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E-mail: yjn@caltech.edu**Keywords:** mineral dust, PM_{2.5}, emission attribution, natural experiment, factor separation, GEOS-Chem, air quality**Abstract**

Abrupt societal disruptions, including economic shocks, pandemic lockdowns, and armed conflicts, are widely used as natural experiments for attributing changes in air quality to changes in emissions. Such attribution commonly rests on observed concentrations: combustion tracers fall, and the resulting improvement is credited to reduced emissions. Here we show that coincident natural aerosol variability can mask, and in this case reverse, the expected concentration response, so that observation-only attribution can recover the wrong sign. We demonstrate this with the 2026 Iran conflict (28 February to 31 March 2026), combining satellite columns, Tehran ground stations, two aerosol reanalyses, back-trajectory analysis, and GEOS-Chem factor-separation simulations. TROPOMI columns and ground stations confirm substantial reductions in SO₂, NO₂, and CO, the signature ordinarily read as an air-quality improvement. Over the same period and domain, surface PM_{2.5} instead rose by 67.7 $\mu\text{g m}^{-3}$. Factor separation attributes the increase to mineral dust (+74.8 $\mu\text{g m}^{-3}$, exceeding the net anomaly itself), which overwhelms the emission-driven reduction (−2.7 $\mu\text{g m}^{-3}$) and a small meteorological term (−0.8 $\mu\text{g m}^{-3}$). Friction-velocity diagnostics place the driver in the tail of the wind distribution rather than in the mean: extreme wind-stress events over the Iraq–Kuwait source region became roughly three times more frequent, a signal that cancels in region-mean statistics but is amplified by the nonlinear threshold response of dust emission. The inferred sign is also scale-dependent, since urban stations in Tehran record cleaner air while the surrounding region deteriorates. We conclude that attribution during abrupt disruptions requires explicit separation of natural and anthropogenic aerosol contributions, and that combustion-tracer columns alone are not sufficient evidence of an air-quality benefit.

1 Introduction

Reductions in anthropogenic emissions are generally expected to improve air quality and reduce human exposure to fine particulate matter (PM_{2.5}). This assumption underpins air-quality management strategies worldwide and is supported by observations following emission-control policies, economic slowdowns, and temporary reductions in industrial activity (J. Wang et al., 2017; S. Wang et al., 2010; Zhou et al., 2017). However, atmospheric particulate matter is influenced not only by anthropogenic emissions but also by meteorological variability and natural aerosol sources, creating the potential for air-quality responses that diverge from expectations (Fiore et al., 2015; Seinfeld & Pandis, 2016).

Recent studies have highlighted the complexity of aerosol responses to abrupt societal disruptions. During the COVID-19 pandemic, for example, substantial reductions in transportation and industrial activity did not always lead to proportional decreases in $\text{PM}_{2.5}$ concentrations (Biswal et al., 2021; Heald et al., 2026; Laughner et al., 2021; Le et al., 2020; Miyazaki et al., 2021; Yang et al., 2021). Previous work has emphasized the importance of meteorological conditions and nonlinear aerosol chemistry in shaping these responses (e.g., Heald et al., 2026; Le et al., 2020). Yet the role of mineral dust sources remains much less constrained, particularly during large-scale disruptions that simultaneously affect both human activities and environmental conditions (Kok et al., 2023).

Armed conflicts offer an opportunity to examine these interactions directly. The Middle East is a particularly informative setting because it contains several of the most active dust-producing regions on Earth (Hamidi et al., 2013; Middleton, 2017; Notaro et al., 2013). The Iraq–Kuwait–Mesopotamian region is a major source of mineral dust, and Iran frequently experiences severe dust episodes associated with transport from these upwind sources (Gholami et al., 2020; Hamidi et al., 2013; Middleton, 2017; Shalaby et al., 2015). Dust storm frequency in Iran peaks in spring and early summer, particularly from March to May, and MODIS AOD data confirm a rising annual aerosol load that peaks in May (Shirgholami et al., 2025). Warfare, meanwhile, can rapidly suppress transportation, industrial production, energy consumption, and maritime activity, producing large localized changes in anthropogenic emissions (Diamond & Boss, 2025; Mao et al., 2025). The conflict that began in Iran on 28 February 2026 therefore imposed an abrupt reduction in combustion emissions on one of the world’s most active dust regions, at the onset of the spring dust season.

That coincidence is what makes the event diagnostically useful, and it frames the general problem we address. Studies of abrupt disruptions typically infer an emission effect from observed concentrations, an inference that holds only if natural aerosol variability over the same window is small or can reasonably be assumed away. That assumption is rarely tested, and where a disruption coincides with an active natural source it may fail. Here we ask how large the resulting error can be, and whether it can change the sign of the inferred response. We combine satellite observations, ground-based measurements, aerosol reanalyses, back-trajectory analysis, and GEOS-Chem factor-separation experiments to partition the observed $\text{PM}_{2.5}$ change into meteorological, anthropogenic-emission, and mineral-dust contributions, and to identify the mechanism controlling composition during the disruption. The Iran conflict is the demonstration case; the methodological point, that observation-only attribution during such events can recover the wrong sign, is not specific to it.

