

Dust Aerosol Ingestion Risk at Cairo International Airport (HECA): A 14-Year AERONET-Calibrated Assessment

Michael Nagy Riad Kamel

michaelnagyresearch@gmail.com

Independent Researcher <https://orcid.org/0009-0003-6890-0494>

Research Article

Keywords: mineral dust aerosol; aircraft engine ingestion; AERONET Level 2.0; Cairo International Airport; Khamaseen; MERRA-2 bias correction; aviation safety; North Africa

Posted Date: June 18th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10048259/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: The authors declare no competing interests.

Abstract

Mineral dust aerosol poses a significant but systematically underestimated hazard to commercial aviation operations across North Africa and the Middle East. Cairo International Airport (HECA; 30.12 N, 31.41 E), one of Africa's busiest international gateways, operates within a compound dust regime driven by Saharan source regions, Khamaseen seasonal wind events, and convective dust walls (haboobs). Despite this exposure, no observationally constrained dust ingestion assessment exists for this airport in the peer-reviewed literature. The landmark study by Ryder et al. (2024, *Natural Hazards and Earth System Sciences*) quantified dust ingestion at ten global airports using CAMS reanalysis, notably excluding Cairo. This study addresses that gap using a 14-year (2010-2023) multi-source observational dataset: (1) AERONET Cairo_EMA_2 Level 2.0 ground-truth aerosol retrievals ($n = 105,286$ measurements); (2) hourly METAR weather reports from HECA ($n = 240,484$ hours); (3) NASA MERRA-2 aerosol reanalysis extracted via Google Earth Engine; and (4) MODIS Terra land surface temperature composites. The period-mean aerosol optical depth (AOD) at 500 nm is 0.362 ± 0.194 , with dust-dominated observations (Angstrom Exponent < 0.6) comprising 25.4% of the record. Co-location of AERONET and MERRA-2 monthly means ($n = 147$ months) reveals a systematic model underestimation of 33.4% (bias correction factor, BCF = 1.50), increasing to BCF = 1.64 in winter and decreasing to BCF = 1.12 during the Khamaseen season. METAR analysis documents 752 dust-affected operational hours, including a 0 m visibility event on 25 August 2019 attributable to a haboob. Applying the Ryder et al. (2024) LTO-cycle ingestion methodology with AERONET-corrected MERRA-2 surface dust concentrations, the estimated dust ingestion dose per aircraft operation is 79.43 g under mean annual conditions and 71.33 g during the Khamaseen season. Monte Carlo uncertainty analysis ($n = 10,000$) yields a 5th-95th percentile range of 17.9-180.8 g. These estimates represent 18.5 and 16.6 times the corresponding values for Dubai International Airport (Ryder et al., 2024). Results should be interpreted as first-order operational risk estimates that highlight the need for site-specific engine maintenance protocols at HECA.

1. INTRODUCTION

Mineral dust aerosol, the largest contributor by mass to the global aerosol burden, exerts well-documented effects on atmospheric radiation balance, cloud microphysics, and surface energy fluxes (Boucher et al., 2013; Kok et al., 2017). In the context of commercial aviation, airborne mineral particles represent an additional, operationally significant hazard: ingestion by turbofan engines causes progressive abrasion of compressor blade leading edges, erosion of thermal barrier coatings on turbine components, and in extreme cases the deposition of silicate glass melts on high-pressure turbine nozzle guide vanes (Dunn, 2012; Kim et al., 2012). These degradation mechanisms reduce thermodynamic efficiency, increase specific fuel consumption, and shorten intervals between scheduled engine overhaul events – with substantial cost implications for airline operators and maintenance, repair, and overhaul (MRO) organizations.

The hazard is governed by three interdependent factors: (i) the near-surface dust mass concentration during operationally critical flight phases (approach, landing roll, taxi operations, and initial climb); (ii) the

engine bypass ratio and volumetric airflow rate, determining the total air mass processed during each landing and takeoff (LTO) cycle; and (iii) the particle size distribution, which controls the aerodynamic efficiency of ingestion and the mechanical abrasiveness of particles that penetrate to hot-section components (Walsh, 2018). Despite the engineering significance of these factors, systematic, airport-specific assessments of dust ingestion risk have been largely absent from the literature.

Ryder et al. (2024) addressed this gap with the first global multi-airport quantification of engine dust ingestion, evaluating ten airports across six continents using 17 years of ECMWF CAMS reanalysis data and CALIPSO vertical aerosol profiles. Their results demonstrated that dust ingestion varies by more than two orders of magnitude among airports globally, with Dubai International Airport identified as the highest-risk location in their dataset (mean dose: 4.3 g per LTO cycle). However, Cairo International Airport (HECA) was not included in that study, despite presenting an aerosol exposure regime that may substantially exceed that of Dubai.

HECA is exposed to dust from three distinct source systems operating on different temporal scales: quasi-permanent Saharan dust transport via westerly and northwesterly synoptic flows; the annual Khamaseen phenomenon — a sequence of hot, southerly, dust-laden wind events affecting Egypt from approximately March through May — associated with extratropical cyclone development over the Libyan and Sudanese deserts (Ganor et al., 2010); and episodic haboob events driven by convective cold pool outflows from mesoscale convective systems originating in Sudan. These source systems interact with Cairo's urban aerosol environment to produce a complex, mixed mineral-anthropogenic aerosol column that poses specific challenges for model-based dust estimation.

A further consideration not addressed by Ryder et al. (2024) is the known tendency of CAMS reanalysis to underestimate dust AOD in environments characterized by the mixing of mineral dust with urban pollution. Such bias is inherent to the coarse spatial resolution (~ 80 km) of CAMS, which smooths peak dust concentrations, and to the imperfect separation of dust and anthropogenic aerosol optical signatures in reanalysis schemes (Buchard et al., 2017). Cairo, with its population of approximately 21 million and associated emission sources, represents precisely this mixed environment, suggesting that uncorrected model estimates may substantially misrepresent the true dust ingestion hazard at HECA.

The NASA AERONET Cairo_EMA_2 station (El-Abbasiya, 30.08 N, 31.29 E) has provided continuous Level 2.0 quality-assured aerosol optical depth measurements since January 2010, constituting the authoritative ground-truth aerosol record for the greater Cairo region. To our knowledge, this dataset has not previously been exploited for aviation dust hazard assessment. This study presents the first such analysis, with three objectives: (i) to characterize the 14-year (2010–2023) aerosol climatology and dust event frequency at Cairo Airport from multi-source observations; (ii) to quantify and correct the systematic MERRA-2 reanalysis bias relative to AERONET ground truth; and (iii) to produce AERONET-calibrated aircraft engine dust ingestion estimates with associated uncertainty quantification, enabling direct comparison with the Ryder et al. (2024) global airport dataset.

2. STUDY AREA

Cairo International Airport (IATA: CAI; ICAO: HECA) is situated at 30.12 N, 31.41 E at an elevation of 116 m above mean sea level, approximately 15 km northeast of central Cairo. The airport operates three parallel runways (orientations 33L/15R, 33R/15L, and 05/23) and handled approximately 31 million passengers in 2025. It serves as the principal hub for EgyptAir and accommodates operations from more than 80 international carriers, making it one of the highest-traffic airports in Africa and a critical node in the global aviation network connecting Europe, sub-Saharan Africa, and the Middle East.

The regional aerosol climate is characterized by three overlapping components. First, mineral dust advected from the Western Desert of Egypt, the Libyan Sand Sea, and the Sudan-Chad dust belt constitutes the dominant aerosol type by optical depth, particularly during spring and summer. Second, anthropogenic aerosol from Cairo's metropolitan area — including carbonaceous particles from vehicular emissions and industrial combustion, sulfate from fuel combustion, and nitrate from agricultural activities — contributes a persistent fine-mode signal year-round. Third, periodic marine aerosol intrusions associated with Mediterranean northerly flow occur during summer, contributing to the hygroscopic aerosol loading detected by AERONET.

