Article

Numerical Simulation of Topography Impact on Transport and Source Apportionment on PM_{2.5} in a Polluted City in Fenwei Plain

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Abstract: The unique energy structure, high intensity of coal production, and complex terrain, make Fenwei Plain a highly polluted region in China. In this study, we characterized the transport characteristic and sources of PM_{2.5} (the fraction of particulate matter $\leq 2.5 \mu\text{m}$) in Sanmenxia, a polluted city in canyon terrain. The results showed that special topography in Sanmenxia had an important role in the transport of particulates. Sanmenxia is located between two northeast-southwest facing mountains, showing a special local circulation. The local circulation was dominated by a downslope wind at nighttime, while the cross–mountain airflow and zonal wind were dominant during the daytime in the canyon terrain. PM_{2.5} accumulated near Sanmenxia with the influence of downslope, zonal wind, and topography. The main regional transport paths could be summarized into an eastern path, a northern path, and a western path during the severe haze episodes. The PM_{2.5} source apportionment revealed by an on-line tracer-tagged of the Nested Air Quality Prediction Model System (NAQPMS) showed that the main regional sources of Sanmenxia were Yuncheng, Sanmenxia, and Weinan. The contribution to PM_{2.5} concentration in Sanmenxia was 39%, 25%, and 11%, respectively. The northern path had the most important impact on Sanmenxia. The results can provide scientific basis for the establishment of severe haze control in Sanmenxia and regional joint control.

Keywords: PM_{2.5}; Sanmenxia; canyon terrain; transport; source apportionment

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1. Introduction

In recently decades, with the development of economy and the acceleration of urbanization, the problem of air pollution has become prominent in China [1,2]. The frequent occurrence of severe haze episodes has threatened human daily life and health and has attracted widespread attention [3,4]. PM_{2.5}, the fraction of particle with an aerodynamic diameter less than 2.5 μm , is an important pollutant for environmental issues. Presently, there are many studies on the complexity mechanisms leading to the formation of haze episodes. It is beneficial to develop effective mitigation policies to reduce the pollutant concentration and the impact of pollutants on social activities and global climate [5–7].

The concentration of air pollution is affected by many factors, while emission, chemical transformation, meteorology, and transport play important roles. Pollutants can come from direct emissions (primary pollutants) or be formed by chemical transformation in the atmosphere (secondary pollutants). In general, local emissions are the most direct factor

affecting the concentration of pollutants, and massive efforts have been made to control direct emissions. Secondary inorganic aerosol, such as sulfate, nitrate, and ammonium formed by chemical transformation, are dominant ionic components in $PM_{2.5}$ [8,9]. Besides the influence of emission and chemical transformation, the pollutant concentrations are also highly impacted by meteorology factors. Wind, relative humidity, and precipitation directly affect the pollutant concentration, and the weather pattern, local circulation, and boundary layer also influence the diffusion and deposition of pollutants [10–12]. The combination of meteorological condition and topography leads to complex transport processes. Li et al. [13] found that the accumulation of transported $PM_{2.5}$ in Beijing was related to terrain and meteorological condition. $PM_{2.5}$ from southern Hebei transported northward to Beijing and encountered high mountains in northern Beijing. In stable boundary layer and weak winds situations, $PM_{2.5}$ accumulated at the base of the mountains. Li et al. [14] investigated the air pollutant transport characteristics in Southern China by using a HYSPLIT model with 10 years data and found that major transport paths were mainly within the mixing layer. The probability of haze trajectories across the mixing layer was low and associated with long-distance transport and higher terrain height over Western China.

