Spatiotemporal evolution characteristics of winter atmospheric pollution events in the urban agglomeration on the northern slope of the Tianshan Mountains from 2000 to 2023: postprint

Authors: Zhixiang Yu, Yu Xiaojing, Chen Shiyong, Li Xia, Mei Zhen

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Abstract

Based on the 2000–2023 China High-Resolution Air Pollution (CHAP) near-surface air pollutant dataset, wintertime atmospheric pollution events in the cities along the northern slope of the Tianshan Mountains are identified using the Air Quality Index (AQI), and the spatiotemporal evolution characteristics of such metrics as annual mean number of polluted days, annual mean occurrence frequency, maximum duration, and intensity are clarified. The results show that: (1) Wintertime atmospheric pollutants in the urban agglomeration on the northern slope of the Tianshan Mountains are dominated by $PM_{2.5}$, and $PM_{2.5}$-dominated polluted days account for more than 95% of the total polluted days (AQI > 100). (2) From a climatological perspective, the characteristic quantities of wintertime atmospheric pollution events of different grades in the urban agglomeration on the northern slope of the Tianshan Mountains weaken gradually from the core cities Urumqi, Changji, and Shihezi (collectively referred to as "Wuchangshi") toward the surrounding areas. In the core region, the annual mean AQI exceeds 190, and the annual mean proportion of polluted days is more than 80%. Specifically, mild pollution events ($101 \leq$ AQI ≤ 150) in winter occur frequently and cover a wide area, with an annual mean of 25.7 days, a maximum annual mean occurrence frequency of 17.4 times $\cdot a^{-1}$, and a maximum duration of 29.0 days for a single pollution episode. Moderate pollution events ($151 \leq$ AQI ≤ 200) mostly occur in the central and eastern parts of the region, with an annual mean of 5 days, a maximum annual mean occurrence frequency of 14.5 times $\cdot a^{-1}$, and a maximum duration of 12.3 days for a single episode. Heavy and severe pollution events (AQI ≥ 201) are concentrated in the "Wuchangshi" area, where the AQI can exceed 500 and the maximum duration of a single pollution episode is 11.3 days, exhibiting an evolution characterized by "short duration and high intensity." (3) In most areas (75.8%) of the urban agglomeration on

the northern slope of the Tianshan Mountains, mild and moderate pollution events show a decreasing trend, whereas pollution events of heavy and above grades show an increasing trend in the "Wuchangshi" region. (4) There are significant inter-city differences in the characteristics of atmospheric pollution events among the nine key cities in the urban agglomeration on the northern slope of the Tianshan Mountains. Among them, Urumqi, Changji, and Shihezi are the most heavily polluted, followed by Wujiaqu, Kuitun, and Fukang, while Wusu, Karamay, and Bole experience the lightest pollution. In the "Wuchangshi" region, the intensity, annual mean number of days, annual mean occurrence frequency, and maximum duration of moderate and above pollution events are far higher than those in other cities, whereas Bole and Karamay are dominated mainly by mild pollution.

Full Text

Preamble

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Title

Spatiotemporal Evolution Characteristics of Winter Air Pollution Events in the Urban Agglomeration on the Northern Slope of Tianshan Mountains from 2000 to 2023

Authors

YU Zhixiang[1], **YU Xiaojing**[2], **CHEN Shiyong**[2], **LI Xia**[3], **MEI Zhen**[1]

[1] Urumqi Meteorological Satellite Ground Station, Urumqi 830011, Xinjiang, China
[2] College of Geography and Remote Sensing Sciences, Xinjiang University, Urumqi 830017, Xinjiang, China
[3] Institute of Desert Meteorology, Chinese Meteorological Administration, Urumqi 830002, Xinjiang, China

Abstract

Based on the China High Air Pollutants (CHAP) dataset from 2000 to 2023, this study identifies winter air pollution events in the urban agglomeration on the northern slope of Tianshan Mountains using the Air Quality Index (AQI) and analyzes the spatiotemporal evolution characteristics of key metrics including annual mean number of days, annual mean frequency, maximum duration, and intensity. The results demonstrate that: (1) PM2.5 is the dominant air pollutant during winter in this region, accounting for over 95.0% of total polluted days (AQI>100). (2) Climatologically, pollution characteristics for different grades show a gradual weakening from the Urumqi-Changji-Shihezi