2 Methods

2.1 Satellite, reanalysis, and ground-based observations

Tropospheric column densities of NO_2 , SO_2 , and CO were derived from offline Level-2 products of the TROPOspheric Monitoring Instrument (TROPOMI) onboard the Copernicus Sentinel-5 Precursor satellite (Veefkind et al., 2012) for 2021–2026; only pixels with $\text{qa_value} > 0.5$ were retained, and swath observations were regridded onto a regular 10 km grid using area-weighted averaging. Aerosol optical depth (AOD) was taken from the MODIS Collection 6.1 Level-2 Deep Blue product at 550 nm over land (MOD04.L2 and MYD04.L2; MODIS Atmosphere Science Team, 2017), retaining only good and very good quality retrievals. Meteorological variables (planetary boundary layer height and 10 m winds) were derived from the ECMWF ERA5 and ERA5-Land reanalyses (Dee et al., 2011). Component-resolved aerosol mass concentrations and AOD were obtained from the MERRA-2 hourly aerosol diagnostics product M2T1NXAER at $0.5^\circ \times 0.625^\circ$ resolution (Global Modeling and Assimilation Office, 2015) and from the Copernicus Atmosphere Monitoring Service (CAMS) global atmospheric composition forecasts at $0.4^\circ \times 0.4^\circ$ resolution (Copernicus Atmosphere Monitoring Service, n.d.). Real-time hourly concentrations of eight pollutants ($\text{PM}_{2.5}$, PM_{10} , O_3 , NO, NO_2 , NO_x , SO_2 , and CO) during 2021–2026 at 18 monitoring stations in Tehran (Figure S9) were obtained from the Tehran Air Quality Control Company; instrumentation and quality assurance and quality control procedures are described elsewhere (Faridi et al., 2019; Yousefian et al., 2020). Daily means required at least 18 valid hourly observations, and 2026 anomalies were computed relative to the 2021–2025 calendar-day climatology. Full details of all datasets and processing steps are provided in Text S1 of the supplementary information.

2.2 GEOS-Chem simulations and factor separation

We used the GEOS-Chem chemical transport model version 14.5.1 (Bey et al., 2001; <https://github.com/geoschem/GCClassic/tree/14.5.1>) in a nested configuration at $0.5^\circ \times 0.625^\circ$ horizontal resolution over the greater Middle East and southwestern Asia (25.0° – 70.0° E, 14.0° – 42.0° N), driven by NASA GEOS-IT assimilated meteorology, with boundary conditions from a $2^\circ \times 2.5^\circ$ global simulation and a model configuration following H. Wang et al. (2022). Simulations covered December 2025 through March 2026, with December serving as spin-up. Emissions are processed by the HEMCO component (Keller et al., 2014); anthropogenic emissions follow the CEDS inventory, with conflict-period changes represented by species-specific daily scaling factors derived from the ratios of TROPOMI-observed NO_2 , SO_2 , and CO columns in 2026 to those in 2023. Mineral dust emissions are computed online with the Dust Entrainment and Deposition (DEAD) scheme (Zender et al., 2003), and dust $\text{PM}_{2.5}$ is diagnosed as dust bin DST1 plus 30% of DST2. To attribute the 2026 $\text{PM}_{2.5}$ anomaly, five simulations (Table 1) separately perturb meteorology, anthropogenic emissions, and dust-driving meteorology relative to a 2021–2025 climatological baseline. Applying the factor-separation method of Stein and Alpert (1993), each factor’s contribution is computed as the difference between its single-factor run and the Default_All baseline, and a nonlinear interaction term is defined as the residual. Details of the climatological forcing construction, emission scaling, $\text{PM}_{2.5}$ speciation, and DEAD scheme parameters are given in Text S1.

Table 1. GEOS-Chem simulation design.

Run	Meteorology	Emissions	Dust sources (DEAD driving meteorology)
Default_All	2021–2025 climatology	2021–2025 climatology	2021–2025 climatology
Full_2026	2026 (real)	2026 conflict-period	2026
Met_Only	2026 (real)	2021–2025 climatology	2021–2025 climatology
Emission_Only	2021–2025 climatology	2026 conflict-period	2021–2025 climatology
Dust_Only	2021–2025 climatology	2021–2025 climatology	2026

2.3 Back-trajectory analysis

Seventy-two-hour back trajectories were computed with the NOAA HYSPLIT model (Stein et al., 2015) driven by GDAS1 meteorological fields for four receptor sites across Iran at release heights of 100, 500, and 1500 m above ground level, daily for the pre-conflict (28 January to 27 February 2026) and conflict (28 February to 31 March 2026) periods. Trajectories were classified by passage through three external dust source regions (the Iraq–Kuwait–Mesopotamian corridor, the Arabian Peninsula, and Central Asia–eastern Iran), and gridded residence frequency maps were constructed on a $1^\circ \times 1^\circ$ grid. A dust-weighted trajectory anomaly, defined as the product of the conflict-minus-pre-conflict change in trajectory residence frequency and the collocated positive GEOS-Chem dust $\text{PM}_{2.5}$ anomaly, identifies pathways that both became more frequent during the conflict and traversed dust-enhanced source regions. Back trajectories constrain air-mass pathways rather than dust emission rates and are therefore interpreted as supporting evidence for the model-based attribution (Text S1).

3 Results

3.1 Emission reductions during the 2026 Iran conflict

NO_2 is emitted primarily by fossil fuel combustion in power plants, heavy industry, and ground transportation, and therefore tracks the activities most directly curtailed by conflict. TROPOMI NO_2 tropospheric columns declined markedly over the conflict zone during the war period relative to the 2021–2025 climatological mean, with negative anomalies of 30 to $60 \mu\text{mol m}^{-2}$ concentrated over northern and southwestern Iran (Figure 1c). Regional NO_2 fell below the climatological 1σ range within days of conflict onset and remained depressed throughout the study period (Figure S1a). SO_2 , emitted predominantly by petroleum refining, metal smelting, and coal-fired power generation, showed similarly widespread column reductions over the conflict zone (Figure S2), consistent with curtailed refining and heavy industrial activity. TROPOMI CO shows a comparable suppression across the same area (Figure S3). Independent corroboration comes from Global Fishing Watch Automatic Identification System (AIS) vessel presence data, which shows an approximately 60% reduction in regional maritime traffic beginning at conflict onset and persisting through May 2026 (Figures S4 and S5), confirming broad disruption of economic activity in