Many studies have characterized the formation and transport process during haze episodes using the observation data or numerical model. $PM_{2.5}$ concentration, emission inventory, and meteorology dataset were used to analyze the spatiotemporal variations of $PM_{2.5}$ in China [15–17]. Some on-line measurements of $PM_{2.5}$ chemical components also were used to characterize the rapid formation and evolution of particles [18,19]. Satellite remote sensing image is an ideal method to analyze the column concentration of trace constituents and the aerosol optical depth on the global scale [20,21]. Another way to study the mechanism of haze episodes is to simulate the physical and chemical processes using a numerical model. Lagrangian models, such as FLEXPART and HYSPLIT, are widely used to track the transport path and potential source area of particles [22,23]. Three-dimensional Euler transmission models, which can quantify the source contributions, are also popular to research the source of pollutants [24,25]. The Community Multiscale Air Quality (CMAQ) model equipped with the Integrated Source Apportionment (ISAM) module was applied to calculate the contribution to the total $PM_{2.5}$ mass of the Beijing-Tianjin-Hebei region, and the results showed that annual mean local contribution ranged from 32–63% in the BTH region [26]. Using the particulate source apportionment technology (PSAT) in comprehensive air quality model with extensions (CAMx), Yang et al. [27] found that Xi'an local emissions were dominant contributors to the surface $PM_{2.5}$ during one severe haze. Wang et al. [28] applied an integrated process contribution analysis and source apportionment technology coupled with the Nested Air Quality Prediction Modeling System (NAQPMS) to analyze a regional haze episode in North China and found that $PM_{2.5}$ in the south of the North China Plain mainly came from the horizontal transmission of the northern and middle area in the phase with continuous high $PM_{2.5}$ concentration. The aforementioned studies mainly focused on the first-tier and second-tier cities in the North China Plain, the Yangtze River Delta region, the Pearl River Delta region, and the Sichuan Basin [29–32]. However, air quality in smaller cities of the polluted regions is also worthy of attention.

Due to the diverse types of emission sources, high emission intensity, and complex topographical characteristics, the air pollution of Fenwei Plain has become an urgent problem, and Fenwei Plain was included in the national air environment key management area in 2018 [33,34]. The comprehensive research on formation and transport mechanisms of air pollution in Fenwei Plain are relatively few. Sanmenxia is a representative city in Fenwei Plain, and it is situated in an intersectional area between the three polluted provinces of Henan, Shanxi, and Shaanxi. At the same time, Sanmenxia is bounded by Zhongtiao Mountain to the north and Qinling Mountain to the south. The local circulation and air pollution mechanism of Sanmenxia that are influenced by complex terrain are worthy of in-depth analysis. In this study, we conducted a wintertime enhanced observation in Sanmenxia from 20 December 2018 to 31 January 2019. The temporal variations of air pollutants were

analyzed by the observation datasets. Then, we used the WRF, FLEXPART–WRF, and NAQPMS models to characterize the local and regional transport paths in special terrain. Furthermore, the source apportionment of different geographical locations and emission categories were studied using the on–line tracer–tagging module in NAQPMS. The results can provide scientific basis for the establishment of severe haze control in Sanmenxia and regional joint control.

2. Materials and Methods

2.1. Observation Data

The hourly concentrations of $\text{PM}_{2.5}$, PM_{10} , SO_2 , and NO_2 at the ground surface during the enhanced observation were obtained from the China Air Quality Online Monitoring and Analysis platform (<https://www.aqistudy.cn>, accessed on 23 March 2019). The hourly meteorological parameters, including wind direction and wind speed, were obtained from the National Meteorological Information Centre (<http://data.cma.cn>, accessed on 25 March 2019). Hourly datasets of $\text{PM}_{2.5}$ chemical species of EC, OM ($=\text{OC} \times 1.4$), SO_4^{2-} , NO_3^- , NH_4^+ , Cl^- , and metal elements were collected from Sanmenxia Environmental Monitoring Station. Ten-level wind profiles from 40 m to 320 m (40, 80, 110, 140, 170, 200, 220, 240, 280, and 320 m) were measured using a Doppler wind lidar (WindCube v1, Leosphere, France) that was installed on the seventh floor (~20 m above the ground level) of the Sanmenxia Ecological Environment Bureau. The aerosol extinction coefficient data derived from a micro pulse lidar (EV–LIDAR, 532 nm) that was also installed on the seventh floor of the Sanmenxia Ecological Environment Bureau.