core (hereafter "Urumqi-Changji-Shihezi") to surrounding areas, with the core region exhibiting annual mean AQI values exceeding 190 and polluted days accounting for over 80% of the winter season. Specifically, mild pollution events (101≤AQI$ 150)occurfrequentlyacrossbroadareas, withanannualmeanof25.7days, maximumannualmeanfr
a{-1}, andmaximumsingle − eventdurationof29.0days.Moderatepollutionevents(151 AQI 200)predominantlyaffectcentralandeastern
1}$ and maximum duration of 12.3 days. Heavy and severe pollution events (AQI$ 201)concentrateintheUrumqi−Changji−Shiheziregion, whereAQIpeakscanexceed650, annualmeand
$a^{-1}, and maximum single-event duration is 11.3 days, exhibiting a "short-duration, high-intensity" evolution pattern. (3) Mild and moderate pollution events show declining trends in 75.8% of the region, whereas heavy and above-grade pollution events exhibit increasing trends in the Urumqi-Changji-Shihezi core area. (4) Significant inter-city variations exist among the nine key cities in the urban agglomeration. Urumqi, Changji, and Shihezi suffer the most severe pollution, followed by Wujiaqu, Kuytun, and Fukang, while Usu, Karamay, and Bole maintain relatively cleaner air. The intensity, annual mean number of days, annual mean frequency, and maximum duration of moderate-to-severe pollution events in the Urumqi-Changji-Shihezi region substantially exceed those of other cities, whereas Bole and Karamay are primarily affected by light pollution.

Keywords: air pollution events; CHAP dataset; Air Quality Index (AQI); spatiotemporal evolution characteristics; urban agglomeration on the northern slope of Tianshan Mountains

Introduction

Intensifying human activities and industrial development have severely impacted the atmospheric environment. Emissions of greenhouse gases and pollutants have caused global warming and deteriorating air quality. Air pollution, characterized by persistence and diversity, not only directly harms human health but also triggers ecological and environmental problems through complex interactions among the atmosphere, hydrosphere, and biosphere. Regional aerosol pollutants (PM2.5) and gaseous pollutants (SO_2, NO_2, etc.) are emitted in large quantities from anthropogenic sources, significantly affecting the Earth-atmosphere system. Air pollution has become a global environmental priority and challenge. Under unfavorable meteorological conditions during winter half-year, the urban agglomeration on the northern slope of Tianshan Mountains experiences frequent continuous heavy pollution episodes, with regional air pollution problems becoming increasingly prominent, forming a new air pollution hotspot in China. The northern part of the region includes the Gurbantünggüt Desert, while the dried lakebed of Ebinur Lake to the west serves as a stable natural dust source, exposing the area to severe dust and salt aerosol threats. The 2022 Xinjiang Ecological Environment Bulletin reported that only 59.9% of cities in Xinjiang met national secondary air quality standards, far below the national average of 80.4%. The "Urumqi-Changji-Shihezi" region had good air quality on 28.6% of days, below the national level, while heavy and above-grade pollution days accounted for 11.3%, far exceeding the national average of 1.8%. Spatial distribution of pollutants is significant, with PM2.5 as the primary pollutant on 85.5% of polluted days. During winter 2020, Shihezi experienced 7 heavy pollution episodes lasting 1-3 days each, nearly continuous pollution. From 2017-2019, annual mean PM2.5 concentrations in the urban agglomeration ranged 53.22-65.74 $\mu g \cdot m^{-3}$, first increasing then decreasing, peaking in 2018. Seasonally, PM2.5 concentrations are "high in winter, low in summer," with monthly concentrations showing a "U-shaped" pattern, daily concentrations exhibiting "pulse-type" periodicity, and hourly concentrations displaying a bimodal pattern across all seasons, similar to other Chinese cities. Following China' s "dual carbon" target proposed in 2020, air pollution is expected to improve further. Therefore, understanding the spatiotemporal evolution characteristics of air pollution processes under carbon neutrality targets and statistically analyzing long-term changes in characteristic metrics such as annual mean days, annual mean frequency, maximum duration, and pollution intensity based on AQI is crucial for scientifically implementing regional air pollution control and understanding air quality improvements under the "dual carbon" target.

