrated during spring and early summer. May recorded the highest frequency (13 events), followed by April (8 events) and March (7 events), together accounting for 82% of all identified events. The remaining events occurred during February, June, July, and August.

Across all identified events, the mean peak total AOD at 500 nm was 0.89 (median = 0.80), while the mean peak coarse-mode AOD reached 0.48. The mean Ångström exponent (0.28) and FMF (0.26) indicate that the aerosol burden was dominated by coarse mineral dust. The most intense event occurred on 11 April 2025, when the peak total AOD reached 2.76, accompanied by a coarse-mode AOD of 2.29 and an FMF of only 0.19. This event coincided with a surface dust storm that reduced visibility to 0.5 km.

To illustrate the temporal evolution of the dust event, Figure 3 presents the sub-hourly variations in total AOD, coarse-mode AOD, and FMF during the most intense event observed on 11 April 2025. Total AOD increased rapidly between 08:00 and 10:00 UTC, reaching a peak value of 2.76. Throughout this period, the FMF remained consistently low (approximately 0.18–0.20), indicating that the increase in aerosol loading was dominated by coarse-mode mineral dust rather than fine anthropogenic particles (Figure 3).

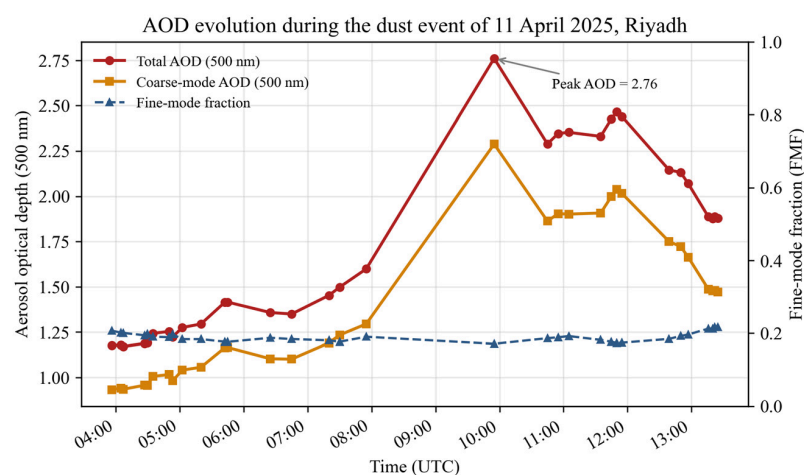


Figure 3. Sub-hourly evolution of total AOD, coarse-mode AOD (500 nm), and fine-mode fraction during the 11 April 2025 dust event over Riyadh, the most intense event in the study period (peak AOD = 2.76 at 09:54 UTC).

3.2. Aerosol Optical Properties and Type

The aerosol optical properties consistently indicate that all identified events were dominated by coarse mineral dust. The uniformly low mean Ångström exponent (0.28) and FMF (0.26) place all 34 events within the coarse-particle aerosol regime, confirming that mineral dust rather than fine anthropogenic aerosol governed the column loading during dust episodes over Riyadh.

This interpretation is supported by the very strong positive association between total and coarse-mode AOD (Spearman's $\rho = 0.97$; Figure 4). The near-unity correlation confirms that variations in total column loading were driven almost entirely by the coarse particle mode, consistent with a mineral-dust-dominated aerosol regime. In contrast, both total and coarse-mode AOD were only weakly and negatively correlated with the Ångström exponent (-0.33 and -0.42 , respectively) and FMF (-0.29 and -0.39), indicating a limited and secondary contribution from fine anthropogenic particles, even during elevated-loading conditions. The Ångström exponent and FMF were themselves very strongly correlated ($\rho = 0.97$), as expected, since both parameters characterize the fine-to-coarse partitioning of the aerosol size distribution, providing an internal consistency check on the retrievals.

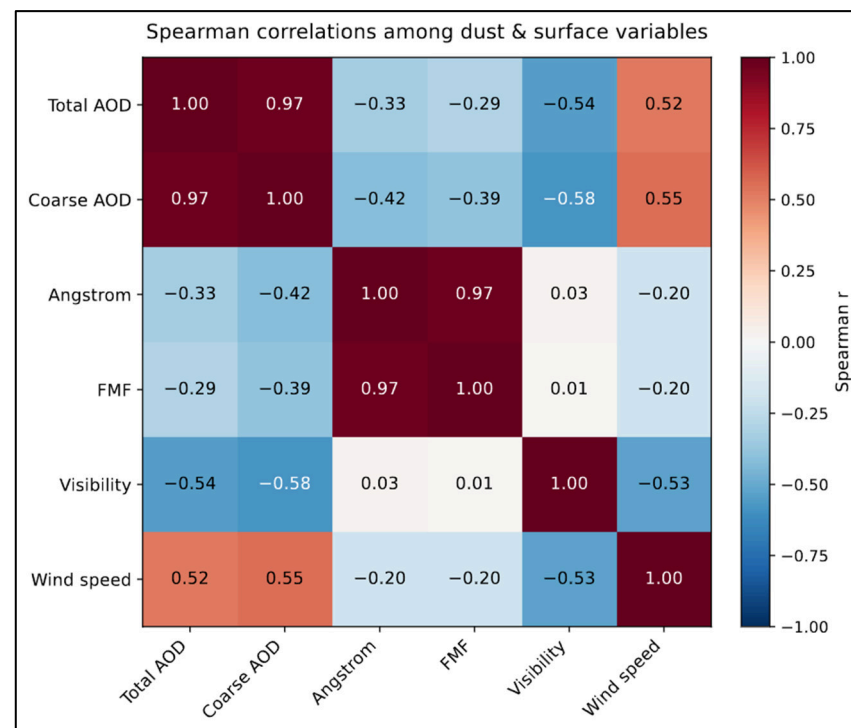


Figure 4. Spearman correlation matrix among aerosol-optical and surface-meteorological variables.

The optical parameters also showed physically coherent links with the surface conditions. Both total and coarse-mode AOD were negatively correlated with horizontal visibility (-0.54 and -0.58) and positively correlated with surface wind speed (0.52 and 0.55), consistent with wind-driven mobilization of coarse dust that simultaneously increases column loading and reduces surface visibility. Accordingly, coarse-mode AOD was adopted as the principal optical indicator of dust intensity in the subsequent transport-pathway and source-region analyses.

3.3. Event Classification

The 34 identified events exhibited substantial variability in surface severity and dust-raising mechanism (Table 2). Based on visibility, two events were classified as dust storms

(visibility < 1 km), seven as dense dust (1–5 km), 17 as moderate dust (5–10 km), and eight as elevated dust events, during which the atmospheric column was dust-laden while surface visibility remained largely unaffected.

Table 2. Classification of the 34 dust events by severity and mechanism.

Severity Class	<i>n</i>	Mechanism	<i>n</i>
Dust storm (<1 km)	2	Transported (suspended)	19
Dense dust (1–5 km)	7	Mixed	4
Moderate dust (5–10 km)	17	Locally raised	3
Elevated (aloft)	8	Unattributed (elevated)	8

Classification according to dust-raising mechanism showed that transported (suspended) dust was the most frequent category, accounting for 19 events, followed by four mixed events and three locally raised events. The remaining eight elevated events could not be assigned to a surface dust-generation mechanism because the dust layer remained aloft.

3.4. Surface Validation

Independent validation was performed using synoptic surface observations. Of the 34 photometrically identified dust events, 26 events (76%) were confirmed by surface weather observations reporting dust on the same day. The remaining eight events (24%) were classified as elevated dust events, characterized by high AOD, high coarse-mode aerosol loading, and low Ångström exponent values, while surface observations reported clear conditions with visibility close to 10 km.

The event of 17 April 2025 exemplifies this category, with elevated aerosol optical signatures together with surface visibility remaining near 10 km throughout the day. The agreement between the optical identification and the surface observations indicates that most photometrically identified dust events were independently confirmed by the surface observations.