2.2. Meteorological Model

The meteorological model used in this study was the Weather Research and Forecasting (WRF) version 3.6 [35], which was driven by the National Centers for Environmental Prediction (NCEP) Final Analysis (GFS–FNL) data with 6–hourly temporal resolution. We divided the whole study region into two domains: domain 1 (d01) covered East Asia with a horizontal resolution of 15 km, and domain 2 (d02) covered Fenwei Plain with a horizontal resolution of 3 km (Figure 1a). The outermost domain centered at 31° N , 102° E . We configured WRF with 30 vertical levels up to 50 hpa. The parameterization schemes used were WRF Single–Moment–3–class scheme (WSM3) for microphysics parameterization; the Rapid Radiative Transfer Model (RRTMG) scheme for longwave and shortwave radiation parameterization [36]; the Revised MM5 Monin–Obukhov scheme for surface layer scheme [37]; the Noah–MP land surface model for land surface scheme [38]; Yonsei University (YSU) scheme for planetary boundary layer parameterization [39]; New Grell (G3) scheme for cumulus parameterization [40].

Figure 1. (a) Model domain setting. (b) Hourly averaged primary PM_{2.5} emission rate. (c) Domain 2 with 26 tracer-tagging regions and (d) the spatial distribution of monitor positions of Sanmenxia.

2.3. Atmospheric Transport Model

A Lagrangian transport and dispersion model FLEXPART–WRF version 3.1 was used to simulate the atmospheric transport processes [41–43]. To optimize the accuracy of the Lagrangian trajectories, we used high-resolution WRF simulation domain 1 outputs as the input meteorological conditions for FLEXPART. The FLEXPART–WRF output was the residence time of particles in each grid cell. The residence time represented the distribution of potential source regions that contributed to the target region, which could also represent the transmission path [44,45]. During the enhanced observation, FLEXPART–WRF was configured for 72-h backward trajectories with the release of 10,000 air particles from Sanmenxia (111.16° E, 34.79° N) at 02:00, 08:00, 14:00, and 20:00 daily. We set up the release

height with 0–300 m. The hourly output domain was set up with a horizontal resolution of 5 km and 21 vertical levels up to 20,000 m.

We used the residence time analysis (RTA) method [46] to analyze the distribution of the particle residence time of each grid cell. RTA is defined as:

$$RTA(i, j) = \frac{t(i, j)}{T} \times 100\%, \quad (1)$$

The resident time $t(i, j)$ at the grid (i, j) can be obtained from the FLEXPART–WRF outputs, and T is the sum of the residence time of all grids.

2.4. Air Quality Model

The air quality model used in this study was the Nested Air Quality Prediction Modeling System (NAQPMS) developed by the Institute of Atmospheric Physics, Chinese Academy of Sciences [47]. NAQPMS is a three-dimensional Euler chemical transport model with terrain-following coordinates, which includes modules of advection, diffusion, dry/wet deposition, and gaseous, aqueous, and heterogeneous chemistry [48–51]. The detailed mechanisms of NAQPMS have been described in previous studies [52,53]. In order to quantify the source–receptor relationship in atmospheric particulate matter, an on–line tracer–tagging module similar to the Particulate Matter Source Apportionment Technology is implemented in NAQPMS [54–56]. The module attributes air pollutant concentrations to different geographical locations and emission categories at each step of the simulation without influencing standard calculations. More details of the module can be found in the previous study [57]. NAQPMS has been widely used in air quality research, and besides, the source apportionment module has been validated by the Ministry of Environmental Protection of China (Ministry of Ecology and Environment of the People's Republic of China) [24].