1.1 Study Area Overview

The urban agglomeration on the northern slope of Tianshan Mountains is located on the northern foothills of Tianshan Mountains and the southern margin of the Junggar Basin, covering approximately 1.2$×10^{5}$ km^2. It represents the core economic development zone of Xinjiang. Centered on Urumqi, the agglomeration includes major cities such as Changji, Shihezi, and Karamay, with a permanent population of about 6 million (nearly one-quarter of Xinjiang's total) and an urbanization rate exceeding 60%. The oasis economic belt formed by Tianshan snowmelt meltwater is rich in coal, oil, and natural gas resources, with an economic structure dominated by energy chemical industry and equipment manufacturing, serving as a key node in the Belt and Road Initiative. This study covers nine cities from Fukang in the east to Bole in the west, encompassing over 60% of Xinjiang' s heavy industry and over 70% of light industry. With rapid economic development, air pollution has become increasingly severe, making pollution research in this region essential.

Note: The base map was produced using the standard map from the Ministry of Natural Resources Standard Map Service (Map Approval No. GS(2017)3320), with no modifications to boundaries. The same applies hereafter.

[Figure 1: see original paper]

1.2 Data Sources

This study utilizes daily PM2.5 data from the China High-resolution High-quality Air Pollutant (CHAP) dataset. The CHAP dataset is generated using multi-source satellite remote sensing and artificial intelligence technology, employing a four-dimensional spatiotemporal approach to fill spatial gaps in

MODIS MAIAC AOD products. It integrates ground-based observations, atmospheric reanalysis, and emission inventories to produce seamless ground-level pollutant data across China. The dataset covers 2000–2023 (updated annually), includes PM2.5 and other parameters across China, has a spatial resolution of 1 km, and offers temporal resolutions of daily, monthly, and yearly averages.

1.3.1 Air Quality Index (AQI) Calculation

This study employs the Air Quality Index (AQI) to identify air pollution events. AQI quantitatively describes air quality status, where higher values indicate more severe pollution. Air quality is classified into six levels: Excellent (0–50), Good (51–100), Light Pollution (101–150), Moderate Pollution (151–200), Heavy Pollution (201–300), and Severe Pollution (>300). According to the Xinjiang Uygur Autonomous Region Environmental Status Bulletin, days with AQI>100 are defined as exceedance days. Based on pollutant concentrations from the CHAP dataset, individual air quality sub-indices (IAQI) are calculated to determine the primary pollutant, with AQI obtained as the maximum IAQI value. The specific calculation method is as follows:

$$AQI = \max(IAQI_1, IAQI_2, IAQI_3, \cdots, IAQI\ )$$

For each pollutant p, IAQI is calculated using a piecewise linear function based on its concentration C , where IAQI_{Hi} and IAQI_{Lo} represent the upper and lower bounds of the air quality sub-index corresponding to the concentration limits, and BP_{Hi} and BP_{Lo} represent the high and low breakpoint concentrations.

1.3.2 Characterization of Air Pollution Events

Based on run theory, different grades of air pollution events are identified and various characteristic metrics are statistically analyzed. Pollution intensity is defined as the number of pollution processes per year (occurrences $\cdot$ a^{-1}). Average duration represents the mean continuous period of multiple pollution processes (days), while maximum duration indicates the longest single pollution episode (days). The Spearman rank correlation test is applied for time series trend analysis and significance testing. This method ranks the sequence $x_1, x_2, \cdots, x$ in descending order, replacing each x with its rank R . The Spearman correlation coefficient (r) is then computed based on rank differences. At significance level α=0.05 and sample size n=24 (years), the critical value is $rs_{0\cdot05}$. When $|r| > rs_{0\cdot05}$, the trend is statistically significant; otherwise, it is not. This study further reconstructs the winter climatology of PM2.5 mass concentrations for the Tianshan northern slope region from 2000–2023 based on the CHAP dataset, maintaining consistent spatial resolution.

Analysis reveals a significant concentric structure in winter air quality, with a pollution intensity ridge forming along the Usu-Kuytun-Urumqi-Changji-Shihezi axis. The Urumqi-Changji-Shihezi region exhibits extreme AQI values exceeding 190, constituting the regional pollution core. Pollution intensity decreases gradiently outward, aligning with the spatial expansion pattern of the urban agglomeration.

Pollution zoning shows a three-tier structure: dominant good air quality areas (AQI$ $100) in the periphery, a middle ring of light pollution (101–150), and a moderate pollution core area (151-200) centered on the Urumqi-Changji-Shihezi metropolitan region, extending to southern Wujiaqu. Spatial distribution of exceedance day proportions (Fig. 2) demonstrates an outward diffusion pattern from the Urumqi-Changji-Shihezi core, with exceedance rates exceeding 50% in the core area, expanding to 20–50% in peripheral regions. This gradient distribution further reveals the spatial imbalance between urban development and atmospheric environmental carrying capacity, providing a scientific basis for identifying priority air pollution control zones.

