Characteristics and potential sources of wintertime air pollution in Linfen, China

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Abstract Linfen in China’s Shanxi Province suffers severe air pollution in winter. Understanding the characteristics of air pollution and providing scientific support to mitigate such pollution are urgent matters. This study investigated the variations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, O$_3$, and CO in Linfen between December 1, 2019 and February 29, 2020. The mean concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, MDA8 (the maximum daily 8-h average) O$_3$, and CO were 106.2, 139.4, 47.2, 41.0, 57.0 μg m$^{-3}$, and 1.8 mg m$^{-3}$, respectively. Large amounts of pollutants emitted by coal burning, industry, vehicles, and residents contributed to air pollution. Unfavorable meteorological conditions, such as lower temperature, weaker wind, higher relative humidity, and reduced planetary boundary layer height, made the situation worse. Fireworks and firecrackers set off to celebrate traditional Chinese festivals caused the concentration of PM pollutants to spike, with the maximum daily mean concentration of PM$_{2.5}$ reached 314 μg m$^{-3}$ and the peak hourly value reached 378.0 μg m$^{-3}$. Suspensions of commercial and social activities due to COVID-19 reduced anthropogenic emissions, mainly from industry and transportation, which decreased the level of air pollutants other than O$_3$. Analyses involving backward trajectory cluster, the potential source contribution function, and concentration weighted trajectory demonstrated that PM$_{2.5}$ pollution mainly came from local emissions in Shanxi Province and regional transport from Inner Mongolia, Shaanxi, Hebei, Henan, and Gansu provinces. Shanxi and its surrounding provinces should adopt measures such as tightening environmental management standards, promoting the use of renewable energy, and adjusting the transportation structure to reduce regional emissions. This study will help policy-makers draft plans and policies to reduce air pollution in Linfen.

Keywords Air pollution · PM$_{2.5}$ · Meteorological parameters · Potential source · Linfen

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Introduction

Over the past few decades, due to China’s accelerated industrialization and urbanization, the rapid increase in energy demand dominated by fossil fuels has worsened air quality. Air pollution endangers human health, increasing the mortality and morbidity of cardiovascular and respiratory diseases; impedes the sustainable development of society and the economy; and causes climate change (Mulenga & Siziya, 2019; Shang, 2013; Shrivastava, 2017; Xie et al., 2019). As a severe environmental problem, air pollution has elicited concern among government officials and the public.

At the beginning of 2013, extreme and persistent air pollution appeared in China. Measurements in 74 major cities indicated that the daily mean concentrations of particulate matter (PM) with aerodynamic diameters smaller than 2.5 μm (PM_{2.5}) and 10 μm (PM_{10}), nitrogen dioxide (NO_{2}), sulfur dioxide (SO_{2}), carbon monoxide (CO), and the maximum daily 8-h average (MDA8) concentrations of ozone (O_{3}) exceeded the thresholds stipulated by National Ambient Air Quality Standard of China (NAAQS; GB3095-2012, Grade II) in 68.9%, 46.9%, 14.9%, 23.5%, 12.3%, and 1.2% of days in January—with maximum values up to 766 μg m^{-3}, 998 μg m^{-3}, 491 μg m^{-3}, 186 μg m^{-3}, 10.9 mg m^{-3}, and 258 μg m^{-3}, respectively (air quality report of 74 cities in China in January 2013. 2013). The State Council of China promulgated the Action Plan for Air Pollution Prevention and Control (Air pollution prevention and control action plan. 2013) to deal with air pollution and public health protection. A series of stringent policies and measures aimed at reducing pollution emissions and promoting energy conservation have since been implemented.