southwestern Iran. NASA Fire Information for Resource Management System (FIRMS) Visible Infrared Imaging Radiometer Suite (VIIRS) thermal anomaly data classified as Type 2 (static land sources, primarily persistent industrial facilities including oil and gas flaring, refineries, and petrochemical plants) show a sharp reversal from positive domain-mean fire radiative power (FRP) anomalies prior to conflict onset (+14.1 and +24.1 MW in January and February) to strongly negative values following onset (−86.0 MW in March), consistent with widespread disruption of industrial combustion activity across the conflict zone (Figures S6 and S7). Complementary transportation indicators further reinforce this picture. Regional aviation flight distance collapsed by approximately 85% within days of conflict onset before partially recovering through March. Ground-transport congestion levels, derived from TomTom city-level records aggregated across Iran, Iraq, Saudi Arabia, and neighboring countries, declined sharply from pre-conflict highs and remained suppressed throughout the conflict period. Together, these multi-modal indicators confirm the broad cessation of transportation activity following conflict onset (Figure S8).

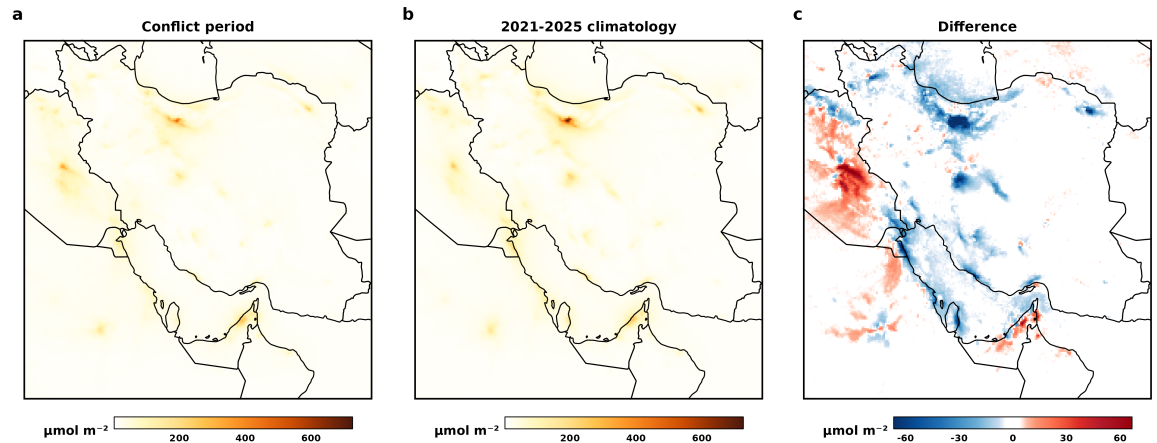


Figure 1. Tropospheric NO₂ columns over the Iran conflict domain during the 2026 war period and the 2021–2025 climatological baseline. (a) Mean TROPOMI tropospheric NO₂ column density averaged over the war period (2026-02-28 to 2026-03-31). (b) Corresponding 2021–2025 climatological mean for the same calendar period. (c) Difference between the war period and climatology (conflict minus climatology). Negative anomalies of 30 to 60 $\mu\text{mol m}^{-2}$ are concentrated over northern and southwestern Iran, while positive anomalies appear over parts of Iraq and the Persian Gulf.

Ground-based monitoring stations across Tehran (Figure S9) recorded lower mean concentrations of SO₂, NO₂, CO, nitric oxide (NO), PM_{2.5}, and coarse particulate matter (PM₁₀) during the conflict period relative to both pre-war 2026 levels and the 2021–2025 climatological war-season mean (Figure 2b). The full daily time series for each variable, spanning January through June 2026 against the 5-year climatology, is presented in Figure S10. Moderate Resolution Imaging Spectroradiometer (MODIS) aerosol optical depth over the domain shows a strongly negative anomaly across Iran during the war period (Figure 2a), reflecting the reduction in sulfate aerosol driven by SO₂ emission decreases. Taken together, these multi-tracer observations confirm a substantial suppression of fossil fuel and industry-related activity across the conflict zone.

3.2 Contrasting regional dust signal from MERRA-2 and CAMS

Despite these emission reductions, reanalysis products reveal an opposing aerosol response at the regional scale. MERRA-2 dust PM_{2.5} was systematically elevated throughout the conflict period, with 2026 values exceeding the 2021–2025 climatological mean by approximately 5 to 10 $\mu\text{g m}^{-3}$ on a regional average basis (Figure S11a). The spatial pattern of the MERRA-2 dust PM_{2.5} anomaly is centered over the Kuwait–Arabian Peninsula source region and extends northeastward into Iran along the prevailing southwesterly transport pathway (Figure S11b). MERRA-2 total PM_{2.5} and AOD show similar positive anomalies over the same region during the conflict period (Figures S12 and S13). MODIS AOD over the broader domain shows a mixed signal: negative anomalies over Iraq and Iran reflecting sulfate reduction, and positive anomalies over the Arabian source region reflecting enhanced dust emission (Figure S14). Because anthropogenic and dust aerosol signals partially cancel in total AOD, the MERRA-2 dust component, which isolates mineral aerosol independently of anthropogenic contributions, provides the most direct measure of the dust enhancement.