3.5. Transport Pathways

Analysis of the complete set of 102 backward trajectories (34 events × three arrival heights) revealed that air masses reaching Riyadh originated predominantly from the north, southwest, southeast, and west (Figure 5). Cluster analysis grouped these trajectories into four representative transport pathways (Figure 5): Cluster 1, a northern pathway originating over the Iraqi–Mesopotamian region (22% of trajectories); Cluster 2, a south-westerly pathway (34%); Cluster 3, an easterly–southeasterly pathway (36%); and Cluster 4, a long-range westerly pathway (8%).

The four pathways varied in occurrence frequency and showed differences in mean associated dust loading. The easterly–southeasterly pathway (Cluster 3) was the most frequently observed yet carried the lowest mean coarse-mode aerosol loading. In contrast, the northern Iraqi–Mesopotamian pathway (Cluster 1), although less frequent, transported the highest coarse-mode concentrations (Section 3.6). These results indicate that transport frequency and aerosol intensity are not directly coupled: the most active corridor delivers comparatively weak dust, whereas the less frequent northern pathway was associated with the highest mean peak coarse-mode AOD.

This distinction is important for interpreting the source-region analysis, because the PSCF and CWT analyses are weighted by coarse-mode AOD rather than by trajectory frequency. Consequently, the Mesopotamian Basin is identified as a major potential source region, while the northern Rub’ al-Khali is identified as a secondary potential source region.

The aerosol characteristics associated with each pathway, together with their statistical significance and implications for source attribution, are examined in the following sections.

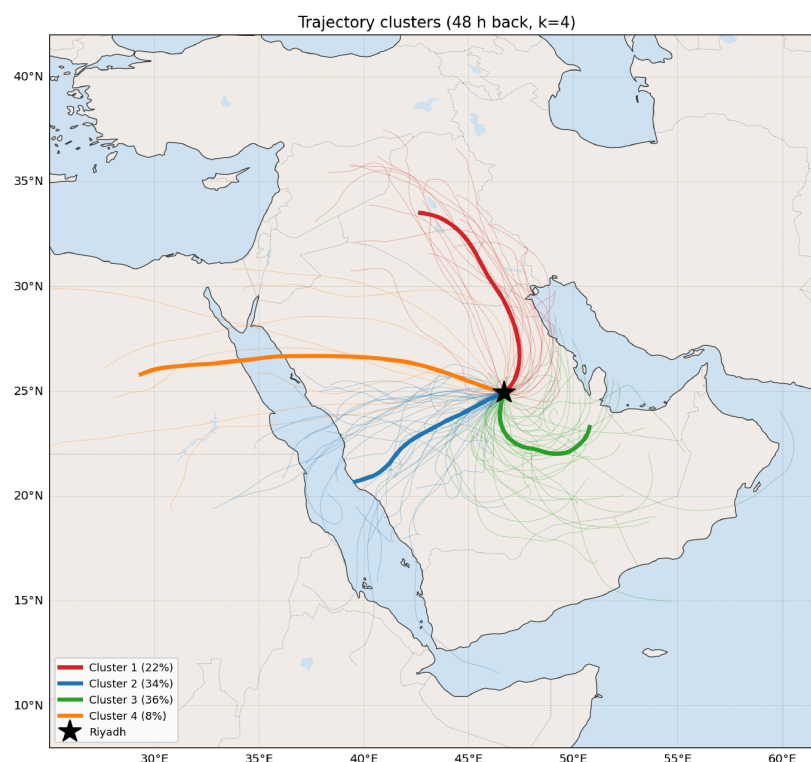


Figure 5. Backward-trajectory clusters (48 h, $k = 4$) for dust events reaching Riyadh, showing the four representative transport pathways. Thin lines represent individual trajectories, while thick lines represent the cluster-mean pathways.

3.6. Dust Intensity Versus Transport Pathway

Dust intensity varied among the four transport pathways. The northern Iraqi–Mesopotamian pathway (Cluster 1) exhibited the highest mean peak coarse-mode AOD (0.83), followed by the long-range westerly (Cluster 4, 0.67) and southwesterly (Cluster 2, 0.66) pathways. The easterly–southeasterly pathway (Cluster 3), which accounted for the greatest share of trajectories (36%), showed the lowest mean peak coarse-mode AOD (0.59) and was dominated by moderate-severity events (Figures 6–8).

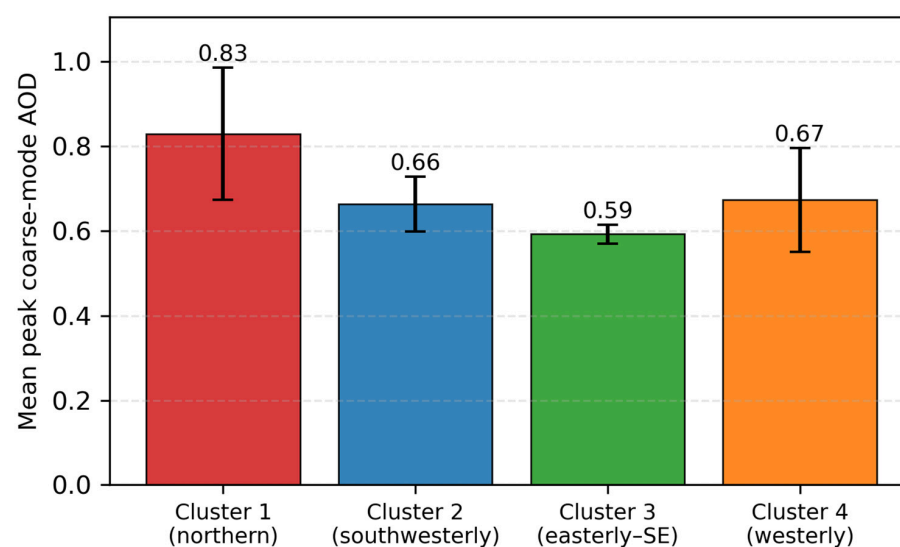


Figure 6. Mean peak coarse-mode AOD by transport-pathway cluster.

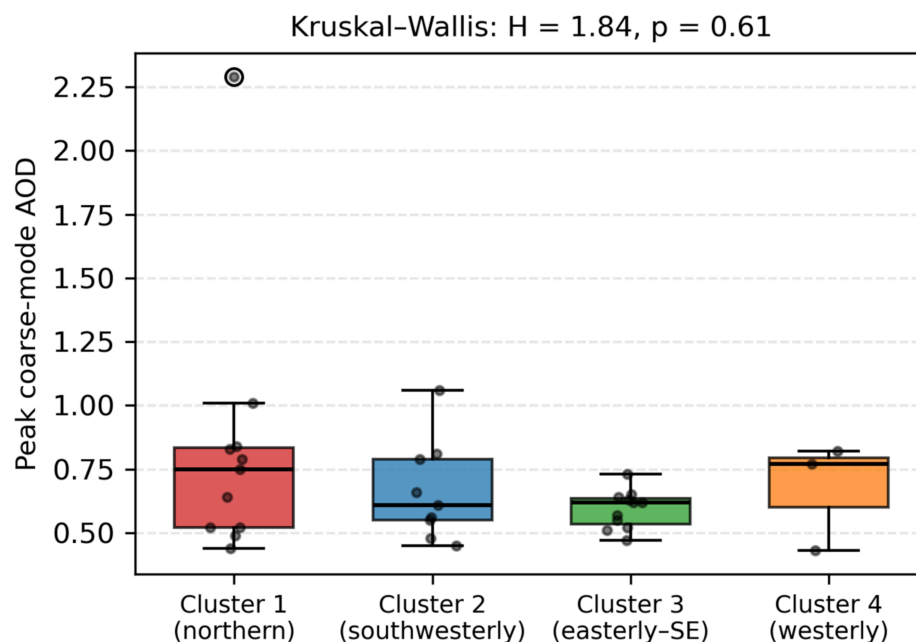


Figure 7. Distribution of peak coarse-mode AOD by transport-pathway cluster (Kruskal–Wallis, $p = 0.61$). The circled point indicates an outlier.