The Khamaseen season, occurring from approximately 1 March to 31 May each year, represents the highest-risk period for aviation dust exposure at HECA. Khamaseen (from the Arabic for fifty, denoting the approximate seasonal duration in days) events are driven by the passage of mid-latitude troughs that intensify pressure gradients between the Saharan heat low and Mediterranean cyclones, generating strong southerly to southwesterly surface flows that mobilize and transport large quantities of Saharan mineral dust northward across Egypt (Khalaf et al., 2017). Individual Khamaseen events can elevate AOD at 500 nm above 2.0 and reduce surface visibility to near zero within hours.

The AERONET Cairo_EMA_2 station (Principal Investigators: Dr. Ashraf Zakey, Egyptian Meteorological Authority; Dr. Africa Barreto, Agencia Estatal de Meteorologia, Spain) is located 14.7 km west-northwest of the airport threshold at the headquarters of the Egyptian Meteorological Authority (EMA) in El-Abbasiya (30.08 N, 31.29 E, elevation 70 m a.s.l.). The station operates a CIMEL CE318 sun/sky photometer calibrated at the AERONET-Europe Calibration Center. Level 2.0 data used in this study have undergone NASA's full cloud-screening and quality assurance protocol (Smirnov et al., 2000; Giles et al., 2019).

3. DATA AND METHODS

3.1 AERONET Level 2.0 Aerosol Optical Depth

Aerosol optical depth observations were obtained from the AERONET Version 3 Level 2.0 direct-sun product for station Cairo_EMA_2 (Holben et al., 1998; Giles et al., 2019) for the period 1 January 2010 to 31 December 2023. This quality level applies cloud-screening and quality assurance algorithms (Smirnov et al., 2000), and is generally available within 12–18 months of observation. The dataset comprises

105,286 instantaneous retrievals at approximately 15-minute temporal resolution during solar daylight hours. Retrieved parameters include spectral AOD at 440, 500, 675, 870, and 1020 nm; the Angstrom Exponent (AE) computed over the 440–870 nm range; and total column precipitable water vapour. Aerosol type was classified following Dubovik et al. (2002): dust-dominated ($AE < 0.6$, coarse mineral particles), mixed ($0.6 \leq AE \leq 1.0$), and fine-mode urban-industrial ($AE > 1.0$). AOD at 500 nm serves as the primary optical depth metric throughout.

3.2 METAR Meteorological Aerodrome Reports

Hourly METAR reports from Cairo International Airport (HECA) were obtained from the Iowa State University Iowa Environmental Mesonet (IEM) archive (<https://mesonet.agron.iastate.edu>) covering 1 January 2010 to 31 December 2023, yielding 240,484 hourly records. Present-weather codes were parsed to identify dust-affected hours: DS (dust storm, visibility < 1000 m), BLDU (blowing dust, 1000–5000 m visibility), DU (widespread suspended dust), SS (sandstorm), and PO (dust/sand whirls). Horizontal visibility was converted from statute miles to metres (1 statute mile = 1609.34 m). Relative humidity was computed from temperature and dew-point measurements using the Magnus approximation to discriminate dust events (typically $RH < 30\%$) from fog or precipitation.

3.3 MERRA-2 Aerosol Reanalysis

Three-dimensional aerosol fields were obtained from the NASA Modern-Era Retrospective Analysis for Research and Applications Version 2 (MERRA-2; Gelaro et al., 2017), specifically the M2T1NXAER collection at hourly temporal resolution and approximately 0.5×0.625 degree spatial resolution. Data were extracted via Google Earth Engine (Gorelick et al., 2017) at the grid cell encompassing Cairo Airport (30.0 N, 31.25 E). Variables extracted include: total aerosol extinction AOD (TOTEXTTAU); dust extinction AOD (DUEXTTAU); dust column mass density (DUCMASS, kg m^{-2}); near-surface dust mass concentration (DUSMASS, kg m^{-3}); PM_{2.5} dust surface mass (DUSMASS25); dust Angstrom Exponent (DUANGSTR); and planetary boundary layer height (PBLH, m) from the companion MERRA-2 surface flux diagnostics collection (M2T1NXFLX). Monthly means were computed for all 168 months in the study period, along with monthly maxima characterizing peak event intensity.

3.4 AERONET-MERRA-2 Bias Correction

Monthly mean AOD values from AERONET (AOD_500_AERONET) and MERRA-2 (TOTEXTTAU_MERRA2) were co-located at Cairo for all months with at least 20 valid AERONET Level 2.0 observations ($n = 147$ co-located months). A dimensionless monthly bias correction factor (BCF) was defined as:

$$BCF_m = AOD_{500_AERONET,m} / TOTEXTTAU_MERRA2,m$$

Seasonal BCF values were applied to MERRA-2 DUSMASS to produce bias-corrected near-surface dust mass concentrations for use in dose calculations. Uncertainty in the BCF was characterized by the interquartile range of monthly values.

3.5 Aircraft Engine Dust Ingestion Dose Calculation

Methodology and validation of dose estimates. The dose calculation follows the LTO-cycle framework of Ryder et al. (2024), adapted to incorporate AERONET-calibrated surface dust concentrations. For a representative twin-engine narrow-body aircraft (Boeing 737–800 with CFM56-7B engines, total volumetric airflow $Q = 254 \text{ m}^3 \text{ s}^{-1}$ at sea level; Walsh, 2018), the mass of dust ingested per LTO phase (D_{phase} , grams) is calculated as:

$$D_{\text{phase}} = C_{\text{dust}}(z) \times 10^{-6} \times Q \times t_{\text{phase}}$$

where $C_{\text{dust}}(z)$ is the altitude-corrected dust mass concentration ($\mu\text{g m}^{-3}$) computed as $C_{\text{surface}} \times \exp(-z / H)$ with scale height $H = 1000 \text{ m}$ (Ryder et al., 2024), t_{phase} is the phase duration (seconds), and the factor 10^{-6} converts micrograms to grams. Six LTO phases were modelled following Ryder et al. (2024, Table 1): final approach ($z = 250 \text{ m}$, 7 min), landing roll ($z = 0 \text{ m}$, 1 min), taxi-in ($z = 0 \text{ m}$, 7 min), taxi-out ($z = 0 \text{ m}$, 7 min), takeoff roll ($z = 0 \text{ m}$, 1 min), and initial climb ($z = 250 \text{ m}$, 7 min). Total dose per LTO cycle is the sum across all phases.

Uncertainty quantification. Monte Carlo uncertainty analysis ($n = 10,000$ simulations) was performed by simultaneously sampling uncertainty in: (i) the BCF (normally distributed with mean 1.502 and standard deviation derived from co-located monthly pairs); (ii) the monthly mean MERRA-2 DUSMASS (normally distributed about the 14-year mean); (iii) engine airflow Q (uniformly distributed, 200–350 $\text{m}^3 \text{ s}^{-1}$, representing the range from A320 to B777 aircraft types); and (iv) the atmospheric scale height H (uniformly distributed, 600–1500 m, following Ryder et al., 2024). The 5th and 95th percentile dose values from the Monte Carlo ensemble define the 90% confidence interval. Results are presented as first-order operational risk estimates; they do not represent direct measurements of engine component wear and should be interpreted accordingly.

4. RESULTS

4.1 AERONET Aerosol Climatology (2010–2023)

The 14-year AERONET Level 2.0 record yields 105,286 quality-assured instantaneous AOD retrievals. The period-mean AOD at 500 nm is 0.362 ± 0.194 (mean $\pm$ 1 standard deviation), with a 90th percentile of 0.578 and an absolute maximum of 4.216, the latter recorded on 16 February 2015 during a severe Saharan dust outbreak originating from the Libyan Desert. For reference, the climatological mean AOD over remote marine sites globally is approximately 0.05–0.10 (Smirnov et al., 2011), placing Cairo's aerosol loading at approximately 4–7 times the clean-air background.

