Variation Characteristics and Potential Source Analysis of Atmospheric Pollutant Concentrations: A Case Study of Urumqi (Postprint)

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Abstract

Statistical analysis was performed on meteorological parameters and atmospheric pollutant concentrations in Urumqi for the year 2017, the variation characteristics of atmospheric pollutant concentrations were examined, and trajectory cluster analysis, Potential Source Contribution Function (PSCF), and Concentration Weighted Trajectory (CWT) method were utilized to investigate the transport pathways and potential source regions of PM2.5 in Urumqi. The results demonstrate that: the primary atmospheric pollutants exceeding standards in Urumqi are PM2.5 and PM10; with the exception of O3, concentrations of all pollutants are higher during the heating period than during the non-heating period; low temperature, low wind speed, high relative humidity, Urumqi' s topographical feature of being surrounded by mountains on three sides, and temperature inversion weather constitute important factors contributing to severe particulate matter pollution during the heating period; regional transport of PM2.5 predominantly originates from the northwest direction, and during the heating period, it is substantially influenced by short-distance transport air masses from Nileke County, Shawan County, Hutubi County, and Fukang City; potential source regions of PM2.5 are primarily concentrated in Fukang City, Hejing County, Shawan County, Changji City, Shawan County, Jimsar County, and Manas County; PM2.5 concentrations in Urumqi are concurrently affected by both external pollutant input and local pollution source emissions.

Full Text

Abstract

Meteorological parameters and atmospheric pollutant concentrations in Urumqi during 2017 were statistically analyzed to investigate the concentration variation characteristics of air pollutants. Trajectory cluster analysis, potential source contribution function (PSCF), and concentration weighted trajectory (CWT) methods were employed to identify the transport pathways and potential source regions affecting the city. The results indicate that the primary pollutants exceeding national standards in Urumqi were PM2.5 and PM10. Concentrations of all pollutants except O3 were significantly higher during the heating period than during the non-heating period. Low temperatures, low wind speeds, high relative humidity, the city's topography surrounded by mountains on three sides, and frequent temperature inversion events were identified as critical factors contributing to severe particulate pollution during the heating season. Regional transport originated mainly from the northwest, with short-distance transport from Nileke County, Shawan County, Hutubi County, and Fukang City exerting substantial influence during the heating period. The primary potential source regions for PM2.5 were concentrated in Fukang City, Hejing County, Shawan County, Changji City, Jimusaer County, and Manasi County. PM2.5 concentrations in Urumqi were affected by both external pollutant input and local emission sources.

Keywords: atmospheric pollutants; concentration characteristics; backward trajectory; transport pathway; potential source region

Introduction

In recent years, rapid economic development, industrialization, and urbanization, coupled with increased fossil fuel consumption and vehicle ownership, have led to severe atmospheric pollution in China, reducing visibility, affecting agricultural production and public safety, and posing significant health risks. The nature of air pollution in China has shifted from simple coal smoke pollution to complex composite pollution. In addition to local emission sources, meteorological conditions, and topography, cross-regional pollutant transport plays a crucial role in determining local air quality. The characteristics of inter-regional pollutant diffusion and transport can be investigated using backward trajectory models, potential source contribution function analysis, and concentration weighted trajectory methods.

Numerous studies have systematically examined pollutant transport and source identification in various regions. For example, trajectory model studies have shown that during the heating period in Tangshan in 2016, PM2.5 was influenced by air masses from Beijing, Tianjin, and western Tangshan with frequencies of 36.7%, 32.7%, and 30.6%, respectively. Research on the Sichuan Basin identified southeastern and western regions as the primary potential sources of PM2.5 for Chengdu. Studies using backward trajectory models have demonstrated that during heavy pollution episodes in Beijing, high particulate concentrations resulted from the combined effects of primary pollutant accumulation, secondary pollutant formation, and long-range transport from surrounding areas.

