

# Spatio-Temporal Dynamics of Air Pollution in Central Asian Urban Agglomerations: Integrating Ground-Based Monitoring, Satellite Remote Sensing, and Health Risk Assessment

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**Abstract.** Air pollution poses a critical health risk in Central Asia, yet multi-city assessments remain scarce. This study presents a secondary analysis of publicly available data on air pollution dynamics in four major cities—Tashkent, Almaty, Bishkek, and Dushanbe—over 2015–2025, integrating ground monitoring records, satellite observations (TROPOMI, MODIS, CALIPSO), and health statistics. Based on this analysis, PM<sub>2.5</sub> concentrations are persistently high, with annual means from 25.6  $\mu\text{g}/\text{m}^3$  (Dushanbe) to 38.4  $\mu\text{g}/\text{m}^3$  (Almaty), far exceeding WHO guidelines. Winter concentrations are 2.5–3.5 times higher than summer, reaching 68.2  $\mu\text{g}/\text{m}^3$  in Almaty and 65.8  $\mu\text{g}/\text{m}^3$  in Bishkek, driven by residential heating (52–55% of winter PM<sub>2.5</sub>) and temperature inversions. Source apportionment identifies five contributors: residential heating, traffic, industry, secondary aerosol, and dust, with city-specific patterns. Health impact assessment estimates 7,800 premature deaths annually across the four cities attributable to PM<sub>2.5</sub>, with older adults (65+ years) bearing a disproportionate burden (55–65% of mortality). Residential heating dominates winter pollution in Almaty and Bishkek, while traffic emissions contribute year-round across all cities. Priority interventions include clean fuel subsidies, stove replacement, and vehicle emissions standards. This assessment provides evidence for targeted air quality strategies in Central Asia, supporting SDG 3, SDG 11, and SDG 13. **Keywords:** Air pollution, PM<sub>2.5</sub>, source apportionment, health impact assessment, Central Asia, urban air quality, satellite remote sensing, SDG nexus

## 1 Introduction

Air pollution is one of the most significant environmental health risks globally, responsible for approximately 7 million premature deaths annually [1]. Particulate matter (PM<sub>2.5</sub>) is of particular concern due to its ability to penetrate deep into the respiratory system, causing cardiovascular diseases, respiratory infections, and lung cancer [2, 3]. The United Nations Sustainable Development Goals (SDGs) explicitly recognize this challenge through targets 3.9 (reducing deaths from pollution) and 11.6 (reducing environmental impact of cities) [4]. Central Asia faces acute air pollution challenges yet remains critically understudied. The region's major urban centers—Tashkent (Uzbekistan, >3 million), Almaty (Kazakhstan, >2 million), Bishkek (Kyrgyzstan, >1 million), and Dushanbe (Tajikistan, >1 million)—are among the most polluted globally [5, 11, 12, 33]. Key factors include aging Soviet-era infrastructure, coal-fired heating, outdated vehicle fleets, dust storms from the Aral Sea, and widespread use of low-quality coal in informal settlements [6, 7, 8]. Winter PM<sub>2.5</sub> concentrations routinely exceed WHO guidelines

by factors of 10–20 [9]. Despite the severity, systematic multi-city analyses remain scarce. Existing studies are limited to single cities or short periods, lack integrated approaches combining ground and satellite data, and rarely quantify health impacts [10, 11]. This study addresses these gaps by: (1) characterizing spatio-temporal pollution patterns across four cities (2015–2025), (2) identifying source contributions using positive matrix factorization (PMF), (3) assessing health burden using Global Burden of Disease methodology, and (4) developing evidence-based policy recommendations.

## 2 Materials and Methods

### 2.1. Study Area and Data Sources

The study focuses on Tashkent (41.3°N, 69.2°E), Almaty (43.2°N, 76.9°E), Bishkek (42.9°N, 74.6°E), and Dushanbe (38.5°N, 68.8°E). These cities represent the region's major urban centers with diverse geographical settings that influence pollution dispersion [12, 13, 14]. Ground-based data: Hourly PM<sub>2.5</sub>, PM<sub>10</sub>, NO<sub>2</sub>, SO<sub>2</sub>, CO, and O<sub>3</sub> concentrations (2015–2025) were obtained from national hydrometeorological services of Uzbekistan,

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Kazakhstan, Kyrgyzstan, and Tajikistan, supplemented by OpenAQ and IQAir platforms [15]. Data underwent quality control (removal of negative values, outlier filtering beyond  $3\sigma$ ) with completeness criteria of  $\geq 75\%$  per season.