The CAMS reanalysis independently corroborates MERRA-2. PM_{2.5} and PM₁₀ during the

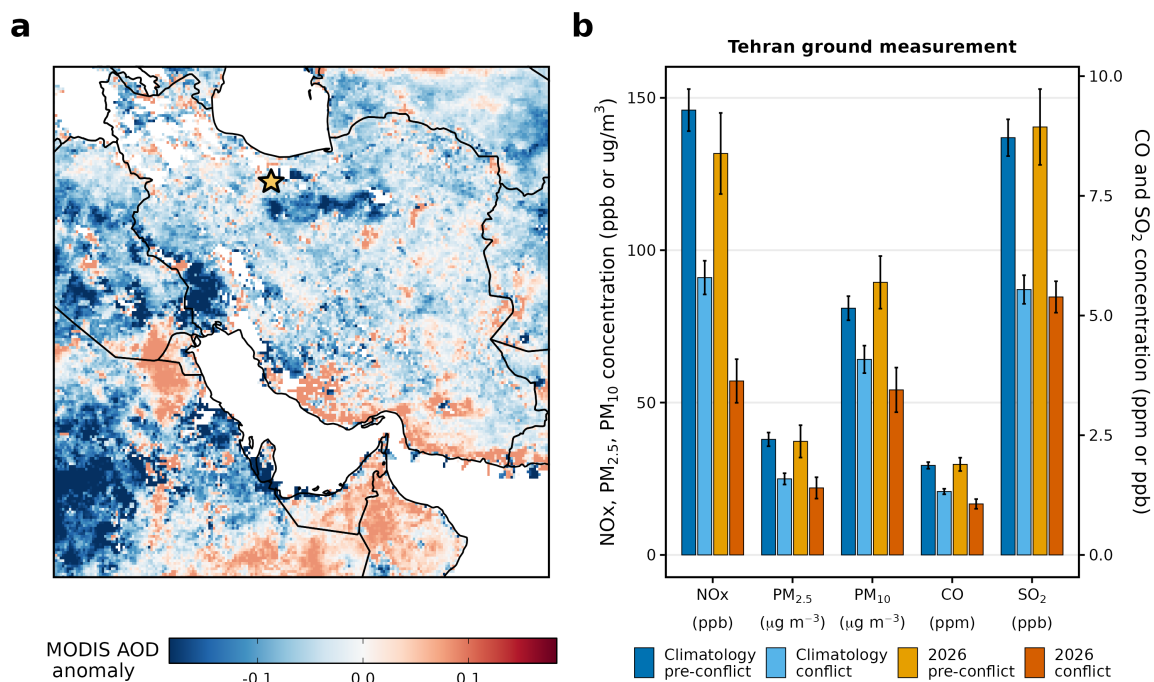


Figure 2. Regional MODIS aerosol optical depth anomaly and Tehran ground-based air quality measurements during the 2026 conflict period. (a) Spatial map of MODIS aerosol optical depth (AOD) anomaly (conflict period minus 2021–2025 climatology) over the study domain. Negative anomalies (blue) dominate across Iran and Iraq. Positive anomalies (red) are concentrated over the Arabian Peninsula and Persian Gulf source region. The gold star denotes the location of Tehran. (b) Mean concentrations of nitrogen oxides (NO_x, ppb), PM_{2.5} (μg m⁻³), PM₁₀ (μg m⁻³), CO (ppm), and SO₂ (ppb) measured at Tehran ground stations during four periods: the 2021–2025 climatological pre-conflict season (dark blue), the 2021–2025 climatological conflict season (light blue), the 2026 pre-conflict period (orange), and the 2026 conflict period (dark orange). Error bars denote 95% confidence intervals calculated from the day-to-day variability of city-level daily means within each period. Hourly measurements were first averaged by station and day, then averaged across stations to obtain daily city means. All five pollutants show lower concentrations during the 2026 conflict period relative to both the 2026 pre-conflict period and the climatological conflict-season mean, consistent with broad suppression of combustion-related activity across the conflict zone.

conflict period are both elevated relative to the 2021–2025 climatological mean, with the positive anomaly concentrated over Iraq, Kuwait, and the Arabian Peninsula (Figures S15 and S16). The CAMS dust AOD component shows a broad positive anomaly extending across the Iraq–Kuwait region, the Arabian Peninsula, and into southern Iran (Figure S17). At Tehran, total CAMS AOD remains at or below the climatological mean during the conflict period, consistent with the near-cancellation between dust enhancement and emission reduction observed at the city scale, whereas Tehran dust AOD alone is uniformly elevated (Figures S17 and S18). Together, the agreement between MERRA-2 and CAMS dust diagnostics, derived from independent reanalysis systems with different assimilation strategies and emission inventories, strengthens confidence that the regional dust enhancement is a robust feature of the conflict period.

3.3 Factor-separation attribution of the $PM_{2.5}$ anomaly

The GEOS-Chem Full_2026 simulation captures the observed temporal evolution of $PM_{2.5}$ and AOD at both the domain scale and Tehran, including the episodic dust peaks visible in the daily time series (Figure S19). The domain-mean $PM_{2.5}$ anomaly (Full_2026 minus Default_All) is $+67.7 \mu\text{g m}^{-3}$ relative to a climatological baseline of $19.3 \mu\text{g m}^{-3}$. Factor separation yields a dust contribution of $+74.8 \mu\text{g m}^{-3}$, which exceeds the net anomaly itself (111%) (Figure 3c). Conflict-period anthropogenic emission changes contribute only $-2.7 \mu\text{g m}^{-3}$ (−4%), meteorology $-0.8 \mu\text{g m}^{-3}$, and nonlinear interactions $-3.6 \mu\text{g m}^{-3}$. The full factor-separation heatmap across aerosol species and trace gases, for both the domain mean and Tehran, is presented in Figure S20. Among emission-driven aerosol changes, sulfate declines most sharply at $-2.4 \mu\text{g m}^{-3}$ (−35.7% of the default value), consistent with the 51.1% reduction in SO_2 column from the Emission_Only run. The dominance of dust is reflected in a wholesale shift in aerosol composition: domain-mean $PM_{2.5}$ increases from $19.3 \mu\text{g m}^{-3}$ in Default_All to $86.9 \mu\text{g m}^{-3}$ in Full_2026, with the dust mass fraction rising from 37% to 91% (Figure 3d). Composition across all five simulations at both the domain mean and Tehran is shown in Figure S21. The temporal evolution of domain-mean $\Delta PM_{2.5}$ and $\Delta \text{Dust } PM_{2.5}$ time series are nearly indistinguishable throughout the conflict period, confirming that day-to-day $PM_{2.5}$ variability is controlled almost entirely by episodic dust transport rather than by changes in anthropogenic emissions (Figure 3a). Spatially, the regional dust loading explains the spatial structure of the full $PM_{2.5}$ anomaly, with the strongest signal along a southwest-to-northeast corridor from Iraq through western Iran; the ΔSO_2 column and ΔAOD_{550} maps show opposing negative anomalies over the conflict zone (Figure 3b), while the full set of spatial attribution maps is in Figure S22.