Reports on Urumqi' s atmospheric environment have primarily focused on pollution status assessment, spatiotemporal distribution characteristics, and source apportionment, with relatively few studies examining pollutant transport features and their impacts. Ren et al. used backward trajectory models to analyze daily PM2.5 air mass trajectories in Taiyuan during 2016, revealing that spring, autumn, and winter transport pathways were dominated by short-distance, slow-moving trajectories from the west and northwest, while summer transport came mainly from the south and east. Zhang et al. employed backward trajectory models to study PM2.5 transport pathways and potential sources during different seasons in Taiyuan. Given this research gap, we conducted a comprehensive statistical analysis of six atmospheric pollutants and related meteorological parameters in Urumqi during 2017 to investigate concentration variation characteristics and, using backward trajectory modeling combined with PSCF and CWT methods, to examine transport pathways and potential source impacts. This study aims to provide scientific support for understanding Urumqi's air pollution and formulating effective control measures, offering reference significance for regional joint prevention and control efforts.

1.1 Study Area Overview

Urumqi is located on the northern foothills of the Tianshan Mountains in central Xinjiang, on the southern edge of the Junggar Basin. The city is surrounded by mountains on its east, south, and west sides, and sits at the northern opening of the Tianshan Mountain pass, with the southern end of the pass connecting to the Turpan Basin, earning it the designation of a "mountain-pass city." Urumqi experiences a mid-temperate continental arid climate, with an average annual precipitation of $ $200 mm and average annual temperature of -15.2~25.7 °C. Due to its unique geographical location, the city suffers from intense summer heat and long, cold winters, resulting in an extended heating period. Before 2012, coal was the primary energy source, particularly during the long winter heating season, which frequently caused severe atmospheric pollution. During the "Eleventh Five-Year Plan" period, Urumqi ranked last among 113 key environmental protection cities in national urban environmental comprehensive improvement assessments. In January 2013, Urumqi' s air quality remained at level 5 (heavy pollution) for 26 consecutive days, ranking last among 74 environmental protection cities. Since 2012, the city has continuously implemented a "coal-to-gas" conversion program, gradually shifting to a natural gas-dominated energy structure, which significantly improved its ranking among 74 key monitored cities nationwide and made it one of the cities with the most notable air quality improvement.

1.2 Data Sources

Mass concentration data for PM2.5, PM10, SO2, NO2, CO, and O3 were obtained from the Xinjiang Uygur Autonomous Region Environmental Monitoring Center Station (87.572176°E, 43.870369°N). This monitoring station is a national first-class environmental monitoring station and serves as an urban evaluation point, reflecting the overall air quality of Urumqi' s urban area. Daily average values for temperature, humidity, wind speed, and visibility were sourced from the Xinjiang Meteorological Bureau website (http://172.23.163.249/RadatDoc/WeatherService.aspx). Meteorological data for backward trajectory modeling were obtained from the National Centers for Environmental Prediction (NCEP).

1.3 Research Methods

Using the Xinjiang Uygur Autonomous Region Environmental Monitoring Center Station in Urumqi as the starting point, we employed the HYSPLIT backward trajectory model combined with cluster analysis, PSCF analysis, and CWT analysis to investigate pollution sources and transport pathways. The simulation starting height was set at 500 m, with a grid size of 0.2°$×$0.2°. The standard values referenced were the secondary daily concentration limits from the "Ambient Air Quality Standards" (GB3095-2012). The study period was divided as follows: November 2017–March 2018 as the heating period, April–May and September–October 2017 as transition periods, and June–August 2017 as the non-heating period.