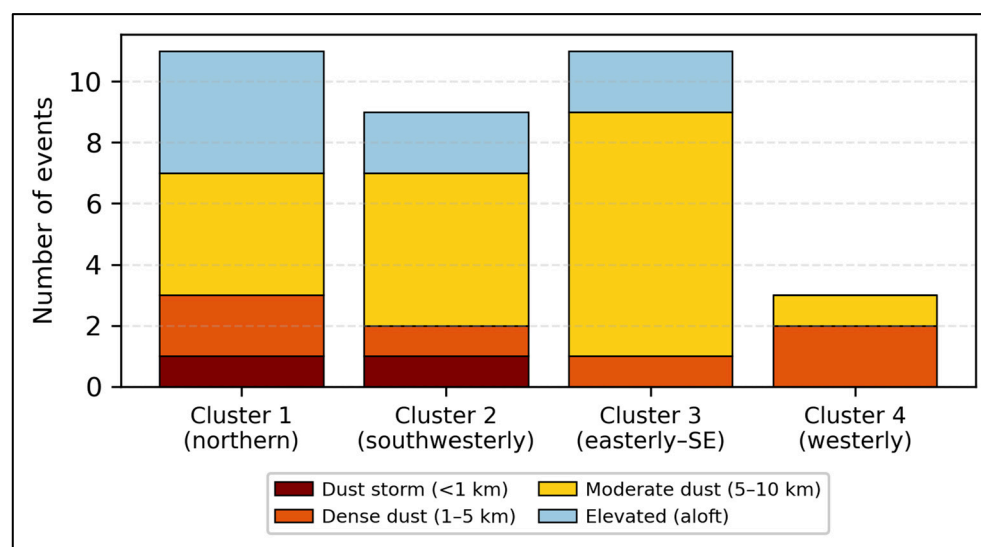


Figure 8. Severity composition of dust events by transport-pathway cluster.

These values indicate that the most frequently activated corridor was not the most intense: The easterly–southeasterly pathway occurred most often yet delivered the weakest coarse-mode loading, whereas the less frequent northern pathway produced the highest coarse-mode concentrations. The severity composition is consistent with this pattern: Cluster 3 was dominated by moderate-severity events (8/11), whereas the northern pathway encompassed the full severity range, including the only dust-storm (<1 km) event, dense-dust events, and several elevated (aloft) events (Figure 8).

It should be emphasized, however, that a Kruskal–Wallis test indicated that the differences in peak coarse-mode AOD among the four pathways were not statistically significant ($H = 1.84$, $p = 0.61$; Figure 7). Given the limited number of events per cluster over the two-year period—particularly in the long-range westerly pathway (three events)—this ordering should be interpreted as an indicative tendency rather than a firm statistical distinction. Despite the absence of statistical significance, the broad consistency between the mean

coarse-mode AOD, the severity composition, and the source-region analysis (Section 3.7) qualitatively supports the interpretation that transport frequency and dust intensity are not directly coupled over Riyadh.

3.7. Dust-Raising Mechanism, Wind Speed, and Transport Pathway

The relationship between the dust-raising mechanism, surface wind speed, and transport pathway was examined. Locally raised dust events occurred under significantly stronger surface winds than transported dust events, with mean wind speeds of 4.97 m s^{-1} and 3.28 m s^{-1} , respectively, while mixed events showed intermediate wind speeds (mean $\approx 4.6 \text{ m s}^{-1}$). The difference between locally raised and transported events was statistically significant (Mann–Whitney U test, $p = 0.034$; Figure 9). This is physically consistent, as locally raised dust requires strong surface winds to mobilize particles, whereas transported dust can arrive under weaker local winds. The coarse-mode AOD showed a complementary pattern, with mixed and locally raised events exhibiting higher median coarse-mode loading than transported events (Figure 9).

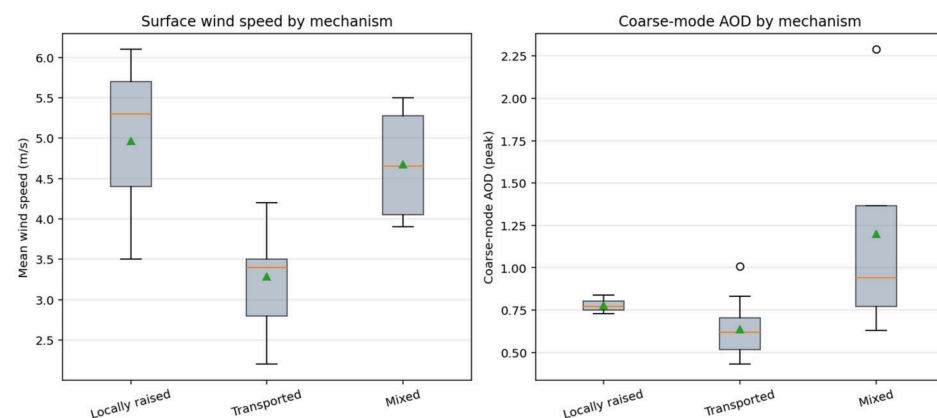


Figure 9. Surface wind speed (left) and peak coarse-mode AOD (right) by dust-raising mechanism. Green triangles indicate means, and open circles indicate outliers.

Transport-pathway analysis showed that elevated (aloft) dust events occurred most frequently within the northern pathway (Cluster 1); four of the eleven events assigned to this pathway were classified as elevated. Together, these results indicate that locally raised dust events were associated with higher surface wind speeds, while elevated dust events occurred most frequently within the northern transport pathway.

3.8. Correlation Analysis

Spearman rank-correlation analysis examined the relationships between aerosol optical properties, surface meteorological conditions, and dust-event severity (Figure 4; Table 3). Coarse-mode AOD showed a significant positive correlation with both mean ($\rho = 0.54$, $p = 0.0010$) and maximum ($\rho = 0.57$, $p = 0.0005$) surface wind speed. Likewise, coarse-mode AOD exhibited a significant negative correlation with minimum surface visibility ($\rho = -0.58$, $p = 0.0004$; Figure 10).

Surface wind speed also showed a significant positive association with dust-event severity. Both mean and maximum wind speed were positively correlated with event severity ($\rho = 0.57$ and 0.53 , respectively), while the Kruskal–Wallis test indicated significant differences in maximum wind speed among the severity classes ($H = 10.83$, $p = 0.013$). In contrast, sea-level pressure showed no statistically significant association with dust-event severity ($\rho = -0.27$, $p = 0.12$).

As expected, visibility exhibited a very strong negative correlation with dust-event severity ($\rho = -0.83$, $p < 0.0001$). Because event severity was defined using visibility thresh-

olds, this relationship is presented as an internal consistency check rather than an independent finding.

Table 3. Spearman correlations of surface meteorology with dust severity and coarse-mode AOD ($n = 34$).