At Tehran the competing effects are more nearly balanced: dust contributes $+24.5 \mu\text{g m}^{-3}$, while meteorology ($-14.4 \mu\text{g m}^{-3}$) and anthropogenic emission reductions ($-7.3 \mu\text{g m}^{-3}$) partially offset this, yielding a net $PM_{2.5}$ anomaly of $+2.8 \mu\text{g m}^{-3}$. This reconciles the apparent contradiction between the reduced $PM_{2.5}$ concentrations at Tehran ground stations (Figure 2b) and the strongly positive regional dust signal: urban monitoring stations within Tehran’s anthropogenically dominated boundary layer are more sensitive to local emission changes than to regional dust transport. Model evaluation against Tehran ground observations confirms that GEOS-Chem captures gas-phase temporal variability well, with Pearson correlations of $R = 0.72$ to 0.76 for ozone (O_3), NO_2 , and SO_2 , and $R = 0.67$ for non-dust $PM_{2.5}$ after removal of the dust contribution (Figure S23). The systematic excess of observed total $PM_{2.5}$ over modeled non-dust $PM_{2.5}$ during January and February is itself consistent with the dust loading identified in the simulations, providing independent ground-based confirmation of the regional dust enhancement.

3.4 Dust corridor activation by extreme wind stress

HYSPLIT back-trajectory analysis was conducted for four receptor sites across Iran at three heights (100, 500, and 1500 m above ground level), comparing the pre-conflict period (28 January to 27 February 2026) with the conflict period (28 February to 31 March 2026). Case-study 72-hour back trajectories during dust-peak days show air masses arriving from the Iraq–Kuwait direction under both periods, but with markedly higher dust loadings during the conflict (Figure S24). The Iraq–Kuwait–Mesopotamian corridor shows the largest increase in source-region association of all Iranian receptors, rising from 63.8% to 70.7% of trajectories (+6.8 percentage points); Arabian Peninsula association changes negligibly (+0.5 pp), and Central Asia association declines (−1.7 pp; Figure 4d and Figure S25). Trajectory residence frequency maps at all three receptor heights consistently identify the Mesopotamian sector as the region of greatest conflict-period increase in air-mass residence (Figure S26). The dust-weighted trajectory anomaly is concentrated precisely over the conflict zone and Mesopotamian sector (Figure 4c and Figure S27), confirming that the increased corridor association reflects air masses traversing dust-enhanced source regions rather