2.1 Meteorological Factors Analysis

Figure 1 shows the daily variation of meteorological parameters in Urumqi during 2017. During the heating, transition, and non-heating periods, the average daily temperatures were 12.2$±1.7°C, −5.6±1.0°C, and21.0±1.0°C, respectively; averagerelativehumidityvalu
s{-1}, 0.9±0.1m · s{-1}, and1.5±0.1m·s{-1}, respectively.Visibilityvalueswere8.0±0.6km, 3.0±0.3km, and9.2±0.2km, respectively.
1}$). Temperature inversions frequently occur in winter, resulting in stable atmospheric stratification. Urumqi' s unique topography and meteorological conditions are highly unfavorable for pollutant diffusion. Lower visibility corresponds to lower temperatures and wind speeds but higher humidity. Spearman correlation analysis revealed that visibility was significantly negatively correlated with humidity ($r < 0.01$) and positively correlated with wind speed ($r = 0.353$) and temperature ($r = 0.890$). The heating period is characterized by high relative humidity, low wind speed, low temperature, and low visibility, creating conditions conducive to temperature inversion events and severe pollution episodes.

2.2 Characteristics of Atmospheric Pollutant Concentration Variations

Figure 2 shows the monthly variation of PM2.5, PM10, SO2, NO2, CO, and O3 concentrations in Urumqi during 2017. The annual average daily PM2.5 concentration was below the secondary standard limit, but 30.1% of days exceeded the 75 $g·m^{-3}$ daily standard, and 15.5% of days exceeded the 80 $g·m^{-3}$ daily standard, indicating that PM2.5 was the primary pollutant exceeding standards. The monthly concentration trends for all pollutants except O3 showed a

"U-shaped" distribution, with heating period concentrations significantly higher than non-heating period concentrations and substantial intra-monthly fluctuations. Conversely, O3 showed an inverted "U-shaped" distribution, with non-heating period concentrations higher than heating period concentrations.

Urumqi implemented a natural gas substitution strategy for coal-based heating in 2017, which led to a notable decreasing trend in SO2 concentration. However, some exceedances still occurred, likely related to the increasing vehicle ownership in recent years. By the end of 2017, Urumqi had 1.10×10^{6} motor vehicles, with 8.53×10^{5} private cars. Nitrogen oxide control measures have lagged behind, and mobile source emissions have become increasingly prominent. Li et al. found that vehicle emissions in Urumqi have exceeded coal combustion as a pollution source, indicating a shift to a composite pollution pattern characterized by both exhaust and coal pollution. O3 is photochemically generated, and strong solar radiation and elevated temperatures during the non-heating period, combined with low particulate concentrations and weak light extinction, result in higher O3 concentrations during the non-heating period compared to the heating period.

2.3 Analysis of PM2.5 Transport Pathways

Using the HYSPLIT model combined with cluster analysis, air masses reaching Urumqi originated primarily from four directions (Figure 3). The frequency distribution of trajectory clusters during different periods is shown in Figure 4. Trajectory cluster A represents short-distance transport from the west, occurring during heating, non-heating, and transition periods, passing through Nileke County, Shawan County, and Hutubi County. These areas have relatively high PM2.5 concentrations, and the short transport distance and slow air mass movement hinder pollutant dispersion, resulting in high average PM2.5 concentrations ($73.93\ \text{g}\cdot\text{m}^{-3}$). Trajectory cluster B represents long-distance transport from the northwest, appearing during all three periods with similar frequencies, passing through Wusu City, Bole City, Changji City, Jinghe County, Wenquan County, Shawan County, and Hutubi County. Although this cluster accounted for the smallest proportion of total trajectories (11.64%), its corresponding PM2.5 concentration was not low ($50.13\ \text{g}\cdot\text{m}^{-3}$), and its impact on Urumqi' s air quality cannot be ignored.