Relationship	ρ	p	Significance
Mean wind speed vs. severity	+0.57	0.0004	Significant
Max wind speed vs. severity	+0.53	0.0012	Significant
Mean wind speed vs. coarse AOD	+0.54	0.0010	Significant
Max wind speed vs. coarse AOD	+0.57	0.0005	Significant
Visibility vs. coarse AOD	−0.58	0.0004	Significant
Visibility vs. severity (consistency)	−0.83	<0.0001	Definitional
Sea-level pressure vs. severity	−0.27	0.12	Not significant

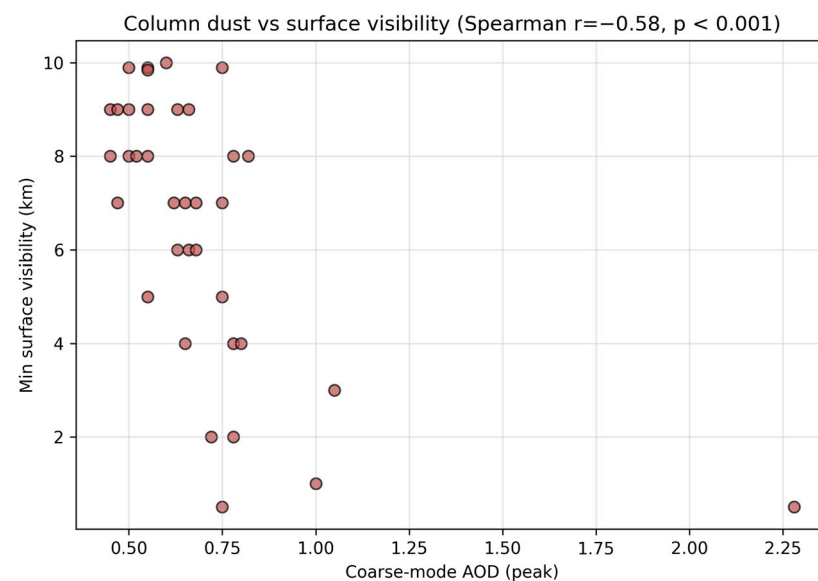


Figure 10. Peak coarse-mode AOD versus minimum surface visibility (Spearman $\rho = -0.58$).

In addition, Figure 11 shows the distribution of surface wind directions during the identified dust events. Dust events occurred under a range of wind directions, with the highest frequencies associated with the southeasterly and southerly sectors. The bar colors indicate the corresponding peak coarse-mode AOD for each event, illustrating that elevated aerosol loading was observed under multiple surface wind directions.

3.9. Probable Source Regions (PSCF and CWT)

The PSCF and CWT analyses identified two potential dust source regions associated with dust events affecting Riyadh (Figures 12 and 13). The highest CWT values were located over the Mesopotamian Basin and the northern Arabian Peninsula (approximately 33–35° N, 42–44° E). A second area of elevated CWT values was identified over the northern Rub' al-Khali (approximately 19–22° N, 44–46° E).

The PSCF analysis identified a corresponding high-probability transport corridor extending from Iraq through central Najd to the Empty Quarter, showing a similar spatial distribution to the CWT results. Together with the backward trajectory clustering analysis, these results identify the Iraqi–Mesopotamian region and the northern Rub' al-Khali as the principal source regions associated with the identified dust events. The identified source regions are consistent with previous regional studies.

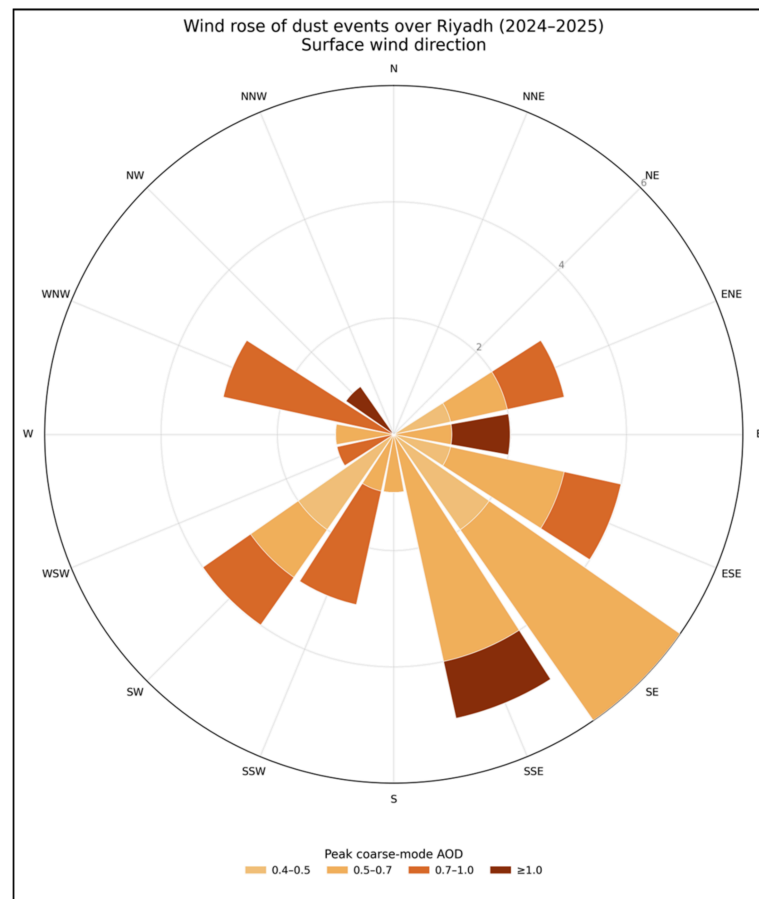


Figure 11. Wind rose of dust-event days over Riyadh (2024–2025). Bar colors represent peak coarse-mode AOD (500 nm).

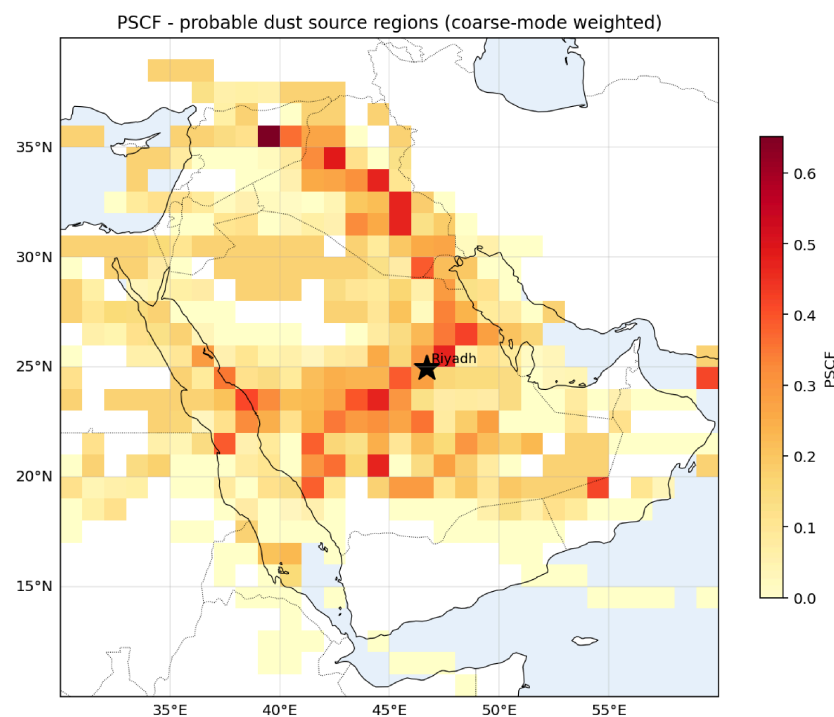


Figure 12. Coarse-mode-weighted PSCF map showing probable dust source regions for Riyadh.