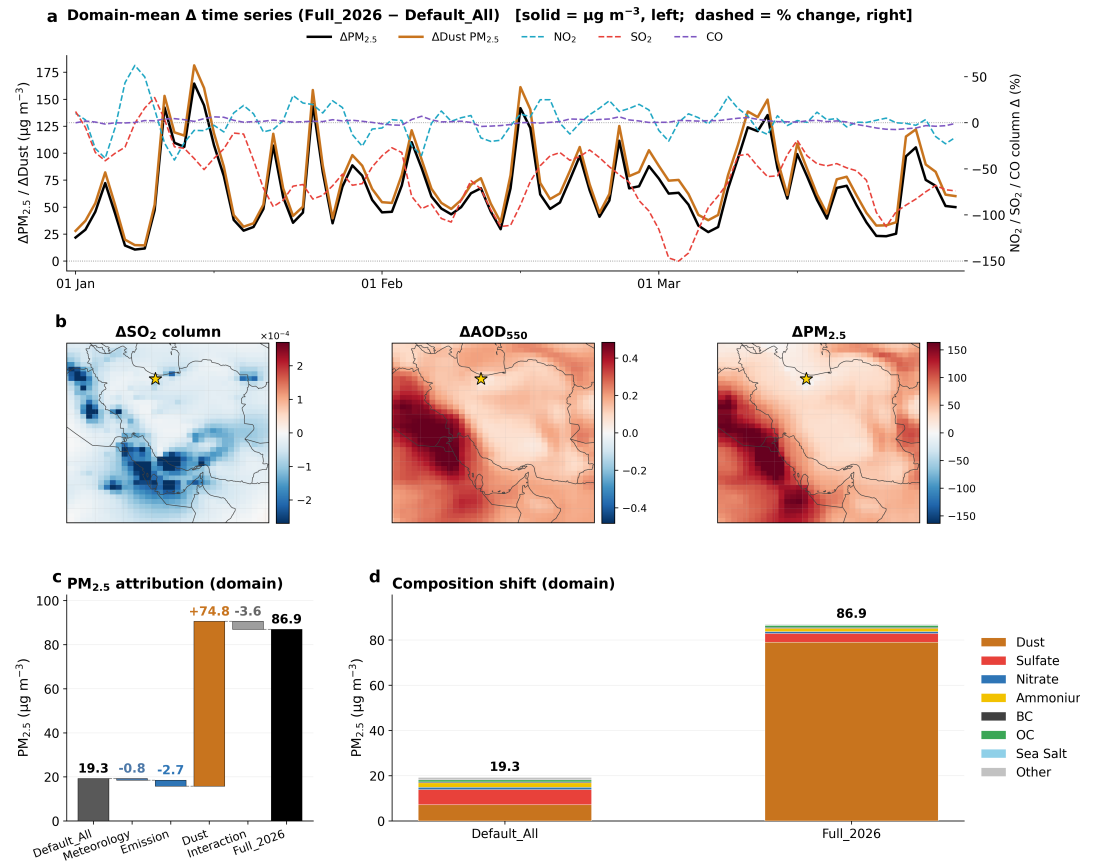


Figure 3. Dust drives the 2026 PM_{2.5} increase over Iran while combustion tracers decline. (a) Domain-mean anomaly time series (Full_2026 minus Default_All): $\Delta\text{PM}_{2.5}$ (black) and $\Delta\text{Dust PM}_{2.5}$ (orange) on the left axis ($\mu\text{g m}^{-3}$, solid lines), and tropospheric NO₂, SO₂, and CO columns expressed as percent change relative to the Default_All mean on the right axis (dashed lines); dotted lines mark zero. $\Delta\text{PM}_{2.5}$ closely tracks ΔDust and remains positive throughout, whereas combustion-tracer columns decline, with SO₂ reaching approximately -100% during the most dust-active periods, illustrating that PM_{2.5} rises even as anthropogenic tracers fall. (b) Spatial anomaly maps (Full_2026 minus Default_All) of the SO₂ column, AOD₅₅₀, and surface PM_{2.5} averaged over the study period; the gold star marks Tehran. SO₂ decreases over the conflict zone while AOD₅₅₀ and PM_{2.5} increase along the southwest-to-northeast Iraq–Kuwait–Mesopotamian dust corridor. (c) Attribution of the domain-mean PM_{2.5} anomaly by factor separation, showing the stepwise contributions from the Default_All baseline (19.3 $\mu\text{g m}^{-3}$) through meteorology (-0.8), emissions (-2.7), dust (+74.8), and nonlinear interactions (-3.6) to the Full_2026 total (86.9 $\mu\text{g m}^{-3}$); dust overwhelmingly dominates while emissions slightly reduce PM_{2.5}. (d) Domain-mean surface PM_{2.5} composition for Default_All versus Full_2026, showing the shift from a mixed sulfate-nitrate-dust aerosol (19.3 $\mu\text{g m}^{-3}$) to a strongly dust-dominated composition (86.9 $\mu\text{g m}^{-3}$).

than a general broadening of transport pathways. This spatial correspondence between HYSPLIT pathway anomalies and GEOS-Chem dust anomalies provides an independent, transport-based constraint supporting the model attribution.