2.1 Overall Distribution Characteristics of Winter Air Pollution

Previous research has validated the applicability of the CHAP dataset using ground-based monitoring stations (Fig. 2). The spatial distribution of winter exceedance day proportions exhibits an outward diffusion pattern centered on the Urumqi-Changji-Shihezi region. The core area shows exceedance rates exceeding 50%, expanding to 20–50% in surrounding areas. This gradient distribution further reveals the spatial imbalance between urban agglomeration development and atmospheric environmental carrying capacity, providing scientific guidance for delineating priority air pollution control zones.

2.2 Climatological Patterns of Winter Air Pollution Events

The CHAP dataset systematically reveals the climatological spatial patterns of different-grade air pollution events across the urban agglomeration on the northern slope of Tianshan Mountains during winter 2000–2023. Blank areas represent Lake Sayram and Lake Ebinur regions where CHAP data are unavailable.

[Figure 2: see original paper]

Figure 2 shows the spatial distributions of annual mean AQI, changing trends, and exceedance day proportions. The annual mean AQI and annual mean number of days for different pollution grades are presented in Figure 3. The analysis demonstrates significant geographical gradients, with pollution intensity increasing from southwest to northeast across grades. Heavy and severe pollution events concentrate in the central-eastern part of the urban agglomeration.

**Light Pollution (101≤AQI$ 150) : **Thisgradeshowsthemostextensivecoverageandsignificantspatialvaria
easternregionsexhibitvaluesof170–180.Theannualmeannumberofdaysis25.7, withthehighestannualmeanfr
a^{-1}$. Maximum single-event duration reaches 29.0 days, indicating persistent pollution characteristics.

**Moderate Pollution (151≤AQI$ 200) : **Theaffectedareacontractssignificantly, withminimalpollutionrec
easternregionsshowannualmeanAQIvaluesof170–180, withlocalextremevaluesexceeding180insoutheasternl
a^{-1}$ and maximum duration of 12.3 days. Notably, Changji exhibits a "dual-high" pattern for moderate pollution, maintaining the highest frequency while also showing the longest average duration (4.0 days) and maximum single-event duration (12.3 days), establishing it as the regional pollution core.

Heavy Pollution (201≤AQI$ $300): The affected area shifts further northeast, with extreme values appearing near Lake Ebinur and Karamay. A pollution corridor forms along the Usu-Kuytun-Shihezi-Changji-Urumqi axis, where annual mean days exceed 30, with local maxima reaching 50-60 days, constituting persistent pollution hotspots. The annual mean number of days for heavy pollution is 5-6, accounting for 59.4% of the total area, with maximum AQI values exceeding 500.

Severe Pollution (AQI$ $301): This grade occurs primarily in the northeastern area, with regions exceeding 5-6 annual mean days comprising only 0.16% of the total area. The maximum single-event duration reaches 29.0 days, with an average duration peak of 12.5 days, demonstrating significant persistent pollution characteristics.

Regarding frequency and duration, all metrics show stepwise decreasing trends with progressively narrowing high-value zones. Light pollution occurs frequently across broad areas, with the highest frequency zone (17.4 occurrences $\cdot$ a^{-1}) concentrated along the Usu-Kuytun-Urumqi-Changji corridor. Moderate pollution high-frequency zones (14.5 occurrences $\cdot$ a^{-1}) shift to the Urumqi-Changji-Shihezi region, with average duration of 4.0 days. Heavy pollution high-frequency zones (4.0 occurrences $\cdot$ a^{-1}) contract to the Urumqi-Changji-Shihezi area, with average duration of 3.9 days, though maximum single-event duration reaches 11.3 days, indicating that specific meteorological conditions can still produce persistent heavy pollution. Severe pollution shows a dispersed distribution pattern, mainly in Changji, Urumqi, and Wujiaqu, with frequency of 2.8 occurrences $\cdot$ a^{-1}, average duration of 1.8 days, and maximum duration of 5-10 days.

[Figure 3: see original paper] [Figure 4: see original paper]

2.3 Long-term Variation Trends

To quantitatively evaluate temporal changes in winter pollution events across different grades, the Spearman rank correlation test was applied to analyze long-term trends and significance. Figure 5 presents the spatial distributions of trends for annual mean days, annual mean frequency, and maximum duration.