Satellite data: TROPOMI (Sentinel-5P) provided NO<sub>2</sub> and SO<sub>2</sub> columns (3.5×5.5 km resolution) [16]; MODIS (Terra/Aqua) provided aerosol optical depth (AOD) at 550 nm (10 km resolution) [17]; CALIPSO provided vertical aerosol profiles [18]; VIIRS provided nighttime lights data [19].

Meteorological data: ERA5 reanalysis provided temperature, wind, boundary layer height, and precipitation at 0.25° resolution [20]. Radiosonde data from local stations characterized temperature inversions.

## 2.2. Analytical Methods

This study is based on secondary analysis of publicly available data. The authors did not conduct primary field measurements of air pollution. Instead, we downloaded and analyzed ground-based monitoring data from national hydrometeorological services and OpenAQ, satellite data from TROPOMI, MODIS, and CALIPSO, and meteorological data from ERA5. All data processing, statistical analysis, PMF modeling, and health impact calculations were performed by the authors using open-source software (R, Python, QGIS, Google Earth Engine). Statistical analysis: Mann-Kendall and Theil-Sen quantified trends; STL decomposed time series [21]. Spatial analysis: Ordinary kriging interpolated measurements [22]; Getis-Ord  $G_i^*$  identified hotspots [23]; Pearson correlation validated satellite data.

Source apportionment – PMF: PMF 5.0 analyzed speciated PM<sub>2.5</sub> (2018–2022,  $n=1,460$ ) including OC, EC, SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>, and 15 trace elements [24]. Uncertainty = analytical +5% of concentration (below DL: concentration = DL/2, uncertainty = 5/6 DL). Model ran with 100 iterations (seed 12345). Five factors selected ( $Q/Q_{exp}=1.12$ , 87% residuals within  $\pm 3$ ).

Uncertainty assessment (BS-DISP): Bootstrap-dispatched analysis (200 runs) calculated 95% CIs and CV. Factors with CV<0.3 well-determined; all five reproduced in >85% of runs.

Factor validation: Validated against literature profiles ( $R^2=0.79-0.88$ ) using tracers: residential heating (OC, EC, K, levoglucosan); traffic (EC, OC, Cu, Zn, NO<sub>3</sub><sup>-</sup>); industrial (SO<sub>4</sub><sup>2-</sup>, Pb, As, Cd); secondary (SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>); dust (Si, Ca, Al, Fe, Ti).

HYSPLIT & meteorological normalization: HYSPLIT calculated 72-hour back-trajectories [25]; random forest isolated meteorology ( $R^2=0.82$ , RMSE=9.4  $\mu\text{g}/\text{m}^3$ ) [26].

Health impact assessment: Population-weighted PM<sub>2.5</sub> via GWR ( $R^2=0.74$ , RMSE=8.2  $\mu\text{g}/\text{m}^3$ ) [27]. GBD exposure-response functions estimated mortality for five outcomes [28,29]. PAF =  $(RR(c)-1)/RR(c)$  with TMREL=2.4  $\mu\text{g}/\text{m}^3$ . Baseline mortality from GBD 2021; population from WorldPop (2020 extrapolated to 2025). Monte Carlo (10,000 iterations) quantified uncertainty.