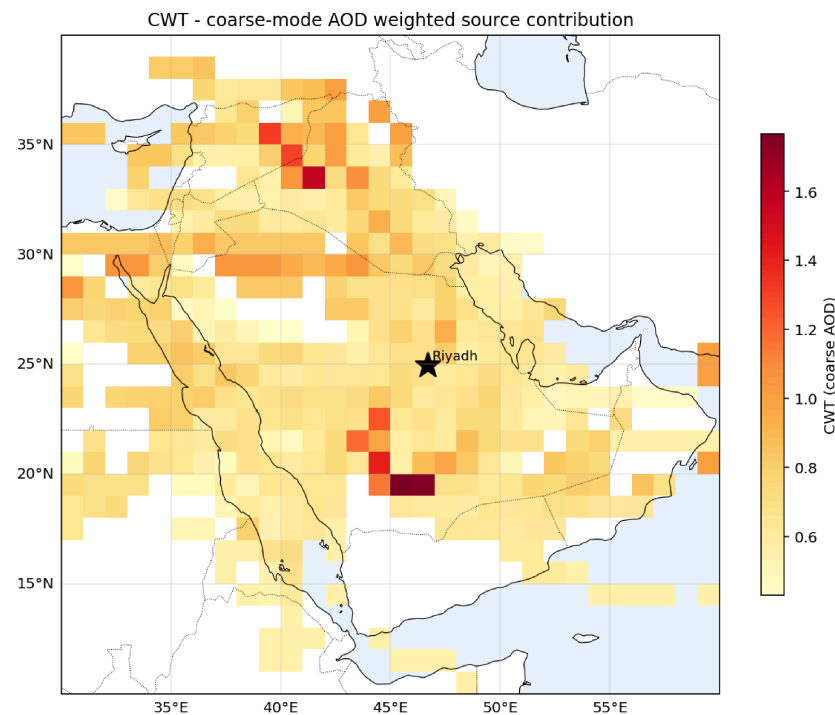


Figure 13. Coarse-mode-weighted CWT map showing the relative contribution strength of source regions.

4. Discussion

4.1. Seasonal Occurrence and Aerosol Characteristics

The predominance of spring dust events observed in the present study agrees with previous regional observations. Yu et al. [39] reported that dust activity over the Arabian Peninsula reached its maximum during spring and summer. Similarly, Shalaby et al. [40] identified spring as the principal dust season over Saudi Arabia, whereas Mashat et al. [41] linked dusty spring days over central Saudi Arabia to characteristic synoptic conditions. More recently, Assiri et al. [42] also reported that spring remained the dominant dust season across Saudi Arabia. The agreement with these studies indicates that the seasonal pattern observed in Riyadh during 2024–2025 is consistent with previously reported regional patterns.

The aerosol optical properties observed during the identified events are also consistent with previous AERONET observations over central Saudi Arabia. Al Otaibi et al. [27] reported that spring dust events were characterized by elevated aerosol loading and a predominance of coarse particles, reflected by low Ångström exponent values and increased coarse-mode aerosols. The predominance of coarse-mode aerosols in the present study is consistent with the established optical characteristics of desert dust, which is typically associated with low Ångström exponent values and coarse-particle dominance [43,44]. Similar optical characteristics have been reported in other arid regions. Basart et al. [45], using AERONET observations across North Africa and adjacent regions, reported mineral-dust conditions characterized by elevated AOD and low Ångström exponent values, consistent with coarse-particle dominance. This comparison indicates that the optical characteristics observed during the Riyadh dust events are consistent with those reported for mineral dust using AERONET observations in other dust-affected arid regions.

The intensity of the strongest event observed in the present study can also be compared with previous observations over Saudi Arabia. The peak AOD of 2.76 recorded on 11 April 2025, was slightly higher than the AOD of approximately 2.3 during a major dust storm over Riyadh on 20 March 2017, reported by Labban and Farahat [46]. This comparison

places the 2025 event among the high-aerosol-loading dust events previously documented over Riyadh. However, the comparison is limited to the reported AOD magnitude and does not imply equivalence between the two events.

4.2. Transport Pathways and Source Regions

The PSCF and CWT analyses were consistent with the backward-trajectory analysis, indicating the Mesopotamian Basin as a major potential source region and the northern Rub' al-Khali as a secondary potential source region associated with dust events affecting Riyadh. The spatial correspondence among these trajectory-based analyses provides a consistent representation of the identified transport pathways and potential source regions. Notably, trajectory frequency did not correspond directly to the mean dust loading associated with each pathway. Although the easterly–southeasterly pathway was the most frequently observed (36% of trajectories), it was associated with the lowest mean peak coarse-mode AOD (0.59), whereas the less frequent northern Iraqi–Mesopotamian pathway (22%) was associated with the highest mean value (0.83). However, the differences in peak coarse-mode AOD among the four pathways were not statistically significant (Kruskal–Wallis, $p = 0.61$). The observed ordering should therefore be interpreted as an indicative tendency within the present dataset rather than a statistically established difference among transport pathways.

The identification of the Iraqi–Mesopotamian region as a potential source is consistent with previous investigations of dust transport over Saudi Arabia and the Arabian Peninsula. Notaro et al. [47] showed that dust affecting the central Arabian Peninsula can be transported from the Iraqi and Syrian deserts by northwesterly Shamal winds, while Ashrafi et al. [31] identified Iraq and surrounding desert regions as important contributors to dust transport across the Middle East. Yassin et al. [33] likewise reported dust transport from northern source regions toward Saudi Arabia. The location identified in the present analysis is also consistent with the geomorphological characteristics reported for the Tigris–Euphrates basin. Gandham et al. [48] identified fluvial and alluvial deposits, ephemeral drainage systems, and dry lakebeds as dust-emitting surfaces within this region, including active emission areas extending from southern Iraq toward the northern Saudi border. Moreover, the source-region pattern is consistent with Albanai et al. [49], who identified southern Mesopotamia and northern Kuwait as important dust-emitting regions in the northeastern Arabian Peninsula and reported the role of northwesterly Shamal winds in regional dust transport. In addition to the northern source region, the PSCF and CWT results in the present study identified the northern Rub' al-Khali as a secondary potential source region. Overall, the source–receptor results and backward trajectories show a consistent spatial association with the Iraqi–Mesopotamian region and, secondarily, the northern Rub' al-Khali, while the lack of statistically significant differences in coarse-mode AOD among the trajectory clusters limits stronger conclusions regarding differences in dust intensity between individual transport pathways.

4.3. Surface Versus Elevated Dust Events

The comparison between AERONET observations and surface synoptic records showed that not all dust events detected within the atmospheric column were accompanied by reduced surface visibility. Of the 34 events identified from the AERONET record, 26 (76%) were confirmed by a same-day surface dust report. The remaining eight (24%) were classified as elevated dust events, in which the column retrievals indicated high coarse-mode loading and a low Ångström exponent, yet no dust-related ww code was reported at the co-located ISD. The 17 April 2025 event exemplifies this category, with elevated column dust signatures while surface visibility remained near 10 km.

A similar discrepancy between column-integrated aerosol observations and surface measurements was reported by Gkikas et al. [50], who demonstrated that elevated dust layers may be clearly detected by remote-sensing observations while remaining weakly represented in surface measurements because the dust is transported aloft. This interpretation is further supported by Marinou et al. [51], whose spaceborne-lidar climatology of Saharan dust resolved distinct elevated dust layers at 2–6 km that were vertically decoupled from near-surface observations. Observations from another arid environment also demonstrate the vertical extension of aerosol layers. Nelli et al. [52] reported vertically extended aerosol layers over the United Arab Emirates using CALIPSO observations, with aerosol extinction extending to approximately 3–4 km in the summer. These observations provide regional context for the distinction between column-integrated aerosol detection and surface meteorological observations.

The elevated dust events identified in the present study therefore illustrate the complementary information provided by column-integrated aerosol retrievals and surface meteorological observations. AERONET characterizes aerosol loading through the atmospheric column, whereas surface visibility and synoptic weather reports describe conditions near the surface. The agreement between the AERONET-based detection and same-day surface dust reports for 26 of the 34 identified events provides independent observational support for the event-identification approach. Meanwhile, the eight elevated events demonstrate that the two observational datasets do not necessarily represent the same vertical portion of the atmosphere.

