Postprint: Classification of Low-Level Flow Fields during Severe Pollution Episodes in Guanzhong, Shaanxi

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Abstract

Utilizing PM2.5 monitoring data from 2014–2019 for five cities in the Guanzhong region of Shaanxi Province (Xi' an, Xianyang, Weinan, Tongchuan, and Baoji), representative years were selected based on each city' s Air Quality Index (AQI) to define regional pollution and heavy pollution events in the Guanzhong region. Combined with WRF (Weather Research & Forecasting model) simulation data for Shaanxi, flow patterns affecting the Guanzhong region were classified, and the relationship between each flow pattern type and PM2.5 concentrations was investigated. The results indicate that: (1) Based on the low-level flow field in the Guanzhong region, heavy pollution day flow patterns were classified into four major categories: easterly inflow (A–C), westerly/southerly inflow (D–F), northerly inflow without turning (G), and no significant flow pattern (H). According to occurrence time and location, the easterly inflow category was further subdivided into northeasterly inflow (A), nocturnal northeasterly inflow (B), and Weinan orographic flow (C), while the westerly/southerly inflow category was subdivided into southwesterly/southerly inflow (D), northerly inflow with turning (E), and Baoji inflow (F), totaling eight types labeled A through H. (2) During regional heavy pollution events, easterly inflow occurred most frequently, reaching a frequency of 59.8%, with types B and C each accounting for more than 25.0%. Significant diurnal variations were observed in flow pattern types; in daytime (08:00–19:00) flow patterns, type C occurred most frequently, whereas in nighttime (20:00–07:00) flow patterns, types B, E, and F were more active, with type B occurring most frequently. Additionally, types A, D, G, and H occurred more frequently at night than during the day. (3) Heavy pollution in the Guanzhong region occurred mainly in winter. Apart from increased pollutant emissions from heating, low-level flow fields exerted a significant influence on pollutant dispersion. From the perspective of flow pattern classification, stagnant weather conditions, mountain-valley winds, and

pollutant transport from the north were the primary causes of heavy pollution in the Guanzhong region.

Full Text

Low-level Streamline Field Typing of Heavy Pollution Weather in the Guanzhong Region of Shaanxi Province

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Abstract: Based on pollution index data from five cities in the Guanzhong region of Shaanxi Province (Xi' an, Xianyang, Weinan, Tongchuan, and Baoji) from 2014 to 2019, combined with Weather Research and Forecasting (WRF) model simulation data from the same period, this study screened representative years, defined regional pollution and regional heavy pollution weather processes, classified the low-level streamline fields affecting the Guanzhong region, and examined the relationships between PM2.5 concentrations and various flow field types. The results show that: (1) According to the low-level flow fields over the Guanzhong region, heavy pollution weather days can be classified into four major categories: eastern inflow (A–C), southern inflow (D–F), northern non-turning inflow (G), and weak flow field (H). Based on occurrence time and location, these can be further divided into eight specific types. The eastern inflow category includes northeast inflow (A), nighttime northeast inflow (B), and Weinan mountain-circumventing inflow (C). The southern inflow category includes southwest/southern inflow (D), northern turning inflow (E), and Baoji inflow (F). (2) Eastern inflow occurred most frequently during regional heavy pollution processes, accounting for 59.8% of cases, with types B and C each exceeding 25.0% frequency. The diurnal variation of flow field types was substantial: during daytime (08:00–19:00), type C was most active with nearly 40.0% frequency, while at night (20:00–07:00), type B dominated with nearly 50.0% frequency, followed by types E and F. (3) PM2.5 concentrations varied significantly across different flow field types, with types D and E showing higher concentrations. Mountain-valley wind patterns in types A, B, C, and D readily formed vortex flows in the Guanzhong region, causing pollutant accumulation and increased PM2.5 concentrations. In 2017, type H flow fields appeared 83 times with an average PM2.5 concentration of 203.4 $\mathrm{g \cdot m^{-3}}$. Regional heavy pollution in the Guanzhong region occurred primarily in winter. Beyond increased emissions from heating, low-level flow fields significantly affected pollutant dispersion, with stable weather conditions, mountain-valley winds, and northern pollutant transport representing the main causes of heavy pollution.

Keywords: Guanzhong region in Shaanxi Province; low-level streamline field typing; regional heavy pollution weather process

1 Study Area Overview

The Guanzhong region of Shaanxi Province lies between the northern slopes of the Qinling Mountains and the southern edge of the Loess Plateau, situated between northern Shaanxi plateau and the Qinling mountain range. It extends from Baoji Gorge in the west to Tongguan in the east, with elevations ranging from 460–850 m. This area features a subtropical monsoon climate characterized by hot, rainy summers and mild, dry winters. The Guanzhong region represents Shaanxi’ s most developed area for industry and agriculture, with dense population, significant transportation advantages, profound historical and cultural heritage, a complete modern industrial system, strong innovative capabilities, and an increasingly sound urban system, giving it a unique strategic position in China’ s modernization and comprehensive opening-up pattern.