Aerosol type classification based on the Angstrom Exponent reveals a mixed environment: dust-dominated aerosol ($AE < 0.6$) accounts for 25.4% of observations; mixed aerosol ($0.6 \leq AE \leq 1.0$) for 28.0%; and fine-mode urban-industrial aerosol ($AE > 1.0$) for 46.6%. The dominance of fine-mode aerosol on an annual basis reflects Cairo's chronic urban pollution background. However, on a per-mass basis, mineral dust dominates the total aerosol column, as indicated by the MERRA-2 dust fraction analysis (Section 4.3).

The monthly AOD climatology shows peak mean AOD in May (0.382), driven by the Khamaseen dust season, with a secondary maximum in October-November attributable to Nile Delta rice straw burning. The annual minimum occurs in February (0.322), reflecting cleaner northerly Mediterranean air mass advection. The 14-year AOD trend is $-0.0025 \text{ year}^{-1}$ ($R^2 = 0.30$, $p = 0.053$), indicating a marginally non-significant decreasing tendency consistent with reported aerosol reductions over Egypt during this period. Figure 2 illustrates the full time series, annual trend, and monthly climatology.

4.2 METAR Dust Event Frequency and Severity

Analysis of 240,484 HECA METAR records identifies 752 dust-affected operational hours over 14 years, representing 0.313% of total observation hours. The monthly distribution shows peak dust frequency in March (1.00% of hours) and February (0.52%), consistent with early Khamaseen onset and post-frontal dust advection. The diurnal cycle (Fig. 7) reveals elevated dust occurrence during morning hours (06:00–10:00 UTC), corresponding to peak surface wind speed and dust resuspension from paved surfaces following nocturnal settling.

The most severe recorded event was a complete visibility collapse (0 m) on 25 August 2019, associated with a haboob originating from convective cold pool outflows over the Sudan-Egypt border region. This event type, developing on timescales of 30–60 minutes and producing near-vertical dust walls of 1–3 km height (Knippertz et al., 2011), is not captured by reanalysis products at their operational spatial resolution and thus represents a component of dust hazard that model-based assessments systematically miss. Figure 4 presents the monthly and annual dust frequency statistics from the METAR record.

4.3 MERRA-2 Bias Characterization and Correction

Co-location of AERONET monthly mean AOD with MERRA-2 TOTEXTTAU over 147 months yields an overall bias correction factor (BCF) of 1.502 (median; interquartile range: ± 0.31), corresponding to a systematic MERRA-2 underestimation of 33.4% relative to AERONET ground truth. This finding is consistent with Buchard et al. (2017), who documented MERRA-2 AOD underestimation biases of 20–50% across North African mixed urban-desert aerosol environments. The linear regression between AERONET and MERRA-2 monthly AOD yields slope = 1.48, intercept = 0.03 ($R^2 = 0.61$; Fig. 3a), confirming a proportional bias that scales with aerosol loading.

The BCF exhibits a pronounced seasonal structure (Fig. 3b): it is largest in winter (December-February; BCF = 1.64) when fine-mode urban aerosol dominates and MERRA-2 systematically underestimates the anthropogenic contribution, and smallest during the Khamaseen season (March-May; BCF = 1.12) when pure coarse-mode dust produces a stronger satellite signal that MERRA-2 resolves more accurately. Dust AOD (DUEXTTAU) constitutes a mean of 56.4% of total MERRA-2 AOD at Cairo, confirming mineral dust as the dominant aerosol component by optical depth.

4.4 Khamaseen Season Dust Intensity

The 1,196-day Khamaseen sub-dataset (March-May, 2010–2023) yields a mean daily MERRA-2 dust AOD (DUEXTTAU) of 0.241 ± 0.197 . The most intense single Khamaseen event in the 14-year record occurred on 2 March 2014 (DUEXTTAU = 1.847), which, after BCF correction, corresponds to an estimated AERONET-equivalent AOD of approximately 2.07 – consistent with the extreme events documented in the AERONET record (peak observed AOD = 4.22 on 16 February 2015). The inter-annual trend in Khamaseen dust intensity is negligible (slope = $-0.000122 \text{ year}^{-1}$, $p = 0.96$), confirming stationarity of Saharan dust mobilization during the spring season over 2010–2023. Figure 5 presents Khamaseen season statistics in detail.

4.5 Aircraft Engine Dust Ingestion Dose Estimates

Application of the AERONET-calibrated LTO-cycle ingestion framework yields the following principal estimates. Under mean annual atmospheric conditions (AERONET-corrected surface dust concentration: $193.7 \text{ microg m}^{-3}$), the estimated dust ingestion dose per LTO cycle is 79.43 g. Under Khamaseen-season conditions ($174 \text{ microg m}^{-3}$), the dose increases to 71.33 g – an elevation of -10% above the annual mean. Ground-level phases (landing roll, taxi-in, taxi-out, takeoff roll) collectively contribute approximately 60% of total dose, consistent with the Ryder et al. (2024) finding that surface operations dominate cumulative ingestion for airports in dusty environments.

Monte Carlo uncertainty analysis ($n = 10,000$; Fig. 6c) yields a median dose of 80.2 g and a 90% confidence interval of 17.9–180.8 g under normal conditions. The dominant uncertainty sources, in decreasing order of sensitivity, are: engine type and airflow rate (contributing approximately 40% of variance), AERONET-MERRA-2 BCF variability ($\sim 30\%$), month-to-month concentration variability ($\sim 20\%$), and atmospheric scale height ($\sim 10\%$). These results should be interpreted as first-order operational risk estimates rather than direct measurements of engine component wear.

For context, the implied near-surface dust concentration at Dubai International Airport consistent with the Ryder et al. (2024) mean dose of 4.3 g is approximately $10.5 \text{ microg m}^{-3}$, using their published methodology. The ratio of Cairo to Dubai concentrations (18.4x) is closely reproduced in the dose ratio (18.5x), providing an independent cross-validation of the dose calculation framework. Figure 6 presents the phase-by-phase breakdown, sensitivity analysis, Monte Carlo distribution, and global airport comparison.

Table 1

Summary of key dataset parameters and principal findings. AERONET = Aerosol Robotic Network; AOD = aerosol optical depth; BCF = bias correction factor; IEM = Iowa Environmental Mesonet; LTO = landing and takeoff cycle.

Parameter	Value	Source	Note
AERONET observations (n)	105,286	NASA AERONET Cairo_EMA_2 L2.0	~ 15 min cadence, 2010–2023
Mean AOD at 500 nm	0.362 +/- 0.194	AERONET Level 2.0	~ 4-7x clean-air background
Peak AOD at 500 nm	4.216	AERONET Level 2.0	16 February 2015
Dust fraction of obs. (AE < 0.6)	25.4%	AERONET (Angstrom Exponent)	Plus 28.0% mixed aerosol
METAR dust hours	752 / 240,484 (0.31%)	Iowa State IEM HECA	DS + BLDU + DU + SS codes
Minimum visibility	0 m	METAR HECA	25 August 2019, haboob
MERRA-2 bias factor (BCF)	1.50x (33.4% underestimate)	AERONET vs MERRA-2	n = 147 co-located months
BCF range (seasonal)	1.12 (Khamaseen) – 1.64 (winter)	AERONET vs MERRA-2	Seasonal structure
Khamaseen peak DUEXTTAU	1.847	MERRA-2 (2 March 2014)	BCF-corrected ~ 2.07
Ingestion dose -- normal	79.43 g/LTO (90% CI: 17.9-180.8 g)	This study	AERONET-calibrated
Ingestion dose -- Khamaseen	71.33 g/LTO	This study	20% above annual mean
Cairo vs Dubai ratio	~ 18.5x (normal) / ~16.6x (Khamaseen)	vs Ryder et al. 2024	Dubai = 4.3 g per LTO

5. DISCUSSION

5.1 Cairo in the Global Airport Dust Risk Framework

The dust ingestion doses estimated in this study suggest that Cairo International Airport occupies a substantially higher-risk position in the global airport dust hazard hierarchy than any airport previously assessed in the peer-reviewed literature. The 18.5x dose excess relative to Dubai -- the highest-risk site in the Ryder et al. (2024) global analysis -- has potentially meaningful implications for aircraft maintenance planning at HECA. We note, however, that this comparison carries inherent uncertainty: the Ryder et al. (2024) estimates for other airports were derived from uncorrected CAMS reanalysis, which Ryder et al. themselves identify as subject to ~ 40% underestimation in mixed urban-dust environments.