After 5 years of effort in implementing these policies, the overall air quality has improved dramatically. The PM_{2.5} mean concentrations in the Beijing–Tianjin–Hebei (BTH) region, the Pearl River Delta region, and the Yangtze River Delta (YRD) region decreased by 39.6%, 27.7%, and 34.3% by 2017 relative to 2013 levels (Announcement on the final assessment results of the implementation of the Air Pollution Prevention and Control Action Plan. 2018). However, air pollution remains serious in North China, with haze events frequently occurring in autumn and winter, especially during the heating period (An, 2019; Liu et al., 2020; Wen et al., 2018, 2020). In June 2018, the policy titled “Three-year action plan for protecting the blue skies” (Three-year action plan for defending the blue sky. 2018) was released. The policy focused on three key regions: the BTH and surrounding areas, the YRD, and the Fenwei Plain (FWP). The plan aims to significantly improve air quality through continued preventive and control measures to realize the sustainable development of the society, economy, and environment.

Because of the massive increase in energy for heating and adverse meteorological conditions, the mean concentrations of PM_{2.5} in the FWP during autumn and winter are approximately twice of those in spring and summer, and heavy pollution days accounted for more than 90% of the whole year of 2018 (Action plan for comprehensive treatment of air pollution in the Fenwei Plain in the autumn and winter of 2019–2020. 2019). Linfen is one of eleven cities in the FWP with major pollution problems. It is situated in the southwest of Shanxi Province (Fig. 1), with Taiyue Mountain and Luliang Mountain around it. The Fen River flows from north to south through the middle of the city, forming the Linfen Basin. Linfen has a semi-arid and semi-humid temperate continental climate with a resident population of approximately 4.5 million. Its GDP has grown at an average annual rate of 7.8%, reaching RMB144 billion in 2018 (A review of the economic and social development achievement of Linfen. 2019). Linfen possesses particularly abundant coal and iron ore resources, with total reserves of 96 billion tons and 420 million tons, respectively. It is an essential part of the energy and chemical industry base of Shanxi Province and is one of the three major high-quality coking coal bases in China. Linfen has a heavy industrial structure, with coal, coke, steel, and electricity as the leading industries, resulting in large quantities of industrial emissions. Numerous industrial factories are located within a few kilometers of the urban area of the city. Coal and coke are mainly transported by road, and vehicle exhaust emissions are a serious problem. Linfen has been suffering perennial severe air pollution (Ma et al., 2015), and in January 2019, it had the worst air quality among Chinese cities (Air quality report
in Chinese cities in January 2019. promulgated the Action Plan for Air Pollution Prevention and Control (2019). Hence, raising awareness of air pollution in Linfen and providing scientific support to mitigate such pollution are urgent matters. However, detailed research related to air pollution in Linfen is still lacking.

This study comprehensively analyzed the characteristics of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, CO, and O$_3$ in Linfen during the winter of 2019 to 2020—a period that covers the Spring Festival and the outbreak of the COVID-19 in China. The Spring Festival is the most important traditional festival in China. Families get together to celebrate the Lunar New Year’s arrival by setting off firecrackers, which may cause severe environmental pollution. Because of the importance of meteorological parameters to air quality, their effects on air pollutant concentrations were discussed. The transport pathways and potential source areas of air pollutants were identified using the backward trajectory cluster, the potential source contribution function (PSCF), and concentration weighted trajectory (CWT). The results will help policy-makers draft plans and policies to reduce air pollution in Linfen.

Methods

Site location and monitoring data

Five national air quality monitoring stations located in Linfen, Shanxi Province, were selected for this study. Figure 1 shows the geographic location of Linfen and the monitoring stations. The stations are situated in the center of Linfen Basin and the urban area of Linfen, including Tangyao Hotel (TH; 36.10°N, 111.51°E), Municipal Committee (MC; 36.09°N, 111.50°E), Technical School (TS; 36.07°N, 111.50°E), Business School (BS; 36.08°N, 111.52°E), and Lingang Hospital (LH; 36.08°N, 111.55°E). The automatic continuous monitoring systems of ambient air quality were used to monitor the concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, CO, and
O3 according to China’s environmental protection standards (HJ817-2018 and HJ 818–2018). The hourly concentrations of PM2.5, PM10, NO2, SO2, CO, and O3 were collected from China’s Urban Air Quality Real-time Publishing Platform (http://106.37.208.233:20035) for the period of December 1, 2019 to February 29, 2020, which coincided with the central heating period in winter. The citywide mean concentrations of pollutants were obtained by averaging the concentrations of all stations. The daily mean concentrations were obtained for an 8-h block when data recorded for more than 20 h per day. The 8-h O3 concentrations were obtained for an 8-h block when data for >6 h of that block were valid. The monthly averages were obtained by averaging the daily values of the month.