## 3 Results

### 3.1. Long-Term Trends and Seasonal Patterns

Annual mean PM<sub>2.5</sub> concentrations ranged from 25.6  $\mu\text{g}/\text{m}^3$  (Dushanbe) to 38.4  $\mu\text{g}/\text{m}^3$  (Almaty), all substantially exceeding the WHO guideline of 5  $\mu\text{g}/\text{m}^3$ . Winter concentrations increased dramatically: Almaty (68.2  $\mu\text{g}/\text{m}^3$ ), Bishkek (65.8  $\mu\text{g}/\text{m}^3$ ), Tashkent (52.4  $\mu\text{g}/\text{m}^3$ ), and Dushanbe (48.6  $\mu\text{g}/\text{m}^3$ ). Peak daily concentrations exceeded 200  $\mu\text{g}/\text{m}^3$  in all cities, reaching 450  $\mu\text{g}/\text{m}^3$  during severe episodes. PM<sub>10</sub> concentrations were higher due to dust: annual means of 68.3  $\mu\text{g}/\text{m}^3$  (Almaty), 62.7  $\mu\text{g}/\text{m}^3$  (Bishkek), 55.8  $\mu\text{g}/\text{m}^3$  (Tashkent), and 52.1  $\mu\text{g}/\text{m}^3$  (Dushanbe). NO<sub>2</sub> was highest in Tashkent (32.5  $\mu\text{g}/\text{m}^3$ ) and Almaty (28.7  $\mu\text{g}/\text{m}^3$ ); SO<sub>2</sub> was elevated in Dushanbe (15.2  $\mu\text{g}/\text{m}^3$ ) and Almaty (12.8  $\mu\text{g}/\text{m}^3$ ). Significant decreasing trends were observed in Almaty (-3.2%/year,  $p<0.01$ ) and Tashkent (-2.1%/year,  $p<0.05$ ). Bishkek showed a non-significant increase (1.8%/year,  $p=0.08$ ). COVID-19 lockdowns in 2020 reduced PM<sub>2.5</sub> by 28% in Almaty, demonstrating anthropogenic contributions. Winter PM<sub>2.5</sub> was 2.5–3.5 times higher than summer. Temperature inversions occurred on 65–80% of winter days in Almaty and Bishkek (40–55% in Tashkent and Dushanbe), with strong correlation to PM<sub>2.5</sub> ( $r=0.72-0.81$ ,  $p<0.001$ ). Diurnal patterns showed bimodal peaks during morning (07:00–09:00) and evening (18:00–20:00) rush hours, with evening peaks more pronounced in Almaty and Bishkek due to heating.

### 3.2. Spatial Distribution

Ground-based interpolation revealed consistent intra-urban gradients: highest PM<sub>2.5</sub> in northern/western Almaty (private housing, industrial zones), western/southwestern Bishkek (informal settlements with coal heating), eastern Tashkent (industrial zones), and northern Dushanbe (industrial areas). Peri-urban solid fuel sources contributed significantly to city-wide pollution. TROPOMI NO<sub>2</sub> columns showed highest values over city centers and transportation corridors, decreasing 2–3 fold to rural areas. Urban plumes extended downwind (north-northeast in winter, northwest in summer). Satellite-ground agreement was good ( $r=0.68-0.75$ ). Plume extent increased 30–50% in winter. CALIPSO showed aerosols concentrated within 500–800 m during winter inversions, extending to 3–5 km during spring dust events.

### 3.3. Source Apportionment

PMF identified five source categories with bootstrap-derived 95% confidence intervals (BS-DISP, 200 runs): Residential heating (biomass/coal): Characterized by OC, EC, K, levoglucosan. Mean contributions (95% CI): Almaty 52% (47–57%), Bishkek 55% (50–60%), Tashkent 32% (28–36%), Dushanbe 28% (24–33%). CV = 0.09–0.12 (well-determined). Almaty vs. Bishkek differences within uncertainty (similar contributions); both significantly higher than Tashkent (CI non-overlap).

Traffic emissions: Characterized by EC, OC, Cu, Zn, NO<sub>3</sub><sup>-</sup>. Mean contributions (95% CI): Tashkent 28% (24–32%), Almaty 25% (21–29%), Bishkek 22% (18–26%), Dushanbe 18% (14–22%). Summer contributions 5–8% higher.

Industrial emissions: Characterized by SO<sub>4</sub><sup>2-</sup>, Pb, As, Cd. Mean contributions (95% CI): Dushanbe 20% (16–24%), Almaty 15% (12–19%), Tashkent 10% (7–13%), Bishkek 8% (5–11%). CV = 0.18–0.25 (moderate uncertainty due to limited heavy metal data).

Secondary aerosol: Characterized by SO<sub>4</sub><sup>2-</sup>, NO<sub>3</sub><sup>-</sup>, NH<sub>4</sub><sup>+</sup>. Winter contributions (95% CI): Almaty 30% (26–34%), Bishkek 28% (24–32%), Tashkent 22% (18–26%), Dushanbe 18% (14–22%).

Dust: Characterized by Si, Ca, Al, Fe, Ti. Spring/summer contributions (95% CI): Tashkent 35% (30–40%), Dushanbe 30% (25–35%), Almaty 25% (21–29%), Bishkek 22% (18–26%).

HYSPLIT analysis: Winter high-PM<sub>2.5</sub> days from stagnant local air masses (<5 m/s, 48–72 h). Spring/summer high-PM<sub>10</sub> days from desert air masses (10–15 m/s, Kyzylkum, Karakum, Aral Sea). Transboundary transport contributed 15–20% of high NO<sub>2</sub> days in Tashkent (southern Kazakhstan).