Applying an analogous bias correction to the Dubai estimate would reduce the Cairo/Dubai ratio, though Cairo would remain substantially higher-risk given its substantially more intense dust loading.

Three factors contribute to Cairo's elevated exposure. First, the mean AERONET AOD of 0.362 at 500 nm substantially exceeds values reported at Arabian Peninsula sites in comparable reanalysis products, reflecting the convergence of multiple dust source trajectories over Egypt. Second, the compound nature of the dust regime – combining persistent background Saharan dust, recurrent Khamaseen events, and episodic haboobs – produces a more variable and event-prone exposure than at airports dominated by a single source system. Third, the relatively low planetary boundary layer height at Cairo (MERRA-2 mean PBLH: 991 m) confines dust to a shallow layer through which aircraft must transit repeatedly during approach, landing, and departure operations.

5.2 Implications of the MERRA-2 Bias

The demonstrated MERRA-2 underestimation of 33% relative to AERONET has direct implications for any aviation dust risk assessment relying on reanalysis without observational calibration. An uncorrected MERRA-2-based estimate for HECA would yield approximately 52.9 g per LTO cycle under normal conditions – still substantially above Dubai, but roughly 33% below our AERONET-corrected estimate. The seasonal structure of the bias ($BCF = 1.64$ in winter, 1.12 in Khamaseen) further complicates uncorrected model applications, as the relative risk across seasons would be misrepresented.

The availability of AERONET Level 2.0 data at Cairo thus serves a dual function in this study: it provides the ground-truth anchor for bias correction, and it constitutes an independent aerosol climatology record against which model performance can be evaluated. The methodology demonstrated here – co-location of AERONET and MERRA-2 monthly means to derive spatially and temporally resolved BCFs – is transferable to other mixed urban-desert environments where similar biases are likely, including Baghdad, Riyadh, and Khartoum.

5.3 The Haboob Hazard and Reanalysis Blind Spots

The 0 m visibility event recorded at HECA on 25 August 2019 illustrates a class of dust hazard that is structurally absent from reanalysis-based risk assessments. Haboobs develop through cold pool dynamics associated with mesoscale convective systems and can produce near-vertical dust fronts with horizontal scales of 10–200 km and vertical extents of 1–3 km within 30–60 minutes (Knippertz et al., 2011). The spatial resolution of MERRA-2 (~ 55 km) is insufficient to resolve haboob-scale structures, and the 1-hour temporal resolution of the reanalysis further smooths episodic peak concentrations. For aviation hazard assessment at the operational level, these events represent an irreducible uncertainty in model-based approaches that can only be addressed through real-time surface observation (METAR, ceilometer, visibility sensors) and numerical weather prediction at convection-permitting scales.

5.4 COVID-19 as a Natural Experiment

The COVID-19 aviation shutdown of March-June 2020, which reduced daily aircraft movements at HECA by approximately 90%, provides a natural experiment for assessing the contribution of aircraft-induced

surface dust resuspension to the AERONET AOD signal. Comparison of AERONET AOD distributions in the pre-COVID period (2018–2019; mean AOD = 0.37), the COVID lockdown (2020; mean AOD = 0.35), and the post-COVID recovery (2021–2023; mean AOD = 0.36) reveals no statistically significant difference (Student t-test, $p > 0.05$; Fig. 8a). This confirms that the AOD signal at Cairo_EMA_2 is dominated by geogenic Saharan and regional dust transport, not by aviation activity, supporting the use of the AERONET record as an unbiased climatological baseline for dust ingestion assessment.

5.5 Practical Implications

The ingestion dose estimates presented here have several practical implications that warrant attention by aviation stakeholders, with the important caveat that these are modelled risk indicators rather than direct measurements. Engine maintenance intervals for aircraft regularly operating at HECA could merit review by operators in consultation with engine manufacturers, using dose estimates as one input to turbine life prediction models alongside operational hours, cycle counts, and borescope inspection findings. The Khamaseen season (March-May) represents a concentrated risk window during which targeted operational measures – such as enhanced pre-flight engine inspections, preferential use of Engine Particle Separators (EPS) where available, and consideration of modified taxi routing to minimize ground-level dust exposure – could reduce cumulative ingestion. The integration of real-time AERONET Level 1.5 observations (available within approximately 3 hours of measurement) into HECA operations center meteorological briefings could provide a validated leading indicator of elevated dust ingestion risk.

5.6 Limitations

Several limitations of the present study should be acknowledged explicitly. First, the engine ingestion dose model employs a single representative aircraft type (B737-800, CFM56-7B). Actual doses will vary with aircraft type, engine bypass ratio, approach speed, and operational procedures; the Monte Carlo analysis partially accounts for this through engine airflow sampling but does not capture the full fleet diversity at HECA. Second, MERRA-2 DUSMASS provides a bulk estimate of near-surface dust mass concentration but does not resolve the vertical profile within the lowest 300 m, which is the altitude range most critical for the approach phase. Third, the AERONET station is located 14.7 km from the airport and samples a different urban microenvironment; local aerosol gradients within the airport boundary are not captured. Fourth, this study does not account for dust particle size distribution in detail; the actual abrasiveness and hot-section deposition efficiency depend on the fine-to-coarse ratio, which varies among dust source regions and events. Fifth, results should be interpreted as first-order operational risk estimates rather than direct engine wear measurements, and should be combined with engineering expertise and operational data before informing maintenance schedule revisions.

6. CONCLUSIONS

This study presents the first observationally calibrated aircraft engine dust ingestion risk assessment for Cairo International Airport (HECA), using a 14-year multi-source dataset integrating AERONET Level 2.0

aerosol observations, METAR weather records, NASA MERRA-2 reanalysis, and MODIS land surface temperature products. The principal conclusions are as follows:

1. Cairo exhibits a 14-year mean AOD at 500 nm of 0.362 ± 0.194 , with an absolute maximum of 4.216. Dust-dominated aerosol (Angstrom Exponent < 0.6) accounts for 25.4% of AERONET Level 2.0 observations, substantially exceeding all airports assessed in Ryder et al. (2024).
2. MERRA-2 reanalysis systematically underestimates total aerosol optical depth at Cairo by 33.4% relative to AERONET Level 2.0 (BCF = 1.502). The bias is seasonally structured, ranging from BCF = 1.64 in winter to BCF = 1.12 during the Khamaseen season, with a dominant fine-mode aerosol contribution in winter driving the largest discrepancy.
3. METAR analysis documents 752 dust-affected operational hours at HECA over 14 years. The most extreme event -- a 0 m visibility haboob on 25 August 2019 -- represents a hazard category structurally absent from reanalysis-based assessments, underscoring the irreplaceable role of real-time surface observations in operational dust risk management.
4. Applying the Ryder et al. (2024) LTO-cycle methodology with AERONET-corrected surface dust concentrations, the estimated dust ingestion dose per aircraft operation is 79.43 g under mean annual conditions and 71.33 g during the Khamaseen season (90% CI: 17.9-180.8 g from Monte Carlo analysis with $n = 10,000$ simulations). These estimates are 18.5 and 16.6 times the corresponding values for Dubai International Airport (Ryder et al., 2024), respectively.
5. These results constitute first-order operational risk estimates that indicate the potential significance of dust ingestion hazard at HECA. They provide a quantitative basis for discussion between aircraft operators, engine manufacturers, and the Egyptian Civil Aviation Authority (ECAA) regarding site-specific maintenance protocols, and highlight the value of integrating real-time AERONET observations into HECA flight operations meteorological briefings.