In this study, we conducted a simulation from 10 December 2018 to 31 January 2019. The first 10 days were used as the spin–up time to reduce the influence of the initial conditions. The lateral and upper boundary conditions for the outmost domain were derived from the global chemistry transport model MOZART–v2.4 [58]. The meteorological field inputs to NAQPMS were provided by WRF, so the domain setting and resolution of NAQPMS were the same as those of the WRF. The vertical dimension was configured with 30 sigma layers up to 20 km. A 2018-based high spatiotemporal resolution anthropogenic emission inventory that included power plant, industry, residential, transportation, and agricultural sources for Henan province was used in this study. The emission factors and local activity data were mainly obtained from governmental statistical yearbooks. For the region outside Henan province in the simulation domain, the multi-resolution emission inventory for China (MEIC) developed by Tsinghua University was used (<http://meicmodel.org>, accessed on 17 October 2019). The emission inventory for the region outside of China is MIX (<http://www.meicmodel.org/dataset-mix>, accessed on 17 October 2019). Biomass burning emissions were provided by the Fire INventory from NCAR (FINN) version 1.5. Figure 1b shows the hourly average primary PM_{2.5} emission rate in domain 2 during the study period. As shown in Figure 1c, the tracer-tagging target domain 2 area consisted of 11 cities in Fenwei Plain, seven other cities of Henan Province, four other cities of Shanxi Province, the rest of Shanxi, Shaanxi and Henan province, and the rest of the area.

2.5. Model Performance

To evaluate the WRF model performance, we presented the correlation coefficient R , root mean square error (RMSE), mean observation value (Mean–Obs), and mean simulation value (Mean–Sim) as statistical parameters. As shown in Figure 2, WRF reproduced the variations of meteorological elements during the enhanced observation. The correlation coefficients (R) between the observed and simulated values of temperature, relative humidity, and wind speed were 0.89, 0.91, and 0.7, respectively, and the root mean square error (RMSE) of all three parameters were relatively small. Besides, it can be seen from the

scatter plot that the simulated values of temperature, relative humidity, and wind direction basically fell between 0.5 and 2 times those of the observed values.

Figure 2. Comparison between the observation (black) and simulation (red) data of (a) temperature, (b) relative humidity, and (c) wind speed and wind direction in Sanmenxia during the period of enhance observation; the scatter plot in (c) was the comparison of wind direction (severe haze episodes, shaded areas).

Similarly, we presented the correlation coefficient (R), root mean square error ($RMSE$), mean observation value ($Mean-Obs$), and mean simulation value ($Mean-Sim$) to assess the NAQPMS model performance. As shown in Figure 3, NAQPMS reproduced the three severe haze episodes, but the simulation results of $PM_{2.5}$ were underestimated a little compared with the observation value. This might be related to the underestimation of water-soluble ions caused by factors such as emission inventory and complex terrain [13]. The other components of $PM_{2.5}$, such as BC and OC were reproduced well during the enhanced observation in Sanmenxia. In general, under the complex topography of Sanmenxia, the model could basically reproduce the distribution of the observed $PM_{2.5}$ concentrations.

Figure 3. Comparison between the observation (black) and simulation (red) data of $PM_{2.5}$ in Sanmenxia during the period of enhance observation (severe haze episodes, shaded areas).