4.4. Wind Speed and Dust-Event Severity

Surface wind speed showed statistically significant associations with both dust-event severity and coarse-mode aerosol loading in the present dataset. The comparison among dust-raising mechanisms also showed that locally raised events occurred under significantly stronger surface winds than transported events, while mixed events exhibited intermediate wind conditions. These results indicate that the wind conditions measured at Riyadh differed among the identified event mechanisms and were associated with variations in both event severity and coarse-mode aerosol loading. The occurrence of elevated aerosol loading under multiple surface wind directions further shows that high coarse-mode loading was not restricted to a single wind sector.

The observed associations are consistent with previous studies conducted over Saudi Arabia. Labban and Butt [53] reported a significant positive correlation ($r = 0.53$) between sand and dust storm occurrence and wind speed based on 30 years of meteorological observations across the Kingdom. Albugami et al. [21] documented the spatial and temporal variability of dust-storm incidence across Saudi Arabia using long-term in situ observations. Gandham et al. [48] also reported an important role of strong northerly Shamal winds in regional dust transport over the Arabian Peninsula. In the present study, the significant associations between surface wind speed, coarse-mode aerosol loading, and event severity are consistent with the relationship between wind conditions and dust occurrence reported in these regional studies. The differences among the dust-raising mechanisms provide additional context for interpreting the surface wind measurements. Locally raised events were associated with higher surface wind speeds than transported events, whereas elevated events occurred most frequently within the northern transport pathway. These two observations describe different aspects of the identified events: the first characterizes surface meteorological conditions at Riyadh, while the second characterizes the pathways derived from the trajectory analysis. They should therefore not be interpreted as measurements of the same process.

This distinction is also important when considering the spatial characteristics of the wind observations. Surface wind speed was measured at the Riyadh receptor site, whereas the backward-trajectory and source–receptor analyses identified potential source regions outside Riyadh. Consequently, the surface wind measurements used in the correlation and mechanism analyses characterize conditions at the receptor and do not provide direct measurements of wind speed at the identified potential source regions. The significant relationships observed in the present study therefore describe statistical associations between surface wind conditions, coarse-mode aerosol loading, and event severity at Riyadh; they do not establish that local surface winds were responsible for dust emission in all events. Considering the surface observations together with the aerosol optical properties and trajectory information allows the locally raised, transported, mixed, and elevated event categories to be interpreted within the observational framework applied in this study.

4.5. Study Implications and Limitations

The integrated use of AERONET aerosol observations, co-located NOAA ISD surface records, HYSPLIT backward trajectories, and PSCF/CWT analyses provided complementary information on the aerosol characteristics, surface conditions, transport pathways, and potential source regions of dust events affecting Riyadh. Together, these complementary datasets provide an integrated event-based framework for characterizing dust events over Riyadh.

The study used the currently available 2024–2025 AERONET record, with Level 1.5 observations because Level 2.0 products are not yet available for the Riyadh Airport SDSC station. Surface validation was based on the co-located NOAA ISD station and therefore reflects conditions reported at this observation site. For elevated events, AERONET indicated column-integrated aerosol properties consistent with dust, while no dust-related ww code was reported at the surface station; the classification therefore does not represent a direct measurement of dust-layer altitude.

HYSPLIT trajectories were used to characterize air-mass transport, while PSCF and CWT identified potential source regions associated with the trajectories and aerosol loading. The identified source regions are therefore interpreted as potential rather than quantitatively determined contributions. Longer observational records, additional observation sites, and vertical-profile measurements could complement the present analysis in future studies.

5. Conclusions

This study characterized dust events affecting Riyadh during 2024–2025 using AERONET aerosol observations, co-located NOAA ISD meteorological records, HYSPLIT backward trajectories, and PSCF/CWT source–receptor analyses. A total of 34 dust events met the adopted optical criteria, of which 82% occurred during spring. The identified events were characterized by elevated aerosol loading and a predominance of coarse-mode aerosols, accompanied by low Ångström exponent and fine-mode fraction values.

Comparison with the co-located NOAA ISD observations showed that 26 of the 34 optically identified events (76%) had a same-day dust-related present-weather report at the surface station. The remaining eight events (24%) were classified as elevated events because no dust-related ww code was reported at the station during the corresponding event day. This distinction shows that column-integrated aerosol observations and surface meteorological records provide complementary information for characterizing dust events at the study site.

The HYSPLIT trajectory, PSCF, and CWT analyses showed a consistent spatial association with the Mesopotamian Basin as a major potential source region and the northern Rub' al-Khali as a secondary potential source region. The easterly–southeasterly pathway was

the most frequently observed (36%), whereas the northern Iraqi–Mesopotamian pathway had the highest mean peak coarse-mode AOD. However, differences in peak coarse-mode AOD among the four transport pathways were not statistically significant ($p = 0.61$). Surface wind speed was significantly and positively associated with both coarse-mode AOD and dust-event severity, whereas sea-level pressure showed no statistically significant association with severity.

The analysis was based on the available 2024–2025 AERONET record from the Riyadh_Airport_SDSC station, with surface validation based on the co-located NOAA ISD station. Accordingly, the results characterize the identified events and transport patterns during the study period at this observation site. Longer observational records and additional monitoring locations could be used in future studies to examine interannual and spatial variability in dust occurrence and transport. In addition, the combined analysis provided information on the seasonal occurrence, aerosol characteristics, surface manifestation, transport pathways, and potential source regions of dust events affecting Riyadh during 2024–2025. The results provide an observational basis for continued investigation of dust occurrence and transport over central Saudi Arabia.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The datasets used in this study are publicly available from the AERONET database (<https://aeronet.gsfc.nasa.gov/>) and the NOAA Integrated Surface Database (ISD). Air-mass backward trajectories were generated using the NOAA HYSPLIT model driven by GDAS1 meteorological data (<https://www.ready.noaa.gov/HYSPLIT.php>, accessed on 20 June 2026).

Acknowledgments: The author gratefully acknowledges the NASA Aerosol Robotic Network (AERONET) program and Jumaan Saad Alqahtani, Principal Investigator of the Riyadh_Airport_SDSC station, for establishing and maintaining the AERONET observations used in this study.

Conflicts of Interest: The author declares no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AERONET	Aerosol Robotic Network
AOD	aerosol optical depth
CWT	concentration weighted trajectory
FMF	fine-mode fraction
GDAS1	Global Data Assimilation System
HYSPLIT	Hybrid Single-Particle Lagrangian Integrated Trajectory
ISD	Integrated Surface Database
PSCF	potential source contribution function
SDA	spectral deconvolution algorithm

References

1. Shepherd, G.; Terradellas, E.; Baklanov, A.; Kang, U.; Sprigg, W.A.; Nickovic, S.; Boloorrani, A.D.; Al-Dousari, A.; Basart, S.; Benedetti, A.; et al. *Global Assessment of Sand and Dust Storms*; United Nations Environment Programme: Nairobi, Kenya, 2016.
2. Middleton, N.; Kang, U. Sand and Dust Storms: Impact Mitigation. *Sustainability* **2017**, *9*, 1053. [[CrossRef](#)]
3. Middleton, N.J. Dust Storms in the Middle East. *J. Arid Environ.* **1986**, *10*, 83–96. [[CrossRef](#)]
4. Liu, Y.; Wang, G.; Hu, Z.; Shi, P.; Lyu, Y.; Zhang, G.; Gu, Y.; Liu, Y.; Hong, C.; Guo, L.; et al. Dust Storm Susceptibility on Different Land Surface Types in Arid and Semiarid Regions of Northern China. *Atmos. Res.* **2020**, *243*, 105031. [[CrossRef](#)]