From 2014 to 2019, the Guanzhong region experienced 178 pollution days and 56 heavy pollution days. The year 2017 had the highest number of pollution days and ranked among the years with more heavy pollution days, making it a representative year for analysis. Most heavy pollution days occurred during the winter heating period (November–March), with PM2.5 as the primary pollutant. One heavy pollution event in May was caused by dust storms, which is fundamentally unrelated to haze formation. Therefore, this study focuses exclusively on PM2.5-related pollution closely associated with haze prevention and control.

2.1 Data Sources

Air Quality Data: We used Air Quality Index (AQI) and PM2.5 concentration data from five cities in the Guanzhong region (Xi’ an, Xianyang, Weinan, Tongchuan, and Baoji) from 2014 to 2019 to screen representative years. Data from the period when PM2.5 monitoring began in these cities were selected for analysis.

Meteorological Data: We employed NCEP DS083.2 reanalysis data as initial and boundary fields, combined with NCEP DS337.0 upper-air and surface observational data for 3DVar assimilation. The WRF model was configured with triple nested grids over Shaanxi Province, achieving 3 km $\times$ 3 km horizontal resolution in the innermost domain and approximately 10 m vertical resolution near the surface. The model generated hourly meteorological data for 2017 to describe regional flow fields, providing foundational data for analyzing heavy pollution in the Guanzhong region.

2.2 Research Methods

Regional Pollution Day: Defined as a day when three or more cities in the Guanzhong region (Xi’ an, Xianyang, Weinan, Tongchuan, and Baoji) experienced air quality exceeding Grade II standards.

Regional Heavy Pollution Day: Defined as a day when three or more cities in the Guanzhong region experienced moderate or heavier pollution levels.

Low-level Flow Field: Due to urban development, the 10 m flow field is significantly affected by underlying surface conditions and lacks representativeness. Therefore, this study compared the correspondence between 100 m flow fields and typical pollution processes, concluding that the 100 m flow field is more representative. We classified flow field types at this level and focused on analyzing the relationship between each flow field type and PM2.5 concentrations.

3.1 Flow Field Classification

Through analysis of flow fields on 56 heavy pollution days, we classified the flow fields affecting the Guanzhong region into four major categories based on daytime (08:00–19:00) and nighttime (20:00–07:00) patterns: eastern inflow, southern inflow, northern non-turning inflow, and weak flow field. These were further divided into eight specific types based on occurrence time and location (Table 1).

Table 1. Classification of daily airflow field in heavy pollution weather

Type	Description
A (Northeast Inflow)	Relatively uniform easterly airflow in the Guanzhong plain, with southerly winds along the southern Qinling Mountains and easterly or westerly winds in the western plain, forming a convergence field.
B (Northeast Inflow Nighttime)	Similar to type A but with pronounced mountain-valley wind characteristics, occurring at all hours but significantly more frequent at night (21:00–06:00).
C (Weinan Mountain-circumventing Inflow)	Occurs less frequently, with clear mountain-valley wind features, more common during daytime (11:00–19:00).
D (Southwest/Southern Inflow)	Relatively uniform westerly airflow in the Guanzhong region, with westerly or calm winds in Baoji, Xi' an, and Xianyang, and southwesterly or westerly winds extending to Weinan and Pucheng.
E (Northern Turning Inflow)	Northerly airflow turns east or west after reaching the Wei River plain. Occurs at all hours but more frequently at night (22:00–24:00).
F (Baoji Inflow)	Occurs infrequently, with few occurrences during daytime (11:00–19:00) and none at night.
G (Northern Non-turning Inflow)	Consistent northerly airflow from northern Shaanxi to the Guanzhong region, typically caused by cold air moving southward.
H (Weak Flow Field)	No significant flow field characteristics, mostly associated with calm winds.

Eastern Inflow: In this pattern, the Guanzhong region experiences relatively uniform easterly airflow, with southerly winds along the southern Qinling Mountains and easterly or westerly winds in the western plain, forming a convergence field. This pattern forms when northeasterly airflow moves southward along northeast-southwest oriented valleys, undergoing cyclonic rotation when passing through urban areas like Xi' an and Xianyang, creating convergent flow. Under special terrain conditions, diurnal flow variations are pronounced, exhibiting local microclimate characteristics influenced by mountain-valley winds and local thermal convection. Based on the origin of the airflow, this category is divided into three types: northeast inflow (A), nighttime northeast inflow (B), and Weinan mountain-circumventing inflow (C). Typical examples of these flow fields are shown in Figures 2-4.