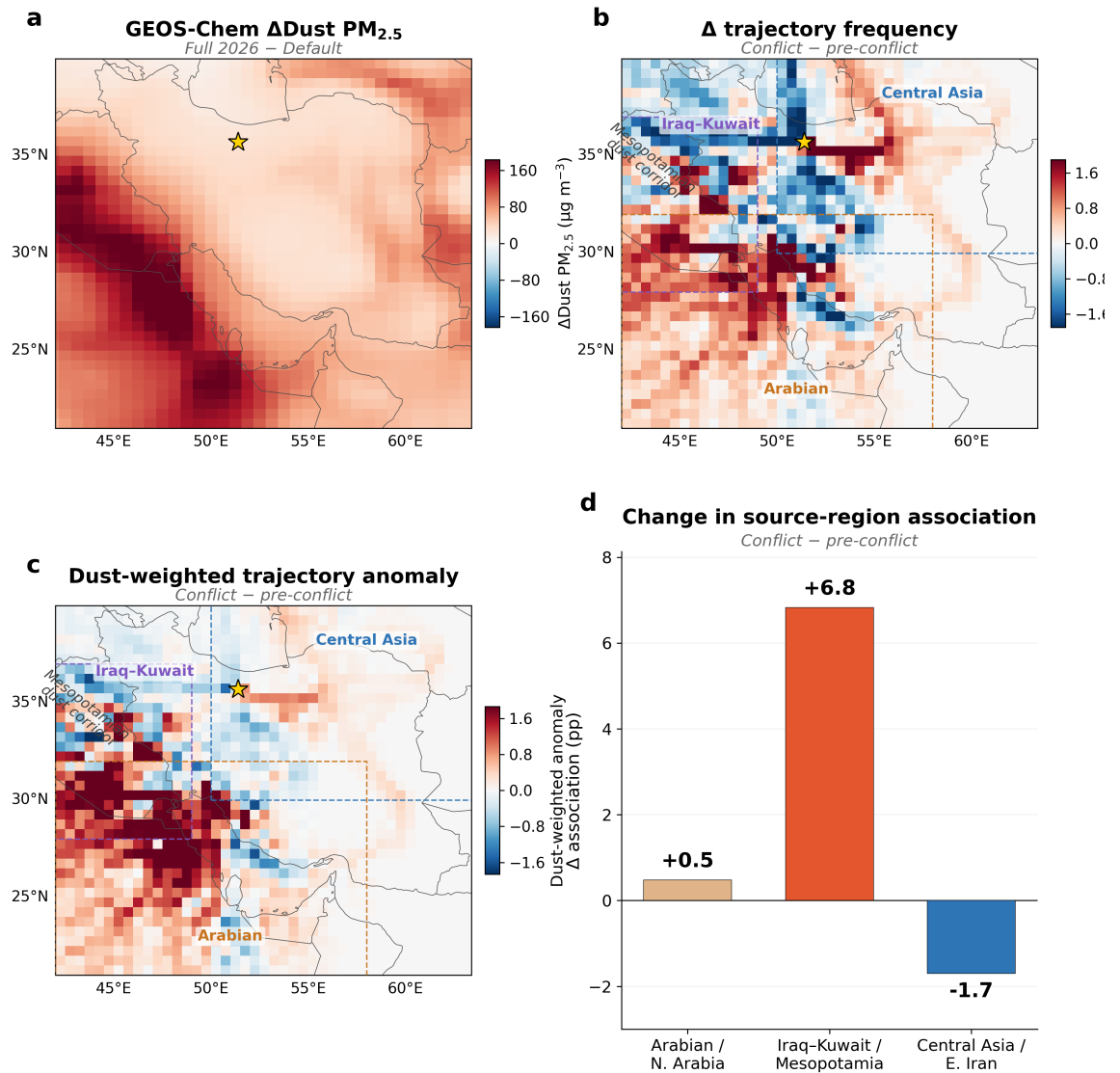


Figure 4. Enhanced transport through the Iraq–Kuwait–Mesopotamian dust corridor supports the dust-driven PM_{2.5} increase. (a) GEOS-Chem surface dust PM_{2.5} anomaly (Full_2026 minus Default_All, $\mu\text{g m}^{-3}$), showing the strongest positive signal along the southwest-to-northeast Iraq–Kuwait–Mesopotamian corridor extending into western Iran. The gold star marks Tehran. (b) Difference in NOAA HYSPLIT trajectory residence frequency between the conflict period (2026-02-28 to 2026-03-31) and pre-conflict period (2026-01-28 to 2026-02-27), expressed as percent of trajectories for all Iranian receptors and release heights combined. Dashed boxes indicate the three source regions: Iraq–Kuwait–Mesopotamia (purple), Arabian/N. Arabia (orange), and Central Asia/E. Iran (cyan). (c) Dust-weighted trajectory anomaly, computed as the product of the conflict-minus-pre-conflict trajectory frequency change and the positive GEOS-Chem dust anomaly, isolating air-mass pathways that both increased in frequency and traversed dust-enhanced source regions. The anomaly is concentrated over the Iraq–Kuwait–Mesopotamian corridor and adjacent Mesopotamian dust source area, spatially coincident with the GEOS-Chem dust PM_{2.5} anomaly in (a). (d) Change in source-region trajectory association between the conflict and pre-conflict periods (percentage points, pp). The Iraq–Kuwait–Mesopotamian corridor shows the largest increase (+6.8 pp), while the Arabian/N. Arabia association changes negligibly (+0.5 pp) and the Central Asia/E. Iran association declines (−1.7 pp). Back trajectories indicate air-mass pathways rather than dust emissions directly and should therefore be interpreted as supporting rather than proving the dust source attribution, providing an independent transport-based constraint on the GEOS-Chem result that dust overwhelmed the anthropogenic emission reductions during the conflict period.

Within the GEOS-Chem framework, dust emission is computed online by the DEAD scheme driven solely by input meteorological fields, with land surface parameters held at climatological values. The Met_Only experiment confirms that domain-scale circulation changes alone yield a

PM_{2.5} anomaly of only $0.8 \mu\text{g m}^{-3}$ below climatology, ruling out transport- and chemistry-mediated meteorological forcing as the driver of the dust enhancement. Because Dust_Only perturbs only the meteorology that drives DEAD, the two experiments separate the transport and chemistry channel (Met_Only) from the source-region emission channel (Dust_Only): the anomaly is meteorologically driven, but acts through dust entrainment rather than circulation.

We therefore examined the friction velocity u_* , the surface shear stress velocity governing dust particle entrainment in the DEAD scheme, extracted from GEOS-Chem StateMet output over the Iraq–Kuwait source region ($29\text{--}33^\circ\text{N}$, $43\text{--}50^\circ\text{E}$). Although the region-mean conflict-period u_* anomaly is non-significant (+6%, $p = 0.281$; Figure S28a), the frequency of extreme- u_* days increases substantially: exceedance of the climatological 95th percentile threshold (0.261 m s^{-1}) rises from 16% to 38% of conflict days (3.2-fold, Fisher exact $p = 0.044$), and exceedance of the 90th percentile rises from 22% to 41% (2.4-fold, Fisher exact $p = 0.088$; Figures S28b–S28d). Positive u_* anomalies are spatially concentrated over northern Iraq and central Iran rather than uniformly distributed across the source region (Figure S29a), explaining why the sub-regional wind enhancement is masked in the region mean. Daily u_* is significantly correlated with the dust emission flux anomaly during the conflict period (Pearson $R = 0.64$, $p = 7.7 \times 10^{-5}$, $n = 32$; Figure S29b), confirming that episodic extreme wind stress events drive the modeled dust emission peaks through the nonlinear response of the DEAD scheme.

4 Discussion

The atmospheric response to armed conflict is not a simple function of the emissions that conflict removes. Although the cessation of industrial and transportation activity produced measurable reductions in combustion-related pollutants, detectable both from orbit and at urban ground stations, these reductions were overwhelmed at the regional scale by enhanced mineral dust loading from the Iraq–Kuwait source region. The net effect on population exposure to PM_{2.5} therefore depends on the spatial scale of analysis and on the proximity of receptors to dust sources, a scale dependence with direct implications for assessing health burdens in conflict-affected populations.

This mechanism differs fundamentally from the meteorology-dominated PM_{2.5} enhancement documented during the COVID-19 lockdown in northern China (Le *et al.*, 2020), where anomalously high humidity and stagnant airflow drove secondary aerosol formation despite large emission reductions. Here the Met_Only experiment (domain PM_{2.5} anomaly: $-0.8 \mu\text{g m}^{-3}$) shows that 2026 meteorological conditions were not, in the mean, anomalously favorable for dust transport. The GEOS-Chem friction velocity output instead points to the tail of the wind distribution: extreme surface wind stress events became more frequent at the sub-regional scale over the Iraq–Kuwait source region, a signal that cancels in region-mean statistics but is amplified by the nonlinear threshold response of the DEAD scheme (Figures S28 and S29). Mean-state diagnostics alone would therefore have missed the driver of this event entirely.