5. Middleton, N.J.; Goudie, A.S.; Wells, G.L. The Frequency and Source Areas of Dust Storms. In *Aeolian Geomorphology*; William, G.N., Ed.; Routledge: London, UK, 2020; pp. 237–259.
6. Opp, C.; Groll, M.; Abbasi, H.; Foroushani, M.A. Causes and Effects of Sand and Dust Storms: What Has Past Research Taught Us? A Survey. *J. Risk Financ. Manag.* **2021**, *14*, 326. [\[CrossRef\]](#)
7. Ghosh, T.; Pal, I. Dust Storm and Its Environmental Implications. *J. Eng. Comput. Appl. Sci.* **2014**, *3*, 30–37.
8. Kok, J.F.; Parteli, E.J.R.; Michaels, T.I.; Karam, D.B. The Physics of Wind-Blown Sand and Dust. *Rep. Prog. Phys.* **2012**, *75*, 106901. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Miri, A.; Ahmadi, H.; Ekhtesasi, M.R.; Panjehkeh, N.; Ghanbari, A. Environmental and Socio-economic Impacts of Dust Storms in Sistan Region, Iran. *Int. J. Environ. Stud.* **2009**, *66*, 343–355. [\[CrossRef\]](#)
10. Kanatani, K.T.; Ito, I.; Al-Delaimy, W.K.; Adachi, Y.; Mathews, W.C.; Ramsdell, J.W.; The Toyama Asian Desert Dust and Asthma Study Team. Desert Dust Exposure Is Associated with Increased Risk of Asthma Hospitalization in Children. *Am. J. Respir. Crit. Care Med.* **2010**, *182*, 1475–1481. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Thalib, L.; Al-Taiar, A. Dust Storms and the Risk of Asthma Admissions to Hospitals in Kuwait. *Sci. Total Environ.* **2012**, *433*, 347–351. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Albugami, S. Influence of Dust Storms and Weather Factors on Daily Pediatric Asthma Emergencies in Al-Khobar, Saudi Arabia. *Egypt. J. Environ. Change* **2026**, *in press*. [\[CrossRef\]](#)
13. Kotwicki, V.; Al Sulaimani, Z. Climates of the Arabian Peninsula—Past, Present, Future. *Int. J. Clim. Change Strateg. Manag.* **2009**, *1*, 297–310. [\[CrossRef\]](#)
14. Roshan, D.R.; Koc, M.; Isaifan, R.; Shahid, M.Z.; Fountoukis, C. Aerosol Optical Thickness over Large Urban Environments of the Arabian Peninsula—Speciation, Variability, and Distributions. *Atmosphere* **2019**, *10*, 228. [\[CrossRef\]](#)
15. Patlakas, P.; Stathopoulos, C.; Flocas, H.; Bartsotas, N.S.; Kallos, G. Precipitation Climatology for the Arid Region of the Arabian Peninsula—Variability, Trends and Extremes. *Climate* **2021**, *9*, 103. [\[CrossRef\]](#)
16. Almazroui, M.; Nazrul Islam, M.; Athar, H.; Jones, P.D.; Rahman, M.A. Recent Climate Change in the Arabian Peninsula: Annual Rainfall and Temperature Analysis of Saudi Arabia for 1978–2009. *Int. J. Climatol.* **2012**, *32*, 953–966. [\[CrossRef\]](#)
17. Aljaddani, A.H. Evaluation of the Land Use Land Cover Impact on Surface Temperature and Urban Thermal Comfort: Insight from Saudi Arabia’s Five Most Populated Cities (2000–2024). *Urban Sci.* **2026**, *10*, 157. [\[CrossRef\]](#)
18. Miller, S.D.; Kuciauskas, A.P.; Liu, M.; Ji, Q.; Reid, J.S.; Breed, D.W.; Walker, A.L.; Mandoos, A.A. Haboob Dust Storms of the Southern Arabian Peninsula. *J. Geophys. Res. Atmos.* **2008**, *113*, D01202. [\[CrossRef\]](#)
19. Modaihsh, A.S.; Al-Barakah, F.N.; Nadeem, M.E.A.; Mahjoub, M.O. Spatial and Temporal Variations of the Particulate Matter in Riyadh City, Saudi Arabia. *J. Environ. Prot.* **2015**, *6*, 1293–1307. [\[CrossRef\]](#)
20. Al-Hajji, Z.; Munir, S.; Qahtani, J.A.; Alexiou, I.; Hafez, M. A Study of Spatial and Temporal Variations of Climatic Variables during Sand and Dust Storm Events in Riyadh Using In-Situ Observations. *Int. J. Environ. Clim. Change* **2025**, *15*, 381–399. [\[CrossRef\]](#)
21. Albugami, S.; Palmer, S.; Cinnamon, J.; Meersmans, J. Spatial and Temporal Variations in the Incidence of Dust Storms in Saudi Arabia Revealed from In Situ Observations. *Geosciences* **2019**, *9*, 162. [\[CrossRef\]](#)
22. Maghrabi, A.; Alharbi, B.; Tapper, N. Impact of the March 2009 Dust Event in Saudi Arabia on Aerosol Optical Properties, Meteorological Parameters, Sky Temperature and Emissivity. *Atmos. Environ.* **2011**, *45*, 2164–2173. [\[CrossRef\]](#)
23. Meo, S.A.; Al-Kheraiji, M.F.A.; AlFaraj, Z.F.; Alwehaibi, N.A.; Aldereihim, A.A. Respiratory and General Health Complaints in Subjects Exposed to Sandstorm at Riyadh, Saudi Arabia. *Pak. J. Med. Sci.* **2013**, *29*, 642–646. [\[CrossRef\]](#) [\[PubMed\]](#)
24. Middleton, N.; Kashani, S.S.; Attarchi, S.; Rahnama, M.; Mosalman, S.T. Synoptic Causes and Socio-Economic Consequences of a Severe Dust Storm in the Middle East. *Atmosphere* **2021**, *12*, 1435. [\[CrossRef\]](#)
25. Eck, T.F.; Holben, B.N.; Dubovik, O.; Smirnov, A.; Goloub, P.; Chen, H.B.; Chatenet, B.; Gomes, L.; Zhang, X.-Y.; Tsay, S.-C.; et al. Columnar Aerosol Optical Properties at AERONET Sites in Central Eastern Asia and Aerosol Transport to the Tropical mid-Pacific. *J. Geophys. Res. Atmos.* **2005**, *110*, D06202. [\[CrossRef\]](#)
26. Giles, D.M.; Holben, B.N.; Eck, T.F.; Sinyuk, A.; Smirnov, A.; Slutsker, I.; Dickerson, R.R.; Thompson, A.M.; Schafer, J.S. An Analysis of AERONET Aerosol Absorption Properties and Classifications Representative of Aerosol Source Regions. *J. Geophys. Res. Atmos.* **2012**, *117*, D17203. [\[CrossRef\]](#)
27. Al Otaibi, M.; Farahat, A.; Tawabini, B.; Omar, M.H.; Ramadan, E.; Abuelgasim, A.; Singh, P.R. Long-Term Aerosol Trends and Variability over Central Saudi Arabia Using Optical Characteristics from Solar Village AERONET Measurements. *Atmosphere* **2019**, *10*, 752. [\[CrossRef\]](#)
28. Maghrabi, A.H.; Alotaibi, R.N. Long-Term Variations of AOD from an AERONET Station in the Central Arabian Peninsula. *Theor. Appl. Climatol.* **2018**, *134*, 1015–1026. [\[CrossRef\]](#)
29. Al-Saadi, J.; Szykman, J.; Pierce, R.B.; Kittaka, C.; Neil, D.; Chu, D.A.; Remer, L.; Gumley, L.; Prins, E.; Weinstock, L.; et al. Improving National Air Quality Forecasts with Satellite Aerosol Observations. *Bull. Am. Meteorol. Soc.* **2005**, *86*, 1249–1262. [\[CrossRef\]](#)