3. Results

3.1. Temporal Variations of Air Pollutants

Figure 4 shows the time series of pollutant concentration and wind fields during the period of enhanced observation in Sanmenxia. The average concentrations of $\text{PM}_{2.5}$ and PM_{10} were $111.09 \mu\text{g}/\text{m}^3$ and $150.34 \mu\text{g}/\text{m}^3$, respectively. During this period, there were three severe haze episodes on 20–21 December 2018 (case1), 2–8 January 2019 (case2) and 11–14 January 2019 (case3), respectively, and the last two sustained longer. During the severe haze episodes, the average concentrations of $\text{PM}_{2.5}$ and PM_{10} were $154.89 \mu\text{g}/\text{m}^3$ and $191.69 \mu\text{g}/\text{m}^3$, respectively. The increase of relative humidity, the decrease of wind speed, and the inverse temperature are meteorological factors that cause the peak value of particulate concentration. In addition, the increase of sulfate concentration caused by emission is also an important factor causing the peak value of particulate concentration. The evolution characteristics of particles were consistent, with $\rho(\text{PM}_{2.5})/\rho(\text{PM}_{10})$ of 0.7, and the contribution of secondary transformation was significant. During the enhanced observation period, the horizontal wind speed was weak, and the prevailing wind direction was south winds. The vertical wind speed was also weak; the prevailing wind direction between 50–320 m was downdraft, and the vertical wind presented an obvious updraft at the stage of pollutant concentration reduction. Besides, we analyzed the hourly data of $\text{PM}_{2.5}$ chemical species, i.e., EC, OM, Cl^- , NO_3^- , SO_4^{2-} , NH_4^+ , and metal elements. Secondary water-soluble ions, i.e., SO_4^{2-} , NO_3^- , and NH_4^+ were key constituents of $\text{PM}_{2.5}$, accounted for 71.0%, and their contribution increased when air quality became worsened. NO_3^- was the primary pollutant, accounting for 37.4% of $\text{PM}_{2.5}$. The results indicated that anthropogenic source emissions associated with NO_3^- contributed greatly to $\text{PM}_{2.5}$ formation during enhanced observation; similar phenomena had been observed in Beijing [59,60] and Shanghai [61] in recent years. The control of SO_2 sources and the increase of motor vehicles made NO_3^- become a main component of $\text{PM}_{2.5}$ rather than SO_4^{2-} [60].

Figure 4. Time series of (a) $\text{PM}_{2.5}$ and PM_{10} , (b) SO_2 and NO_2 , (c) horizontal wind, (d) vertical wind, and (e) $\text{PM}_{2.5}$ chemical species during the period of enhanced observation (severe haze episodes, shaded areas).

Figure 5 shows the extinction coefficient of Sanmenxia during the enhanced observation period retrieved from lidar data. There were three obvious high values of extinction coefficient below 1.5 km on 3–8, 11–14, and 30–31 January 2019. It showed that a great deal of particulate matter was formed and accumulated below 1.5 km in Sanmenxia during these periods, and the first two periods of high extinction coefficient were consistent with the severe haze episodes of Sanmenxia. During the enhanced observation period, the high value areas of the extinction coefficient of aerosols were under 1.5 km, but they were not completely confined to the ground. Thus, we should pay more attention to the characteristics, sources, and transmission of high-altitude pollutants.

Figure 5. Time series of extinction coefficient of Sanmenxia during the period of enhanced observation (severe haze episodes, shaded areas).

3.2. Transport Characteristics

Sanmenxia is located in canyon terrain between Zhongtiao Mountain and the Qinling Mountains. In order to explore the local circulation caused by the special terrain of Sanmenxia, WRF simulation results were used to analyze the circulation of Sanmenxia. The profile positions are shown in Figure 6. The section between A1 and A2 passed through Zhongtiao Mountain and Xiao Mountain in turn, and the section between B1 and B2 was along the southern foot of Zhongtiao Mountain. Namely, A1–A2 transect was along the lateral circulation, and B1–B2 transect was along the valley axis. The combination of two sections can well analyze the characteristics of airflow in canyon.

Based on the statistics of the hourly output wind field data during the enhanced observation of Sanmenxia, the circulation characteristics of the A1–A2 transect and the B1–B2 transect were summarized, as shown in Figure 7. The wind in Figure 7 is the wind vector synthesized by latitude wind component (u) and vertical wind component (w). Because the w was small (Figure 4), in order to reflect the variation characteristics of vertical wind, the wind vectors shown in the figure were synthesized by $w \times 20$ and u . The contour is virtual potential temperature, which can better reflect the rising and sinking of airflow in the actual atmosphere. The virtual potential temperature (θ_v) could be calculated by:

$$\theta_v = T(1 + 0.608q) \left(\frac{p_0}{p} \right)^{k_d} \quad (2)$$

where T is temperature (K), q is mixing ratio (kg/kg), P_0 is standard atmospheric pressure (hpa), and k_d is a constant with a value of 0.286.