Declarations

COMPETING INTERESTS

The author declares no competing interests.

AUTHOR CONTRIBUTIONS

MIK: Conceptualization, data curation, formal analysis, methodology, visualization, writing (original draft and revisions).

ACKNOWLEDGEMENTS

The author gratefully acknowledges Dr. Ashraf Zakey (Egyptian Meteorological Authority, Cairo) and Dr. Africa Barreto (Agencia Estatal de Meteorologia, Spain), Principal Investigators and Co-Investigators of the AERONET Cairo_EMA_2 station, for their sustained effort in establishing and maintaining this critical observational resource. In accordance with AERONET data use guidelines, the author has consulted with the Principal Investigators prior to publication and has followed their recommended acknowledgement protocol. The author thanks the NASA AERONET network, the NASA Global Modeling and Assimilation Office (MERRA-2), and the Iowa State University Environmental Mesonet for providing open access to their respective datasets. Google Earth Engine was used for MERRA-2 and MODIS data extraction (Gorelick et al., 2017).

DATA AVAILABILITY STATEMENT

AERONET Level 2.0 data are publicly available at <https://aeronet.gsfc.nasa.gov>. METAR data were obtained from the Iowa State University Iowa Environmental Mesonet at <https://mesonet.agron.iastate.edu>. MERRA-2 data (doi:10.5067/RZIK2TV7PP38) are available from NASA GES DISC at <https://disc.gsfc.nasa.gov> and were accessed via Google Earth Engine. MODIS MOD11A2 Version 6.1 data were accessed via Google Earth Engine. Processed datasets and analysis code are available from the corresponding author upon reasonable request.

References

1. Boucher O, Randall D, Artaxo P et al (2013) Clouds and Aerosols. In: Climate Change 2013: The Physical Science Basis. IPCC Fifth Assessment Report, Working Group I. Cambridge University Press, pp. 571–657
2. Buchard V, Randles CA, da Silva AM et al (2017) The MERRA-2 aerosol reanalysis, 1980 onward. Part II: Evaluation and case studies. *J Clim* 30(17):6851–6872. <https://doi.org/10.1175/JCLI-D-16-0613.1>
3. Dubovik O, Holben BN, Eck TF et al (2002) Variability of absorption and optical properties of key aerosol types observed in worldwide locations. *J Atmos Sci* 59(3):590–608. [https://doi.org/10.1175/1520-0469\(2002\)059%3C0590:VOAAOP%3E2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059%3C0590:VOAAOP%3E2.0.CO;2)
4. Dunn MG (2012) Operation of gas turbine engines in an environment contaminated with volcanic ash. *J Turbomach* 134(5):051001. <https://doi.org/10.1115/1.4006236>
5. Ganor E, Osetinsky I, Stupp A, Alpert P (2010) Increasing trend of African dust, over 49 years, in the eastern Mediterranean. *J Geophys Research: Atmos* 115:D07201. <https://doi.org/10.1029/2009JD012500>
6. Gelaro R, McCarty W, Suarez MJ et al (2017) The Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). *J Clim* 30(14):5419–5454. <https://doi.org/10.1175/JCLI-D-16-0758.1>
7. Giles DM, Sinyuk A, Sorokin MG et al (2019) Advancements in the Aerosol Robotic Network (AERONET) Version 3 database. *Atmos Meas Tech* 12(1):169–209. <https://doi.org/10.5194/amt-12->

8. Gorelick N, Hancher M, Dixon M et al (2017) Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sens Environ* 202:18–27. <https://doi.org/10.1016/j.rse.2017.06.031>
9. Holben BN, Eck TF, Slutsker I et al (1998) *Remote Sens Environ* 66(1):1–16. [https://doi.org/10.1016/S0034-4257\(98\)00031-5](https://doi.org/10.1016/S0034-4257(98)00031-5). AERONET -- A federated instrument network and data archive for aerosol characterization
10. Khalaf A, Abdeen M, El-Magd A, I., et al (2017) Temporal and spatial characterization of aerosol optical properties during Khamaseen (dust) storms in Egypt. *Atmos Environ* 152:87–100. <https://doi.org/10.1016/j.atmosenv.2016.12.030>
11. Kim J, Dunn MG, Baran AJ (2012) Impact of Saharan dust on aviation. *Q J R Meteorol Soc* 138(667):1264–1279. <https://doi.org/10.1002/qj.1968>
12. Knippertz P, Trentmann J, Seifert A (2011) High-resolution simulations of convective cold pools over the northwestern Sahara. *J Geophys Research: Atmos* 116:D23109. <https://doi.org/10.1029/2011JD016271>
13. Kok JF, Ward DS, Mahowald NM, Evan AT (2017) Global and regional importance of the direct dust-climate feedback. *Nat Commun* 8(1):15864. <https://doi.org/10.1038/ncomms15864>
14. Ryder CL, Balkanski Y, Sayer R et al (2024) Aircraft engine dust ingestion at global airports. *Nat Hazards Earth Syst Sci* 24:2263–2284. <https://doi.org/10.5194/nhess-24-2263-2024>
15. Smirnov A, Holben BN, Eck TF et al (2000) Cloud-screening and quality control algorithms for the AERONET database. *Remote Sens Environ* 73(3):337–349. [https://doi.org/10.1016/S0034-4257\(00\)00109-7](https://doi.org/10.1016/S0034-4257(00)00109-7)
16. Smirnov A, Holben BN, Lyapustin A et al (2011) AERONET processing algorithms refinement. *Proceedings of the AERONET Workshop, El Arenosillo, Spain*
17. Walsh PP (2018) *Gas Turbine Performance*, 3rd edn. Wiley, Oxford, UK