30. Notaro, M.; Alkolibi, F.; Fadda, E.; Bakhrjy, F. Trajectory Analysis of Saudi Arabian Dust Storms. *J. Geophys. Res. Atmos.* **2013**, *118*, 6028–6043. [\[CrossRef\]](#)
31. Ashrafi, K.; Shafiepour-Motlagh, M.; Aslemand, A.; Ghader, S. Dust Storm Simulation over Iran Using HYSPLIT. *J. Environ. Health Sci. Eng.* **2014**, *12*, 9. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Broomandi, P.; Dabir, B.; Bonakdarpour, B.; Rashidi, Y. Identification of Dust Storm Origin in South–West of Iran. *J. Environ. Health Sci. Eng.* **2017**, *15*, 16. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Yassin, M.F.; Almutairi, S.K.; Al-Hemoud, A. Dust Storms Backward Trajectories' and Source Identification over Kuwait. *Atmos. Res.* **2018**, *212*, 158–171. [\[CrossRef\]](#)
34. Al Nadhairi, R.; Al Kalbani, M.; Al Khazami, S.; Al Hashmi, M.; Al Zadai, S.; Al-Rumhi, Y.; Al-Kindi, K.M. Air Quality and Health Risk Assessment during Middle Eastern Dust Storms: A Study of Particulate Matter. *Air Qual. Atmos. Health* **2025**, *18*, 587–603. [\[CrossRef\]](#)
35. Holben, B.N.; Eck, T.F.; Slutsker, I.; Tanré, D.; Buis, J.P.; Setzer, A.; Vermote, E.; Reagan, J.A.; Kaufman, Y.J.; Nakajima, T.; et al. AERONET—A Federated Instrument Network and Data Archive for Aerosol Characterization. *Remote Sens. Environ.* **1998**, *66*, 1–16. [\[CrossRef\]](#)
36. Giles, D.M.; Sinyuk, A.; Sorokin, M.G.; Schafer, J.S.; Smirnov, A.; Slutsker, I.; Eck, T.F.; Holben, B.N.; Lewis, J.R.; Campbell, J.R.; et al. Advancements in the Aerosol Robotic Network (AERONET) Version 3 Database—Automated near-Real-Time Quality Control Algorithm with Improved Cloud Screening for Sun Photometer Aerosol Optical Depth (AOD) Measurements. *Atmos. Meas. Tech.* **2019**, *12*, 169–209. [\[CrossRef\]](#)
37. Ciren, P.; Kondragunta, S. Dust Aerosol Index (DAI) Algorithm for MODIS. *J. Geophys. Res. Atmos.* **2014**, *119*, 4770–4792. [\[CrossRef\]](#)
38. Polissar, A.V.; Hopke, P.K.; Harris, J.M. Source Regions for Atmospheric Aerosol Measured at Barrow, Alaska. *Environ. Sci. Technol.* **2001**, *35*, 4214–4226. [\[CrossRef\]](#) [\[PubMed\]](#)
39. Yu, Y.; Notaro, M.; Liu, Z.; Wang, F.; Alkolibi, F.; Fadda, E.; Bakhrjy, F. Climatic Controls on the Interannual to Decadal Variability in Saudi Arabian Dust Activity: Toward the Development of a Seasonal Dust Prediction Model. *J. Geophys. Res. Atmos.* **2015**, *120*, 1739–1758. [\[CrossRef\]](#)
40. Shalaby, A.; Rappenglueck, B.; Eltahir, E.A.B. The Climatology of Dust Aerosol over the Arabian Peninsula. *Atmos. Chem. Phys. Discuss.* **2015**, *15*, 1523–1571.
41. Mashat, A.-W.S.; Awad, A.M.; Assiri, M.E.; Labban, A.H. Synoptic Pattern of the Red Sea Trough Associated with Spring Dust over the Northern and Western Arabian Peninsula. *Meteorol. Atmos. Phys.* **2021**, *133*, 655–673. [\[CrossRef\]](#)
42. Assiri, M.E.; Islam, M.N.; Ali, M.A.; Zamreeq, A.O.; Ghulam, A.S.; Ismail, M. Dust over Saudi Arabia from Multisource Data: Case Studies in Winter and Spring. *Air Qual. Atmos. Health* **2025**, *18*, 555–573. [\[CrossRef\]](#)
43. Eck, T.F.; Holben, B.N.; Reid, J.S.; Dubovik, O.; Smirnov, A.; O'Neill, N.T.; Slutsker, I.; Kinne, S. Wavelength Dependence of the Optical Depth of Biomass Burning, Urban, and Desert Dust Aerosols. *J. Geophys. Res. Atmos.* **1999**, *104*, 31333–31349. [\[CrossRef\]](#)
44. Dubovik, O.; Holben, B.; Eck, T.F.; Smirnov, A.; Kaufman, Y.J.; King, M.D.; Tanré, D.; Slutsker, I. Variability of Absorption and Optical Properties of Key Aerosol Types Observed in Worldwide Locations. *J. Atmos. Sci.* **2002**, *59*, 590–608. [\[CrossRef\]](#)
45. Basart, S.; Pérez, C.; Cuevas, E.; Baldasano, J.M.; Gobbi, G.P. Aerosol Characterization in Northern Africa, Northeastern Atlantic, Mediterranean Basin and Middle East from Direct-Sun AERONET Observations. *Atmos. Chem. Phys.* **2009**, *9*, 8265–8282. [\[CrossRef\]](#)
46. Labban, A.; Farahat, A. Effect of Major Dust Events on Ambient Temperature and Solar Irradiance Components over Saudi Arabia. *Atmosphere* **2023**, *14*, 408. [\[CrossRef\]](#)
47. Notaro, M.; Yu, Y.; Kalashnikova, O.V. Regime Shift in Arabian Dust Activity, Triggered by Persistent Fertile Crescent Drought. *J. Geophys. Res. Atmos.* **2015**, *120*, 10229–10249. [\[CrossRef\]](#)
48. Gandham, H.; Dasari, H.P.; Langodan, S.; Karumuri, R.K.; Hoteit, I. Major Changes in Extreme Dust Events Dynamics Over the Arabian Peninsula During 2003–2017 Driven by Atmospheric Conditions. *J. Geophys. Res. Atmos.* **2020**, *125*, e2020JD032931. [\[CrossRef\]](#)
49. Albanai, J.A.; Thomas, D.S.G.; Wiggs, G.F.S. Identifying Dust-Emitting Geomorphic Units in Lower Mesopotamia and Kuwait Using Multi-High-Resolution Satellite and Wind Data. *Aeolian Res.* **2026**, *76*, 101050. [\[CrossRef\]](#)
50. Gkikas, A.; Basart, S.; Hatzianastassiou, N.; Marinou, E.; Amiridis, V.; Kazadzis, S.; Pey, J.; Querol, X.; Jorba, O.; Gassó, S.; et al. Mediterranean Intense Desert Dust Outbreaks and Their Vertical Structure Based on Remote Sensing Data. *Atmos. Chem. Phys.* **2016**, *16*, 8609–8642. [\[CrossRef\]](#)
51. Marinou, E.; Amiridis, V.; Biniotoglou, I.; Tsikerdekis, A.; Solomos, S.; Proestakis, E.; Konsta, D.; Papagiannopoulos, N.; Tsekeri, A.; Vlastou, G.; et al. Three-Dimensional Evolution of Saharan Dust Transport towards Europe Based on a 9-Year EARLINET-Optimized CALIPSO Dataset. *Atmos. Chem. Phys.* **2017**, *17*, 5893–5919. [\[CrossRef\]](#)

52. Nelli, N.; Fissehay, S.; Francis, D.; Fonseca, R.; Temimi, M.; Weston, M.; Abida, R.; Nesterov, O. Characteristics of Atmospheric Aerosols Over the UAE Inferred from CALIPSO and Sun Photometer Aerosol Optical Depth. *Earth Space Sci.* **2021**, *8*, e2020EA001360. [[CrossRef](#)]
53. Labban, A.H.; Butt, M.J. Analysis of Sand and Dust Storm Events over Saudi Arabia in Relation with Meteorological Parameters and ENSO. *Arab. J. Geosci.* **2021**, *14*, 22. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.