Figure 6. Topography of Sanmenxia, and the transect locations of A1–A2 and B1–B2. (black star shows the location of Sanmenxia).

Figure 7. Circulation characteristics of (a) A1–A2 transect at daytime, (b) A1–A2 transect at nighttime, (c) B1–B2 section at daytime, and (d) B1–B2 transect at nighttime (mean results during the enhanced observation). Red star shows the location of Sanmenxia. Orography is black.

It can be seen from Figure 7 that along A1–A2 transect, the downslope wind prevailed at night, which was consistent with the typical lateral circulation at night. However, in the daytime, it was dominated by the cross-mountain airflow along a certain direction; that is, the airflow sank down one slope and rose up the other, and the dominant wind direction was westerly. In special atmospheric circulation, the zonal wind direction of high and low altitude was inconsistent, and there was a counterclockwise circulation that rose along the Qinling Mountain and sank along the Zhongtiao Mountain in the daytime or a clockwise circulation that rose along the Zhongtiao Mountain and sank along the Qinling Mountain. The transition of the background wind field at high and low altitudes and the coupling of the cross-mountain airflow along A1–A2 transect caused a special local circulation, which affected the transport and diffusion of pollutants in Sanmenxia. By analyzing the airflow along B1–B2 transect, it was found that the vertical wind speed was very weak and vertical wind near the surface was still dominated by downdrafts. The zonal wind was dominated. This may be due to the increase of horizontal wind speed caused by canyon terrain.

Figure 8 shows the vertical transects of averaged simulated $PM_{2.5}$ of two profiles during the severe haze episodes. The concentration of $PM_{2.5}$ was not homogeneous along the profiles. The polluted layer was about 500 m deeper along A1–A2 transect, and the maximum of $PM_{2.5}$ concentration was near the surface. The $PM_{2.5}$ concentration was higher in the south-eastern part of A1–A2 transect compared to the north–western part. It may be ascribed to the $PM_{2.5}$ transported by the western wind along the A1–A2 transect was obstructed by the Qinling Mountain and downslope winds, $PM_{2.5}$ accumulated at the hillside and foot of the Qinling mountain. Along the B1–B2 transect, the polluted layer was about 500–1000 m deep. Two southwest–northeast facing mountains and downdraft allowed $PM_{2.5}$ to accumulate in the canyon, and the polluted layer was higher, as mentioned in the observations of the aerosol extinction coefficient. Combined with the circulation in both directions, the combination of downslope wind and downdraft near Sanmenxia at nighttime was not conducive to the diffusion of pollutants, while the combination of cross–mountain and zonal wind also plays an important role in particulates transport (Figure 9). The thermal cycle caused by special terrain produced such a special local circulation structure. The reason for the difference between the wind direction in the mountainous areas and the dominant wind in the environment was that, on the one hand, the undulation of the terrain changed the wind direction and speed of the airflow near the ground, and on the other hand, the uneven heating of the special terrain caused thermal circulation [62].

Figure 8. Vertical transects of averaged simulated $PM_{2.5}$ of profile (a) A1–A2 transect and (b) B1–B2 transect during the severe haze episodes. Red star shows the location of Sanmenxia. Orography is white.

Figure 9. Schematic of two types of local circulation in Sanmenxia: (a) zonal wind at daytime, (b) downslope wind at nighttime. Arrows indicate averaged airflow.