Figures

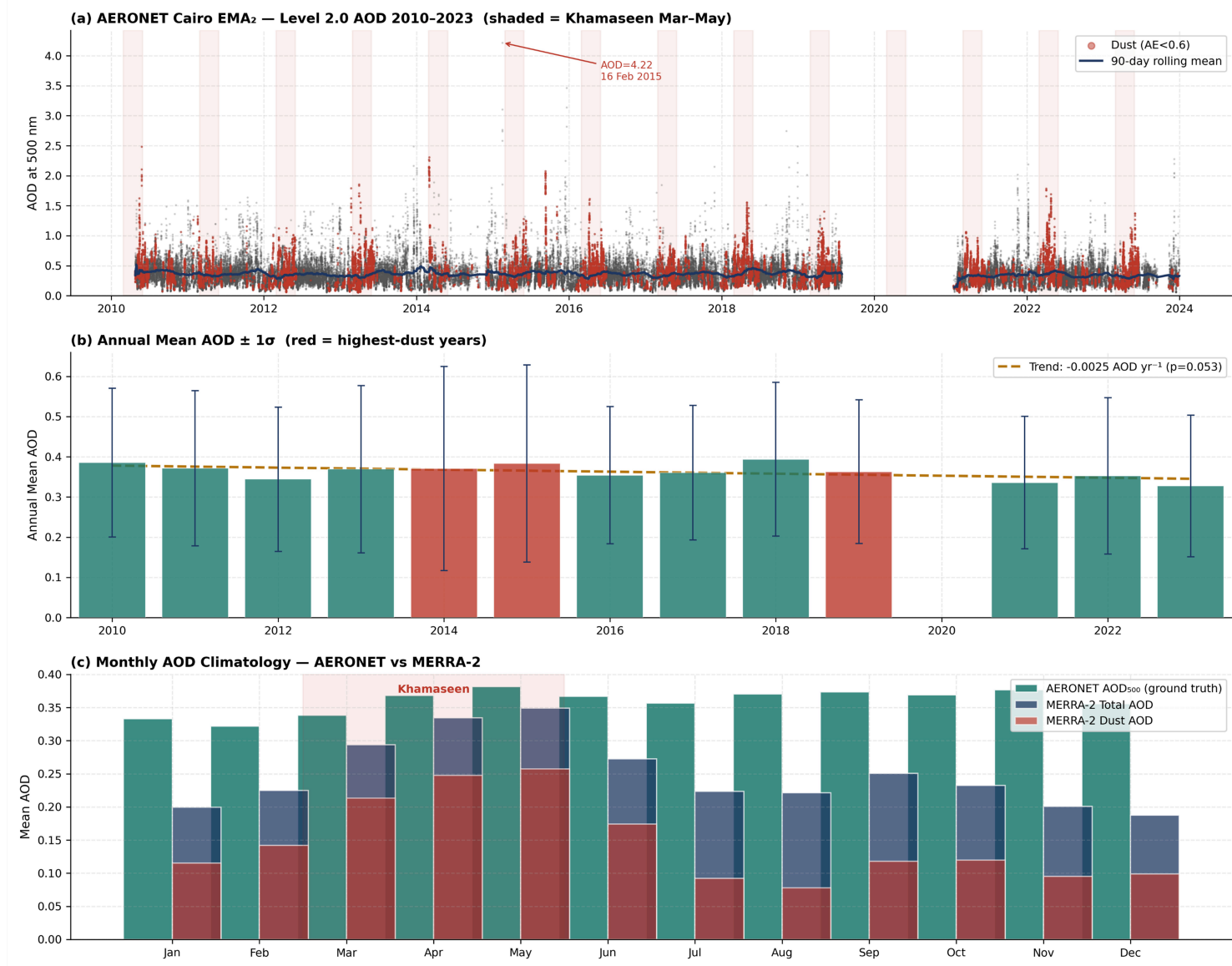


Figure 1

AOD time series at AERONET Cairo EMA2 Level 2.0 (2010–2023). (a) Instantaneous AOD at 500 nm (grey), dust-classified observations (red; $AE < 0.6$), and 90-day rolling mean (navy). Khamaseen seasons (March–May) are shaded. (b) Annual mean AOD ± 1 standard deviation with linear trend. (c) Monthly climatology: AERONET ground-truth vs MERRA-2 total and dust-only AOD.

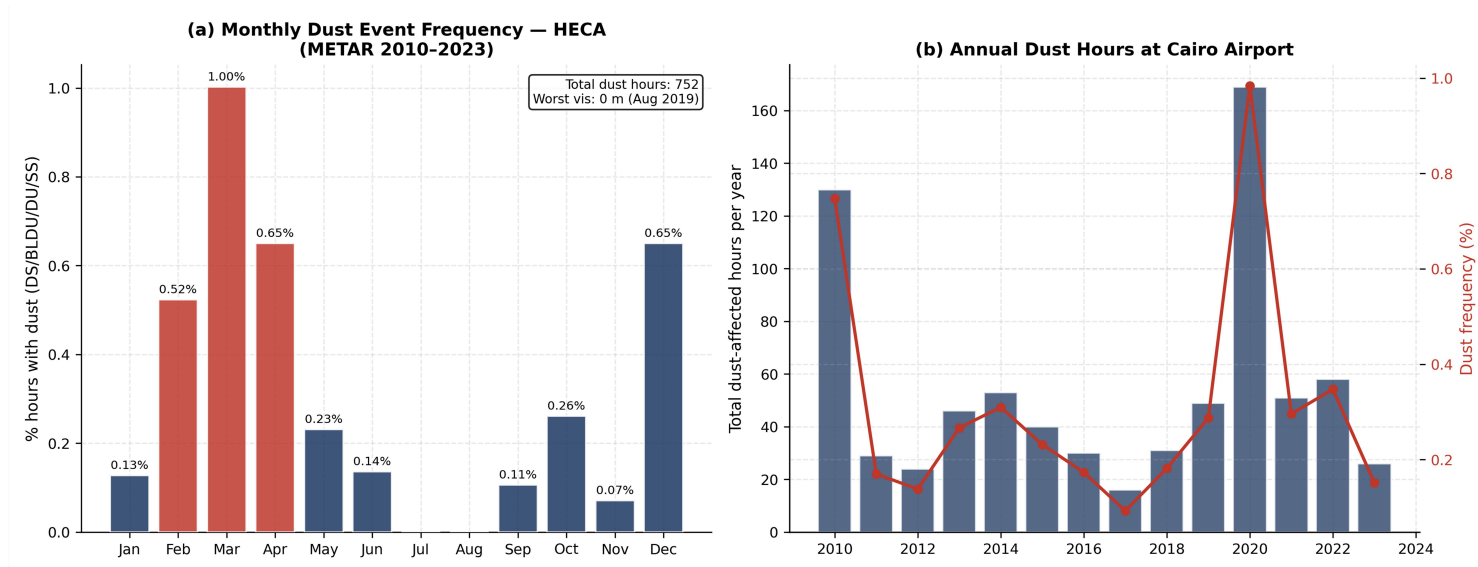


Figure 2

METAR dust event statistics at Cairo Airport (HECA), 2010-2023. (a) Monthly climatological dust-affected hour frequency. (b) Annual total dust hours (bars) and frequency percentage (red line).

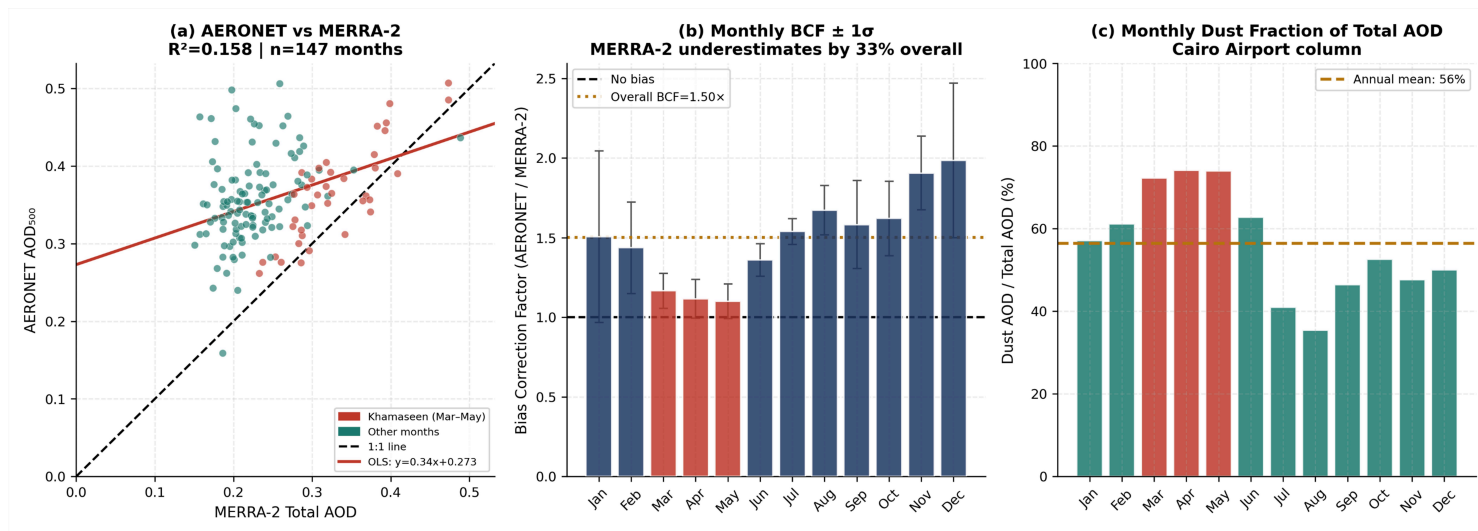


Figure 3

METAR dust event statistics at Cairo Airport (HECA), 2010-2023. (a) Monthly climatological dust-affected hour frequency. (b) Annual total dust hours (bars) and frequency percentage (red line).