Annual Mean Number of Days: Light pollution shows decreasing trends in 75.8% of the region, particularly in southern and southeastern edges (69.3% of area). Significant increasing trends appear in northern Karamay and eastern Bole (30.7% of area). Moderate pollution exhibits typical spatial oscillation, alternating between increase, decrease, and increase from south to north. Areas with increasing trends account for 37.3%, with significant increases in the central Tianshan northern slope core. Heavy pollution annual mean days show increasing trends across the study area, with significant increases comprising 24.2% of the area, located in the northeastern corner, scattered Karamay areas, and the Urumqi-Changji-Shihezi region.

Annual Mean Frequency: Trends in frequency and maximum duration are generally consistent with those of annual mean days. Light pollution frequency shows decreasing trends in 75.8% of the region. Moderate, heavy, and severe pollution frequencies exhibit increasing trends in the Urumqi-Changji-Shihezi core.

[Figure 5: see original paper]

2.4 Characteristics of Key Cities

Nine key cities were selected for detailed analysis: Bole, Karamay, Usu, Kuytun, Shihezi, Changji, Wujiaqu, Urumqi, and Fukang. Table 1 and Figure 6 show the total polluted days and annual mean days by pollution grade for these cities.

Table 1 Total Polluted Days and Proportion of Days with Each Primary Pollutant in Key Cities (Winter 2000–2023)

City	Total Polluted Days by Grade	Primary Pollutant Proportion (%)
	Light	Moderate
Urumqi	650+	500+
Changji	650+	500+
Shihezi	650+	500+
Wujiaqu	400-500	200-300
Kuytun	300-400	100-200
Fukang	300-400	100-200
Usu	200-300	50-100
Karamay	100-200	<50
Bole	100-200	<50

The pollution intensity gradient among the nine cities is significant. Urumqi, Changji, and Shihezi show the most severe pollution, with total moderate-pollution days averaging over 500, heavy-pollution days over 200, and severe-pollution days far exceeding 50. Wujiaqu and Fukang rank second, with moderate pollution levels. Usu and Kuytun experience more light pollution but no severe pollution. Bole and Karamay have relatively light pollution with minimal heavy and above-grade events. PM2.5 is the primary pollutant across all cities, accounting for over 95.0% of polluted days (exceeding 99.3% in Urumqi, Changji, and Shihezi), indicating fine particulate matter is the core winter pollutant. PM10 proportions are slightly higher in Usu and Changji (likely due to local dust or sandstorms), but winter snowfall in the study area suppresses dust and promotes settling, reducing PM10 contributions.

[Figure 6: see original paper]

Figure 7 presents heatmaps of annual occurrence days, frequency, and maximum duration for each city. Light pollution days show decreasing trends in all cities, particularly after 2013, with Wujiaqu and Fukang showing the most significant reductions (1.5 and 0.9 days $\cdot$ a^{-1}, respectively). Moderate pollution days decreased in Shihezi, Changji, Urumqi, and Fukang (Shihezi: -1.0 days $\cdot$ a^{-1}; Urumqi: -0.9 days $\cdot$ a^{-1}), while increasing in other cities (Usu fastest at +0.9 days $\cdot$ a^{-1}). Heavy and severe pollution days are fewer but show upward trends after 2013, particularly in Shihezi, Changji, Wujiaqu, and Urumqi (heavy pollution increasing at 0.1-0.3 days $\cdot$ a^{-1}; severe pollution at 0.1-0.2 days $\cdot$ a^{-1}). Extreme events still occur occasionally, such as severe pollution episodes in Urumqi (2021) and Wujiaqu (2022), and heavy pollution in Shihezi (2023), indicating the arduous task of air pollution control.

Light pollution frequency decreased in all cities, especially after 2013, typically to 10-15 occurrences per year. Shihezi and Changji showed the largest declines. Moderate pollution frequency decreased in Urumqi, Shihezi, Changji, and Fukang (though trends were not significant), while increasing in other cities (Usu fastest at +0.5 occurrences $\cdot$ a^{-1}). Heavy and severe pollution frequencies increased in all cities with severe pollution events. Urumqi showed the fastest increase in severe pollution frequency (+0.3 occurrences $\cdot$ a^{-1}). Overall, Urumqi, Changji, and Shihezi have significantly higher pollution frequencies than other cities (e.g., Bole, Karamay, Usu), which show lower frequencies and smaller interannual variations.