In order to analyze the particulate transport path during severe haze episodes in Sanmenxia, based on FLEXPART-WRF, the 72-h backward residence time distribution of particulates is shown in Figure 10. During this period, the major transport paths could be summarized into a northern path, a western path, and an eastern path. Along the northern path, the particulates from eastern Shanxi province could get over Zhongtiao Mountain and arrive at Sanmenxia. Along the western path, particulates from western Shaanxi province reached Sanmenxia along the Guanzhong Basin. The particulates in the eastern path were transmitted to Sanmenxia along the southern foot of Taihang Mountain through the northern Henan Province. Terrain had an important influence on the long range and local transport of particulates in Sanmenxia.

Figure 10. Horizontal transport paths of particulates in Sanmenxia during the severe haze episodes. (Black dot shows the location of Sanmenxia).

3.3. Source Apportionment

During the enhanced observation period, the concentration of pollutants in Sanmenxia was relatively high; there were three severe haze episodes, and the primary pollutant was $PM_{2.5}$. In order to quantitatively identify the regional and industrial contribution to the concentration of $PM_{2.5}$, an on-line tracer-tagging module was implemented in NAQPMS. Figure 11 shows the contribution of different source categories to $PM_{2.5}$ concentration during the enhanced observation period in Sanmenxia using an on-line tracer-tagging module of NAQPMS. The contributions of residential, industry, power plant, and transport sources to the total $PM_{2.5}$ concentration were 63%, 19%, 7%, and 12%, respectively. Residential was the largest contributor among the primary and secondary components of $PM_{2.5}$, with contributions of 76% and 46%, respectively. The contribution of industry to the primary components was also important, contributing 18% during the severe haze period. Transport sources had a greater contribution to the secondary components. During the severe haze episodes, the contribution of industry and transport to the primary component increased, but for the secondary components, the contribution of industry and transport decreased slightly. To sum up, Sanmenxia should strengthen countermeasures during severe haze episodes, not only on the control of industrial and transport emissions, but they should also pay attention to the management of emissions from residential sources.

Figure 11. Mean $PM_{2.5}$ source apportionments by different source categories in Sanmenxia during the enhanced observation periods.

In this study, the emission area was marked into 26 regions by administrative boundary. To explain the main contributors of $PM_{2.5}$ in Sanmenxia, these source regions were grouped into seven regions: SMX, YC, WN, the other of Henan Province (HN–O, included LY, ZZ, JZ, XX, KF, HB, AY, PDS, and OHN), the other of Shanxi Province (SX–O, included LF, JZ, LL, CZ, JC, YQ, TY, and OSX), the other of Shaanxi Province (SHX–O, included TC, XA, XY, BJ, and OSHX), and OT. Figure 12 shows the $PM_{2.5}$ source apportionments by source regions during the enhanced observation period in Sanmenxia. The source emissions of local and adjacent areas played an important role in Sanmenxia. During the enhanced observation, YC was the largest contributor to the total $PM_{2.5}$ concentration, with contributions of 39%. The local contribution of SMX accounted for 25%. WN also made a great contribution, accounting for 11%. Compared with the mean results, the self-contribution of SMX decreased 8% in case1 and 4% in case2, but it increased 2% in case3. YC was also the largest contributor during the three severe haze episodes, and the contribution of YC in case1 could reach 42%. The contribution of WN ranged from 9–16% during the severe haze episodes. Combined with Figure 10 during the severe haze episodes, the northern path had the greatest impact on Sanmenxia.

Figure 12. Mean $PM_{2.5}$ source apportionments by different source regions in Sanmenxia of enhanced observation period and three severe haze periods.

Table 1 shows the source apportionment by seven regions to the $PM_{2.5}$ chemical species during the enhanced observation in SMX. For the primary components of $PM_{2.5}$, YC was the largest contributor, especially in clean periods, with the contribution of 57%. Local contribution of SMX also had a great impact, and the contribution increased to 44% during the severe haze episodes. Combined with the impact of industrial sources, Sanmenxia should strengthen the control of local residents and industrial sources during the severe haze episodes. For $PM_{2.5}$ secondary components, the contribution of local sources and YC decreased significantly, while the contribution of WN, HN–O, SHX–O, SX–O, and OT increased, especially during the severe haze episodes. The regional transport had an important influence on the secondary components of $PM_{2.5}$. Combined with the horizontal transport path mentioned above, the northern path had the greatest impact on $PM_{2.5}$ concentration in Sanmenxia, while the contribution of the western path increased during the severe haze episodes.