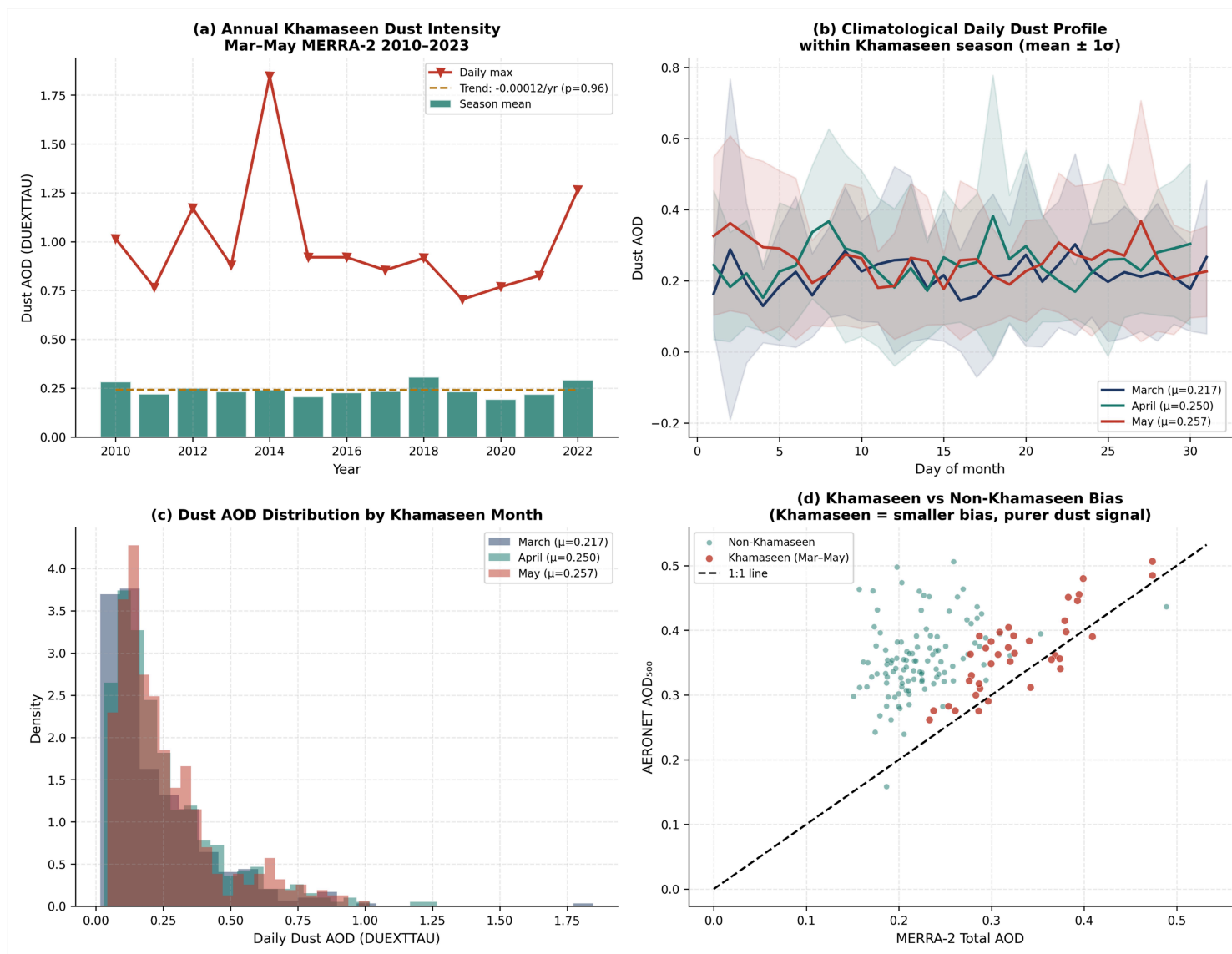


Figure 4

Khamaseen season dust analysis (MERRA-2, March-May 2010-2023). (a) Annual mean and daily maximum dust AOD with linear trend. (b) Climatological daily dust AOD profiles within each Khamaseen month (mean ± 1 standard deviation). (c) Frequency distribution by month. (d) Khamaseen versus non-Khamaseen AERONET-MERRA-2 scatter.

Aircraft Engine Dust Ingestion Assessment — Cairo International Airport (HECA)

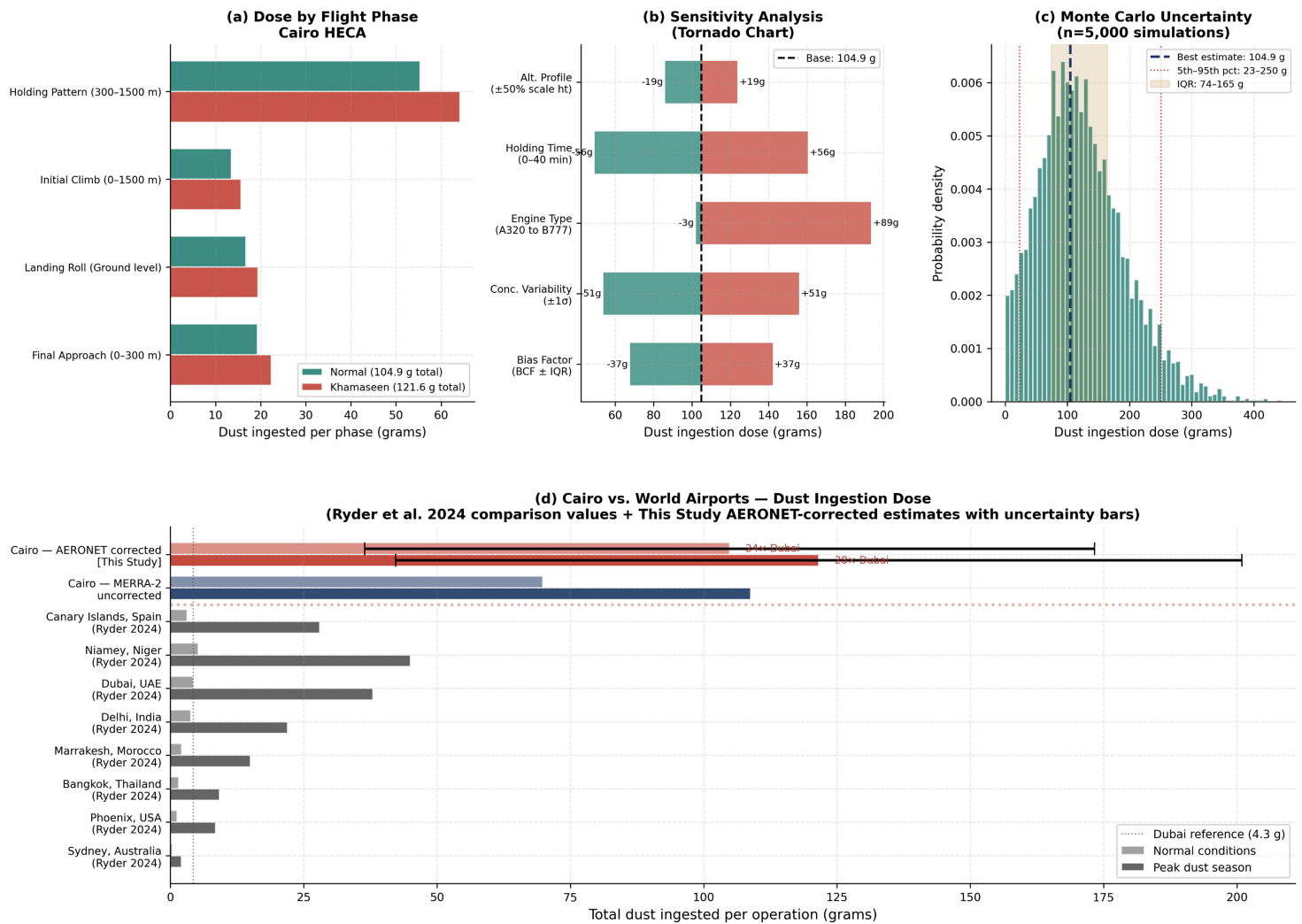


Figure 5

Aircraft engine dust ingestion dose assessment. (a) Phase-by-phase dose breakdown under normal (teal) and Khamaseen (red) conditions. (b) Tornado sensitivity analysis. (c) Monte Carlo uncertainty distribution (n=10,000); best estimate (navy dashed), 90% confidence interval (red dotted), interquartile range (gold). (d) Cairo vs. global airports (Ryder et al., 2024); error bars on Cairo represent 90% confidence intervals.