Southern Inflow: In this pattern, the Guanzhong region experiences relatively uniform westerly airflow, with westerly or calm winds in Baoji, Xi' an, and Xianyang, extending to Weinan and Pucheng as southwesterly or westerly winds, while Changwu, Xunyi, and Binxian experience northerly airflow. Based on the origin of the airflow, this category is divided into three types: southwest/southern inflow (D), northern turning inflow (E), and Baoji inflow (F). The D type represents mountain-valley wind patterns where daytime katabatic winds from the northern Qinling slopes reach the Guanzhong region under calm atmospheric conditions with very low wind speeds, forming convergence. The E type involves northerly airflow descending the southern Loess Plateau slopes, turning east or west upon reaching the Wei River valley due to blocking by the massive Qinling terrain to the south. The F type involves northwesterly airflow moving downstream along the low-lying Wei River valley in the middle reaches of the western Guanzhong region, forming westerly inflow. Typical examples are shown in Figures 5-7.

Northern Non-turning Inflow: In this pattern, consistent northerly airflow extends from northern Shaanxi to the Guanzhong region, typically caused by cold air moving southward. When the cold air reaches the low-lying Wei River valley terrain, warm air in the Guanzhong region is lifted, forming an inversion layer over the special terrain that inhibits pollutant dispersion. A typical example is shown in Figure 8.

Weak Flow Field: This pattern shows no significant flow field characteristics, mostly associated with calm winds.

3.2 Statistics of Flow Field Types

Statistical analysis of hourly flow field types on 56 heavy pollution days (Table 2) reveals that eastern inflow occurred most frequently during regional heavy pollution processes, accounting for 59.8% of cases. Within this category, type B appeared most often (25.0% frequency), followed by type C. The probability of occurrence varied substantially between day and night. During daytime (08:00-19:00), type C was most active with nearly 40.0% frequency, while types A and

B each accounted for about 15.0%. At night (20:00–07:00), type B dominated with nearly 50.0% frequency, followed by types E and F at about 15.0% each. Type G appeared least frequently, with less than 10.0% occurrence. Comparing diurnal distributions shows that type B occurred more frequently at night than during daytime.

Table 2. Occurrence times of flow field classification in 56 heavy pollution days

Hour	A	B	C	D	E	F	G	H
00:00	2	7	1	1	1	0	0	1
01:00	1	8	1	0	1	0	0	1
02:00	1	8	1	0	1	0	0	1
03:00	1	8	1	0	1	0	0	1
04:00	1	8	1	0	1	0	0	1
05:00	1	8	1	0	1	0	0	1
06:00	1	8	1	0	1	0	0	1
07:00	1	7	2	0	1	0	0	1
08:00	2	5	4	0	1	0	0	1
09:00	2	5	4	0	1	0	0	1
10:00	2	5	4	0	1	0	0	1
11:00	2	4	5	0	1	0	0	1
12:00	2	4	5	0	1	0	0	1
13:00	2	4	5	0	1	0	0	1
14:00	2	4	5	0	1	0	0	1
15:00	2	4	5	0	1	0	0	1
16:00	2	4	5	0	1	0	0	1
17:00	2	4	5	0	1	0	0	1
18:00	2	4	5	0	1	0	0	1
19:00	2	4	5	0	1	0	0	1
20:00	2	7	2	0	1	0	0	1
21:00	2	7	2	0	1	0	0	1
22:00	2	7	2	0	1	0	0	1
23:00	2	7	2	0	1	0	0	1

3.3 Relationship Between Flow Field Types and PM2.5 Concentrations

Air pollution in the Guanzhong region during autumn and winter is prominent due to two main factors: increased emissions from winter heating and significantly reduced atmospheric dispersion capacity during these seasons, which may be a primary reason for the increasing number of pollution days in recent years. To further analyze the impact of low-level flow fields on regional pollution, we examined the relationship between flow field types and PM2.5 concentrations using WRF model grid data for the five cities during 2017.

PM2.5 concentrations varied substantially across different flow field types (Table 3). Types D and E were associated with higher PM2.5 concentrations. Mountain-valley wind patterns in types A, B, C, and D readily formed vortex flows in the Guanzhong region, causing pollutant accumulation and increased PM2.5 concentrations that led to regional heavy pollution weather. Pollutant transport along eastern inflow pathways to the Guanzhong region represents one of the main causes of heavy pollution events. Additionally, weak flow fields (type H) in the Guanzhong region occurred 83 times in 2017, with an average PM2.5 concentration of 203.4 $g \cdot m^{-3}$ and a maximum daily concentration of 485.0 $g \cdot m^{-3}$ in Xi' an, indicating that stable atmospheric conditions were a major factor exacerbating regional pollution.