Table 1. Contribution of source regions to PM_{2.5} in Sanmenxia.

	Primary			Secondary		
	Mean Results	Severe Haze Episodes	Clean Periods	Mean Results	Severe Haze Episodes	Clean Periods
SMX	37%	44%	33%	11%	10%	12%
YC	53%	48%	57%	24%	22%	25%
WN	3%	5%	3%	20%	28%	18%
HN-O	6%	2%	6%	16%	7%	16%
SHX-O	1%	1%	1%	18%	24%	18%
SX-O	0%	0%	0%	4%	2%	4%
OT	0%	0%	0%	7%	7%	7%

4. Conclusions

Based on the observation data of pollutant concentration, meteorological elements, aerosol extinction coefficient, vertical wind, PM_{2.5} component concentration, and numerical models of WRF, FLEXPART-WRF, and NAQPMS, this study analyzed the pollutant distribution characteristics, local and regional transport characteristics, and regional and industrial emission sources of PM_{2.5} during the enhanced observation period from 20 December 2018 to 31 January 2019 in Sanmenxia, a polluted city in canyon terrain. The results showed that:

During the winter enhanced observation period from December 2018 to January 2019, the diurnal variations of PM_{2.5}, PM₁₀, and SO₂ were consistent. The proportion of SO₄^{2−}, NO₃[−], and NH₄⁺ in PM_{2.5} could reach 71%, indicating that the secondary conversion of anthropogenic emissions during the enhanced observation period became the important reasons for the growth of PM_{2.5} in Sanmenxia. The wind speed was weak, while the prevailing horizontal wind direction was south, and the vertical wind was dominated by the downdraft between 100–320 m. During the severe haze episodes, the aerosol extinction coefficient was higher in the whole layer of 0–1.5 km.

Sanmenxia is located between two northeast–southwest facing mountains, showing a special local circulation in canyon terrain. During the enhanced observation, the downslope prevailed at night between A1–A2 section. In the daytime, cross-mountain airflow was dominant in the A1–A2 section, and zonal wind was dominant in the B1–B2 section. Downslope flow and zonal wind allow pollutants from the sources to accumulate near Sanmenxia. The special local circulation in the canyon was mainly caused by the thermal difference produced by the uneven heating of the special terrain and the change of wind speed and direction caused by the undulation of the terrain. For regional transport, during the enhanced observation period, main transport paths of Sanmenxia could be summarized into three transport paths: northern path, western path, and eastern path. Special terrain had an important influence on the local and long-range transport of particulates in Sanmenxia.

Source apportionment results showed that the residential source was dominant, especially for the primary component of PM_{2.5}; the contribution of resident source to Sanmenxia could reach 76%. During severe haze episodes, the contribution of industry and transport emissions to PM_{2.5} primary components increased. Sanmenxia should pay more attention to the control of local residential and industrial sources during severe haze episodes. According to the results of regional source apportionments, regional sources of Sanmenxia were dominated by YC, SMX, and WN during the enhanced observation period. YC was the largest contributor to SMX. For primary components of PM_{2.5}, the contribution of YC and local sources had great impact. For PM_{2.5} secondary components, the contribution of WN, HN–O, SHX–O, SX–O, and OT increased, especially during the severe haze episodes. Thus, the regional transport had an important influence on the secondary components of PM_{2.5}. Combined with the horizontal regional transport paths, the northern path had the greatest influence on PM_{2.5} concentration of Sanmenxia, and the influence of the western path on PM_{2.5} was increased during severe haze episodes.

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