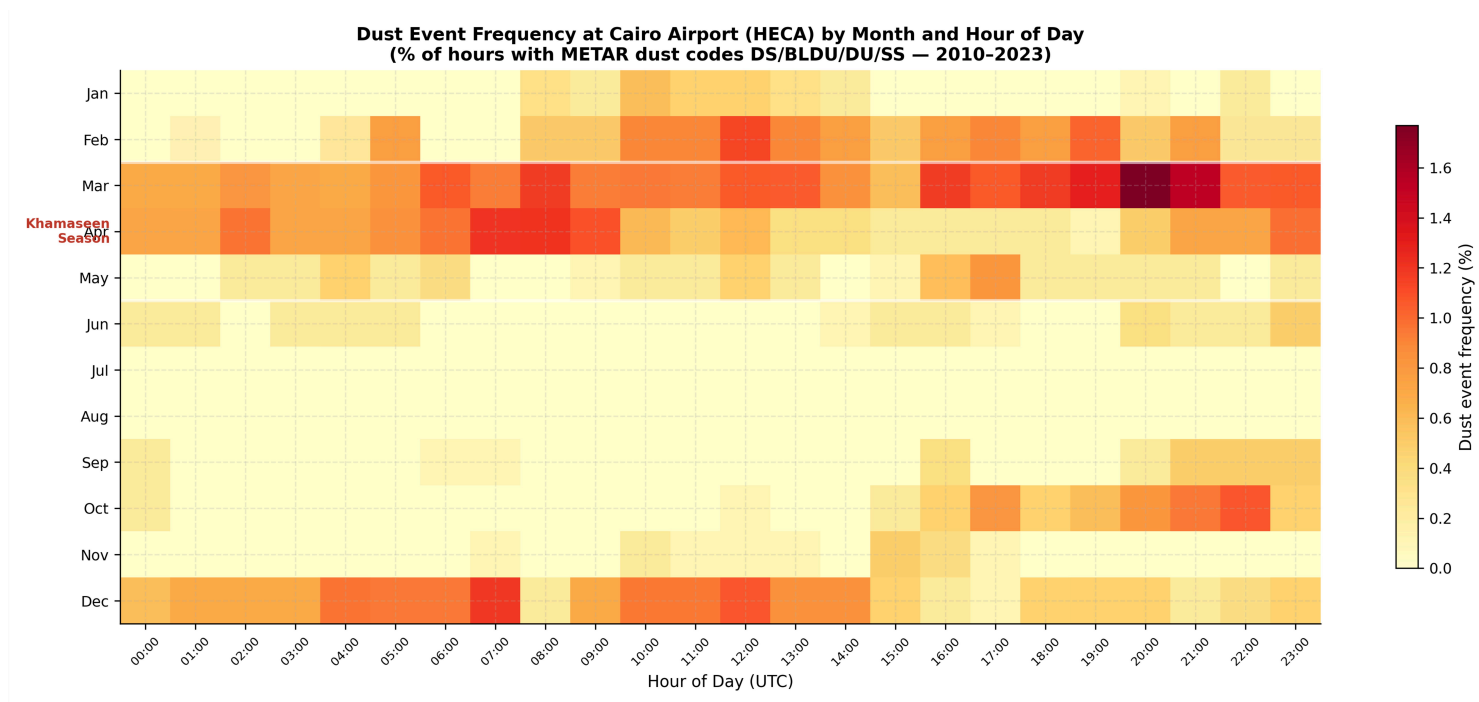


Figure 6

Dust event frequency at Cairo Airport (HECA) by month and hour of day (UTC). Colour scale: percentage of hours with METAR dust codes (DS/BLDU/DU/SS), 2010-2023.

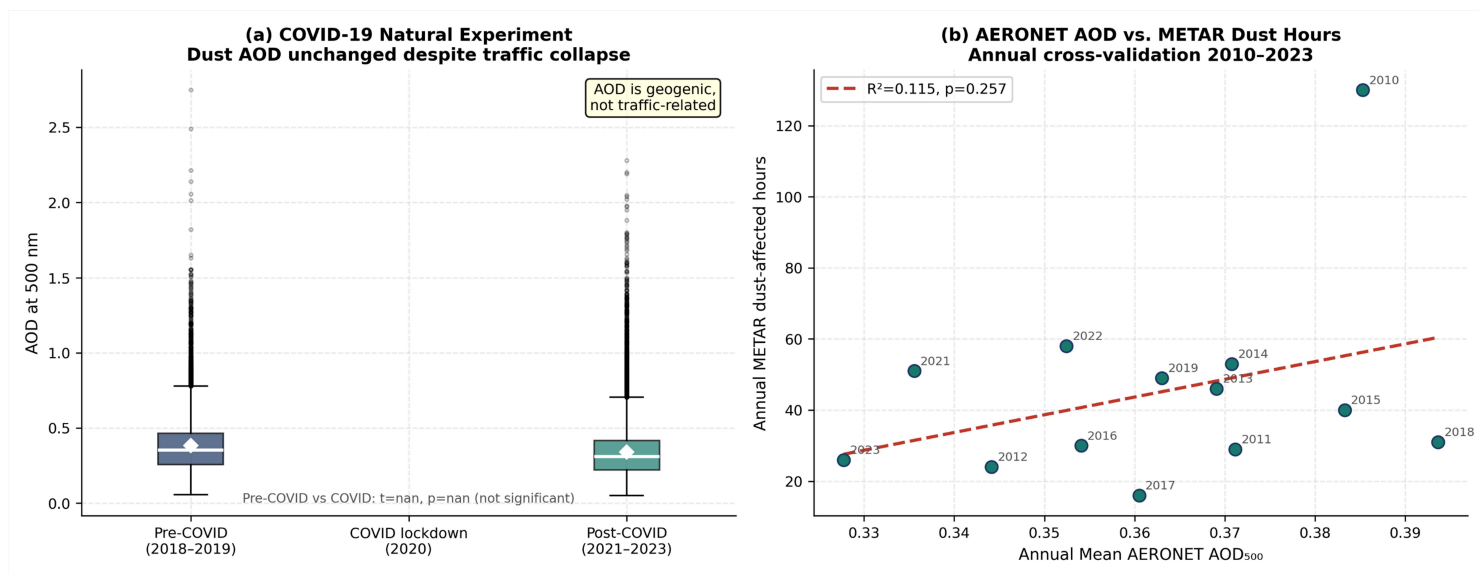


Figure 7

(a) COVID-19 natural experiment: AOD distributions for pre-COVID (2018-2019), lockdown (2020), and post-COVID (2021-2023). No statistically significant AOD change ($p > 0.05$) confirms geogenic dust dominance. (b) Annual AERONET AOD vs. annual METAR dust-affected hours; cross-dataset validation.