The apparent improvement in Tehran’s local air quality during the conflict (Figure 2b, Figure S10) deserves careful interpretation. The ground-based measurements are genuine: combustion-related pollutants declined substantially and surface PM_{2.5} at urban stations was lower than climatological expectations. However, this local signal reflects the dominance of anthropogenic sources within Tehran’s urban boundary layer. The MERRA-2 dust fields (Figure S11) and GEOS-Chem factor separation show that populations in peri-urban and rural areas downwind of the dust source region, where dust dominates and local emission reductions are smaller, likely experienced substantially worse air quality during the conflict period. The domain-mean dust-driven increase of $+74.8 \mu\text{g m}^{-3}$ raises PM_{2.5} to many times the World Health Organization annual guideline (World Health Organization, 2021). That absolute magnitude is model-dependent (see below), but the compositional shift is not: dust rises from 37% to 91% of domain-mean PM_{2.5} mass, underscoring the public health significance of the regional dust loading.

One limitation should be noted. GEOS-Chem overestimates absolute PM_{2.5} at urban stations because of uncertainties in the dust size distribution parameterization. The modeled dust anomaly is correspondingly larger than the MERRA-2 enhancement of 5 to $10 \mu\text{g m}^{-3}$ (Figure S11a), which assimilates satellite AOD and is the more conservative estimate; the two agree in sign, pattern, and timing but not in magnitude, so absolute values here are an upper bound. The non-dust PM_{2.5} validation ($R = 0.67$, Figure S23) nevertheless confirms that anthropogenic aerosol variability is well captured, and the attribution rests on relative differences between model runs rather than on absolute concentrations, so the partitioning reported here is robust to this bias.

5 Conclusions

Abrupt societal disruptions are widely treated as natural experiments in which reduced emissions can be read off as improved air quality. Our results show that this inference can fail, and that it can fail in sign. During the 2026 Iran conflict, combustion tracers declined by every measure we examined, yet domain-mean $\text{PM}_{2.5}$ rose by $67.7 \mu\text{g m}^{-3}$, because a coincident mineral-dust enhancement of $+74.8 \mu\text{g m}^{-3}$ exceeded the entire net anomaly and overwhelmed the $-2.7 \mu\text{g m}^{-3}$ attributable to emission reductions. An observer with satellite columns and urban ground stations alone, which is the evidence base used in most disruption studies, would have concluded that regional air quality improved. It deteriorated.

Three features of this failure extend beyond the present case. First, the masking term need not be anomalous in the mean: the Met_Only experiment yields a domain $\text{PM}_{2.5}$ anomaly of only $-0.8 \mu\text{g m}^{-3}$, and the dust enhancement is driven instead by a higher frequency of extreme wind-stress events, so diagnostics based on mean conditions would not have flagged a problem. Second, the sign of the inferred response is scale-dependent, since Tehran stations record cleaner air while the surrounding region deteriorates, so the scale of assessment determines the conclusion, with direct consequences for exposure and health-burden estimates. Third, the failure is diagnosable here only through a source-resolved model experiment, because the natural and anthropogenic signals partially cancel in total-column measurements. We therefore suggest that attribution studies of abrupt disruptions state explicitly what natural aerosol variability occurred over the same window and, where an active natural source is present, separate it with a factor-separation or equivalent experiment rather than inferring the emission effect from concentrations alone. Emission reductions inferred from NO_2 or SO_2 columns remain valid as statements about emissions; on their own they are not statements about air quality.

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Author contributions

Conceptualization: J.Y., Y.L., M.G., P.C.; Methodology: J.Y., T.L., H.W., L.T., K.-F.L., Y.L.; Investigation: J.Y., T.L., H.W., M.S.A.-T., L.T.; Visualization: J.Y., T.L.; Funding acquisition: J.Y.; Project administration: J.Y.; Supervision: K.-F.L., Y.L., M.G., P.C.; Writing, original draft: J.Y., T.L., H.W., L.T.; Writing, review and editing: K.-F.L., Y.L., M.G., P.C.

Conflict of interest

The authors declare no conflict of interest.

Ethical statement

This study did not involve human participants or animals. All analyses use publicly available satellite retrievals, reanalysis products, model output, and ground-based monitoring data.

Data availability

TROPOMI NO_2 , SO_2 , and CO Level-2 data are available at https://tropomi.gesdisc.eosdis.nasa.gov/data/S5P_TROPOMI_Level2/ (products S5P_L2_NO2____HiR.2, S5P_L2_SO2____HiR.2, and S5P_L2_CO____HiR.2). MODIS Level-2 aerosol products are available at https://doi.org/10.5067/MODIS/MOD04_L2.061 (Terra, MOD04_L2) and https://doi.org/10.5067/MODIS/MYD04_L2.061 (Aqua, MYD04_L2). CAMS global atmospheric composition forecasts are available at <https://ads.atmosphere.copernicus.eu/datasets/cams-global-atmospheric-composition-forecasts>. GEOS-Chem version 14.5.1 is available at <https://github.com/geoschem/GCClassic/tree/14.5.1>, with emission inventory input from <http://geoschemdata.wustl.edu/ExtData/HEMCO/CEDS/v2025-04/2023/> and meteorological input from http://geoschemdata.wustl.edu/ExtData/GEOS_2x2.5/GEOS_IT/. The NOAA HYSPLIT back-trajectory model is available at <https://www.ready.noaa.gov/hypub-bin/trajtype.pl>. Global Fishing Watch AIS Vessel Presence data are available through the Global Fishing Watch 4Wings API (<https://globalfishingwatch.org/our-apis/> documentation). Access requires a free account registered with an email address, after which the data are openly available to all users. NASA FIRMS VIIRS thermal anomaly data are available at <https://www.earthdata.nasa.gov/data/tools/firms/active-fire-data-attributes-modis-viirs>. All analysis code and materials are available at <https://doi.org/10.5281/zenodo.20619437>.

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