Table 3. Statistics of PM2.5 hourly average concentration under different types of flow field

Flow Field Type	Occurrence Rank	Avg. Concentration ($g \cdot m^{-3}$)	Max. Concentration ($g \cdot m^{-3}$)
A	3	185.4	385.2
B	1	195.6	425.8
C	2	180.3	365.4
D	4	210.5	450.6
E	5	205.8	445.3
F	6	175.2	325.7
G	7	165.4	295.8
H	8	203.4	485.0

Analysis of the 10 most severely polluted days revealed that under the influence of the trumpet-shaped terrain, daytime airflow transported along the Fenwei Plain converges in the Guanzhong region, while afternoon airflow moving westward along the mountains also creates convergence. At night, airflow descending the northern Qinling slopes forms vortex flows that trap pollutants. The mountain-valley winds associated with types A and C, particularly type B occurring at night, readily create these conditions, leading to elevated PM2.5 concentrations and regional heavy pollution.

4 Discussion

The Guanzhong region of Shaanxi is a high-frequency, severe pollution area where pollutant emissions and transport are important factors causing heavy pollution. Han Bowei et al. [11] statistically analyzed the large-scale circulation background and meteorological elements during heavy pollution events in the Yangtze River Delta during winter, finding that regional heavy pollution development is closely linked to atmospheric circulation, with terrain influencing pollution primarily through large-scale circulation patterns. The complex trumpet-shaped terrain of the Guanzhong region can cause northeasterly or westerly winds to converge with southwesterly or southerly winds from the northern Qinling slopes, forming cyclonic or shear convergence over the region. Pollutants from northwestern regions (Ningxia, northern Shaanxi) and pollutants from Shanxi accumulating and recirculating between the Guanzhong region and the Fen River valley cause regional heavy pollution. Additionally, complex terrain and local microclimate effects may result in simultaneous occurrence of multiple low-level flow field types, creating composite flow patterns. Future research should further analyze these composite flow fields to clarify how various type combinations affect regional heavy pollution, thereby improving understanding of pollution transport mechanisms and providing theoretical support for government-led joint prevention and control efforts.

5 Conclusions

This study examined the five cities of the Guanzhong region (Xi' an, Xianyang, Weinan, Tongchuan, and Baoji) as an integrated research area, defined regional pollution and heavy pollution weather processes, and reached the following conclusions:

1) Flow fields causing heavy pollution in the Guanzhong region can be classified into four major categories: eastern inflow (A–C), southern inflow (D–F), northern non-turning inflow (G), and weak flow field (H). Based on occurrence time and location, these can be further divided into eight specific types: northeast inflow (A), nighttime northeast inflow (B), Weinan mountain-circumventing inflow (C), southwest/southern inflow (D), northern turning inflow (E), Baoji inflow (F), northern non-turning inflow (G), and weak flow field (H).

2) Eastern inflow occurred most frequently during regional heavy pollution processes, accounting for 59.8% of cases, with types B and C each exceeding 25.0% frequency. Flow field types showed substantial diurnal variation: during daytime, type C was most active with nearly 40.0% frequency, while at night, type B dominated with nearly 50.0% frequency, followed by types E and F at about 15.0% each. Type B occurred more frequently at night than during daytime.

3) Regional heavy pollution in the Guanzhong region occurred primarily in winter. Beyond increased emissions from heating, low-level flow fields significantly affected pollutant dispersion. From the perspective of flow field typing, stable weather conditions, mountain-valley winds, and northern pollutant transport were the main causes of heavy pollution in the region.

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Figure Captions

Fig. 1. Location of Guanzhong Region in Shaanxi Province

Fig. 2. Airflow from northeast (type A) and an example of airflow field at 30 m height (09:00 on February 5, 2017)

Fig. 3. Airflow from northeast airflow at night (type B) and an example of airflow field at 30 m height (04:00 on December 28, 2017)

Fig. 4. Airflow from Weinan around mountains (Type C) and an example of airflow field at 30 m height (07:00 on January 25, 2017)

Fig. 5. Airflow from southwest/south (Type D) and an example of airflow field at 30 m height (10:00 on January 3, 2017)

Fig. 6. Airflow from northern diversion (Type E) and an example of airflow field at 30 m height (21:00 on December 4, 2017)

Fig. 7. Airflow from Baoji (Type F) and an example of airflow field at 30 m height (04:00 on December 3, 2017)

Fig. 8. Airflow from northern (Type G) and an example of airflow field at 30 m height (21:00 on January 26, 2017)

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