Trajectory cluster C, distributed in the northeast direction with a circuitous path, represents short-distance transport from no fixed dominant direction, occurring mainly during the heating period and accounting for a large proportion. Due to low wind speeds and frequent calm, inversion conditions during the heating period, this cluster moves slowly, is not easily dispersed, and has a short transport distance, resulting in the highest average PM2.5 concentration ($75.22\ \text{g}\cdot\text{m}^{-3}$). This cluster transports pollutants from Fukang City to Urumqi, exerting the greatest impact on the city' s air quality. Trajectory cluster D represents long-distance transport from the northwest, occurring mainly during the non-heating period with a frequency of only 3.36% during the heating period, passing through Hutubi County, Karamay City, Toli County, and Yumin County. This cluster moves quickly, is easily dispersed, and has a long transport distance, resulting in the lowest average PM2.5 concentration (29.34 $g \cdot m^{-3}$) and minimal impact on Urumqi.

During the heating period, PM2.5 pollution in Urumqi was dominated by trajectory cluster A, representing short-distance transport from surrounding Nileke County, Shawan County, Hutubi County, and Fukang City, which accounted for 70.65% of pollution trajectories with an average PM2.5 concentration of 136.94$±55.24$\mu g \cdot m^{\{-3\}.Duringthenon-heatingperiod,trajectoryclusterDdominated,withairmassesfromthewest,northwest,an}$
3}$. Overall, regional transport to Urumqi originated mainly from the northwest, with short-distance transport accounting for 69.94% of heating period trajectories, indicating that heating period PM2.5 pollution is strongly influenced by regional short-distance transport.

2.4 Analysis of PM2.5 Potential Source Regions

Potential source contribution analysis and concentration weighted trajectory calculations identified the spatial distribution of potential pollution sources and their contribution to PM2.5 concentrations in Urumqi (Figure 5). Higher WPSCF values indicate greater influence and contribution to Urumqi' s PM2.5 concentration. During the heating period, high WPSCF values were concentrated in Fukang City, Hejing County, Shawan County, Changji City, Jimusaer County, and Manasi County, with values exceeding 0.6. Areas with WPSCF values between 0.4 and 0.6 included Shawan County, western Fukang City, Jimusaer County, Toksun County, and Manasi County. These regions have strong pollution emission sources that contribute significantly to PM2.5 concentrations in Urumqi. The WCWT analysis yielded similar results, with high values concentrated in Hejing County, Shawan County, and Fukang City. Areas contributing PM2.5 concentrations of 60-90 $g \cdot m^{-3}$ included Manasi County, Hutubi County, Changji City, Miquan City, and Jimusaer County, indicating strong emission sources in these regions. Areas contributing 30-60 $g \cdot m^{-3}$ included Turpan City, Toksun County, Xinyuan County, and Karamay City, which had relatively smaller contributions to Urumqi' s PM2.5 concentrations.

Notably, WPSCF values in Urumqi' s immediate vicinity were also high (>0.6), with local PM2.5 emissions exceeding 90 $g \cdot m^{-3}$, indicating substantial local pollution sources. Therefore, Urumqi must address both external pollutant input and local emission sources in its pollution control strategies.

Conclusions

1) In 2017, concentrations of all atmospheric pollutants in Urumqi except O3 were higher during the heating period than during the non-heating period. The primary pollutants exceeding standards were PM2.5 and PM10. During the heating period, PM2.5 and PM10 daily concentrations exceeded standard limits on 98.2% and 87.5% of total exceedance days, respectively.

The extended heating period, characterized by low temperatures, low wind speeds, high relative humidity, and special topography conducive to temperature inversion, created conditions favorable for sustained particulate pollution episodes, making it the period of most severe and concentrated pollution.

2) Regional transport of PM2.5 to Urumqi originated mainly from the northwest, with short-distance transport dominating (accounting for 69.94% of trajectories). During the heating period, short-distance transport air masses from surrounding Nileke County, Shawan County, Hutubi County, and Fukang City exerted substantial influence on Urumqi' s air quality.

3) WPSCF and WCWT analyses identified high-value regions concentrated in Fukang City, Hejing County, Shawan County, Changji City, Jimusaer County, and Manasi County. PM2.5 concentrations in Urumqi were influenced by both external pollutant input and local emission sources.

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