### 3.4. Health Impact Assessment

Estimated annual premature deaths attributable to PM<sub>2.5</sub> in 2025: Almaty (2,450; 95% UI: 1,980–2,980), Tashkent (3,120; 2,520–3,800), Bishkek (1,180; 950–1,440), Dushanbe (1,050; 840–1,290). Total: approximately 7,800 deaths annually (mortality rate 85–120 per 100,000). Disease distribution: ischemic heart disease (35–42%), stroke (25–32%), COPD (12–18%), lung cancer (8–12%), lower respiratory infections (5–8%). Older adults (65+ years) accounted for 55–65% of attributable mortality despite comprising only 10–15% of the population. Years of life lost totaled approximately 45,000 (Tashkent), 35,000 (Almaty), 17,000 (Bishkek), and 15,000 (Dushanbe), with average 12–15 years lost per death. Health burden decreased 8% in Almaty and 5% in Tashkent over the study period, consistent with PM<sub>2.5</sub> trends.

## 4 Discussion

This first multi-city air pollution assessment in Central Asia reveals annual PM<sub>2.5</sub> means of 25.6–38.4 µg/m<sup>3</sup>—a severe public health crisis comparable to South/East Asian industrializing cities [30]. Winter concentrations exceed WHO guidelines 10–20×, indicating months of acute and chronic health risks. Residential heating dominates winter PM<sub>2.5</sub> in Almaty (52%) and Bishkek (55%), identifying this as the primary intervention target. This aligns with Ulaanbaatar (coal heating) [31] and Krakow (coal ban success) [32]. Tashkent's lower contribution (32%) reflects greater natural gas use, suggesting fuel switching yields substantial benefits. Bootstrap uncertainty confirms Almaty/Bishkek vs. Tashkent differences are statistically significant, while the 52% vs. 55% difference between Almaty and Bishkek lies

within confidence intervals and should not be overinterpreted. Traffic emissions (20–30% summer year-round) support vehicle standards, electric vehicles, and public transit. Industrial emissions in Dushanbe and Almaty (15–25%) require source-specific controls. Dust (20–40% spring/summer) points to afforestation and land restoration. Spatial hotspots in peri-urban informal settlements suggest targeted clean fuel access and housing improvements. The health burden—7,800 annual premature deaths—compares to regional road traffic injuries (6,500–8,500) and tuberculosis (5,500–7,000) [29], underscoring urgency. Strengths: Multi-source data integration (ground, satellite, meteorological), complementary methods (trend analysis, PMF with bootstrap uncertainty, health assessment), multi-city design. Limitations: Sparse ground monitoring, limited speciated PM<sub>2.5</sub> data, global exposure-response functions may not fully capture local effects, PM<sub>2.5</sub> focus excludes other harmful pollutants.

Policy & SDG Nexus: Priority interventions (1) residential heating: clean fuel subsidies, stove replacement, district heating; (2) transport: emissions standards, electric vehicles, public transit; (3) industrial: pollution controls; (4) landscape: afforestation. Health burden addresses SDG 3.9; spatial patterns support SDG 11.6; residential heating interventions link to SDG 13.

## 5 Conclusions

This study provides the first comprehensive assessment of air pollution dynamics across Central Asia's major urban agglomerations (2015–2025). Key findings:

1. Persistently high PM<sub>2.5</sub>: Annual means 25.6–38.4 µg/m<sup>3</sup>, winter concentrations 2.5–3.5 times higher, driven by residential heating (52–55% in Almaty/Bishkek), temperature inversions, and reduced mixing.

2. Five source categories: Residential heating, traffic, industry, secondary aerosol, dust—with city-specific patterns reflecting energy sources and urban structure.

3. Substantial health burden: Approximately 7,800 premature deaths annually, predominantly from cardiovascular disease, with disproportionate impact on older adults.

4. Decreasing trends: Almaty (-3.2%/year) and Tashkent (-2.1%/year) show improvement; Bishkek and Dushanbe require urgent attention.

The integrated methodology demonstrates the value of combining ground and satellite data for understanding urban air pollution in data-sparse regions. Evidence-based priorities include residential heating interventions (Almaty, Bishkek), traffic controls (all cities), industrial source controls (Dushanbe, Almaty), and landscape restoration for dust reduction (Tashkent, Dushanbe). Future research should expand monitoring networks, refine source apportionment with local speciation data, and evaluate intervention effectiveness. The human toll is substantial and preventable; with sustained commitment and evidence-based interventions, rapid improvements are achievable.

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