Maximum duration of light and moderate pollution episodes ranges 8-12 days, generally decreasing (Wujiaqu showing the largest decrease). Karamay' s light pollution maximum duration reached 12.3 days. Heavy and severe pollution maximum durations increased in most cities, particularly after 2013 in Urumqi, Changji, and Shihezi (increasing by 0.2-0.5 days $\cdot$ a^{-1}). Heavy pollution maximum durations exceeded 15 days in Urumqi (2021) and Shihezi (2022), while severe pollution maximum durations reached 5-10 days in Wujiaqu (2022) and Changji (2023).

[Figure 7: see original paper]

Discussion

As a core economic development zone in northwestern arid regions, the urban agglomeration on the northern slope of Tianshan Mountains exhibits both common patterns with central and eastern Chinese urban agglomerations and unique regional characteristics. This study reveals the spatial distribution and temporal evolution of different-grade pollution events, statistically analyzing long-term changes in intensity, annual mean days, annual mean frequency, average duration, and maximum duration. The findings are consistent with previous research. Industrial production capacity and population consumption are concentrated in Urumqi, Changji, and Shihezi, where frequent winter temperature inversions create a "lid effect" that traps pollutants, making this region particularly vulnerable to severe pollution and forming a concentric pollution structure that reflects the synergistic effects of economic development patterns and meteorological factors.

After implementing the "Blue Sky Project" in 2013 and the "coal-to-gas" conversion after 2017, the annual mean frequency of light and moderate pollution events decreased significantly, directly attributable to measures such as coal-fired boiler retrofits and ultra-low emission transformations in the steel industry. However, the countervailing increase in heavy and severe pollution events in the core area may be related to atmospheric environmental capacity threshold effects and pollutant accumulation under extreme weather conditions. In 2021, the Xinjiang Uygur Autonomous Region Party Committee and Government issued the "14th Five-Year Plan for Ecological Environmental Protection," setting clear requirements for air quality improvement during the plan period. While overall air quality has improved, high emissions from traditional industries such as steel, cement, and coking may still cause short-term, heavy-pollution events.

Following China' s "dual carbon" target proposed in 2020, regional air pollution control efforts have intensified, leading to significant reductions in the annual mean frequency and average duration of light and moderate pollution events in the urban agglomeration. However, heavy and above-grade pollution events require continued attention. Future efforts must integrate the "dual carbon" target, optimize energy structure, and strengthen regional joint prevention and control mechanisms to achieve long-term scientific governance of air pollution.

Conclusions

This study systematically analyzes winter air pollution events in the urban agglomeration on the northern slope of Tianshan Mountains from 2000–2023, revealing distinct spatiotemporal evolution patterns:

1. **Spatial Distribution Characteristics:** Pollution exhibits a clear concentric structure, with intensity decreasing gradiently along the Urumqi-Changji-Shihezi-Usu-Kuytun axis. The core region (Urumqi-Changji-Shihezi) shows exceedance day proportions exceeding 50%, diffusing outward with decreasing intensity. Light pollution events have the broadest coverage, with annual mean days reaching 50–60 in the Urumqi-Changji-Shihezi region. Moderate pollution concentrates in central-eastern areas with enhanced intensity. Heavy and severe pollution events are mainly confined to the Urumqi-Changji-Shihezi region, featuring fewer annual days and lower frequency but extremely high intensity. In terms of duration, light and moderate events show strong persistence with maximum single-event durations up to 29.0 days,

while heavy and severe events are shorter and more episodic.

2. **Long-term Trends:** Light and moderate pollution events show significant decreasing trends across 75.8% of the region, indicating effective pollution control. Conversely, heavy and severe pollution events exhibit increasing trends in the core Urumqi-Changji-Shihezi region, with rising pollution intensity, annual mean frequency, and maximum duration, presenting ongoing challenges for controlling high-grade pollution events.
3. **Inter-city Variations:** Pollution severity ranks as: Urumqi, Changji, and Shihezi (most severe); Wujiaqu, Kuytun, and Fukang (moderate); Usu, Karamay, and Bole (lightest). The Urumqi-Changji-Shihezi region shows substantially higher annual mean days for moderate and heavy pollution and frequent severe pollution events compared to other cities. Bole and Karamay experience relatively light pollution dominated by light-grade events. PM2.5 is the primary pollutant across all cities, accounting for over 95% of polluted days.

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Note: Figure translations are in progress. See original paper for figures.