Hourly meteorological data of Linfen station (36.07°N, 111.50°E), including temperature, wind speed, wind direction, relative humidity, and visibility, were provided by China National Meteorological Science Data Center (http://data.cma.cn). The planetary boundary layer height (PBLH) was obtained from ERA5 provided by the European Center of Medium-Range Weather Forecasts (https://www.ecmwf.int/).

Backward trajectory cluster analysis

Seventy-two-hour backward trajectories arriving at the center of Linfen (36.08°N, 111.52°E) were computed by the Hybrid Single-Particle Lagrangian Integrated Trajectory model. The meteorological data with a resolution of 1°×1° was obtained from the Global Data Assimilation System of the US National Centers for Environmental Prediction (ftp://arlftp.arlhq.noaa.gov/pub/archives/gdas1). The model was run four times a day at the starting times of 0:00, 6:00, 12:00, and 18:00 local time at the height of 100 m above ground level during the study period. Cluster analysis was applied for group trajectories, and the main transport pathways associated with elevated pollutant concentrations were identified by the combination of trajectories and pollutant concentrations.

Source region analysis

The potential source areas of PM2.5 were determined using the PSCF and CWT methods. Specifically, the estimates of the motion of trajectories were combined with pollutant concentrations of the receptor site using TrajStat, a geographic information system-based software (Wang et al., 2009). The study domain with a 1°×1° latitude and longitude was divided into small grid cells (i×j) with equal size. The PSCF value for cell \(ij\) was computed as follows:

\[
PSCF_{ij} = \frac{m_{ij}}{n_{ij}}
\]

where \(n_{ij}\) represents the number of endpoints falling into the cell \(ij\), and \(m_{ij}\) represents the number of endpoints corresponding to pollutant concentration higher than the pollution criterion in the same cell when reaching the receptor site. The pollution criterion of PM2.5 concentration was set to 75 μg m⁻³.

PSCF cannot tell the difference of grid cells with the same computed values when the pollutant concentrations slightly or significantly exceeded the criterion. The CWT method was used to overcome this limitation of PSCF. In the CWT model, a weighted concentration was assigned to each grid cell by averaging the pollutant concentrations of trajectories related to the grid cell, as shown below:

\[
C_{ij} = \frac{\sum_{l=1}^{M} C_{ij} \tau_{ijl}}{\sum_{l=1}^{M} \tau_{ijl}}
\]

where \(M\) represents the total number of trajectories, \(l\) represents the index of the trajectory, \(C_{ij}\) represents the observed concentration when trajectory \(l\) arrives in cell \(ij\), and \(\tau_{ijl}\) represents the time spent by trajectory \(l\) in cell \(ij\). When \(n_{ij}\) was less than three times of the average value of the endpoints per each cell \(n_{ave}\), an arbitrary weight function \(W_{ij}\) was multiplied by the PSCF and CWT values (Polissar et al., 2001; Wang et al., 2006) to reduce uncertainty in cells:

\[
W_{ij} = \begin{cases} 
1.00, & 3n_{ave} < n_{ij} \\
0.70, & 2n_{ave} < n_{ij} \leq 3n_{ave} \\
0.42, & n_{ave} < n_{ij} \leq 2n_{ave} \\
0.17, & n_{ij} \leq n_{ave}
\end{cases}
\]

A detailed description of \(W_{ij}\) in this study can be found in the Supplementary Materials. Subsequently, the potential source areas with high weighted PSCF (WPSCF) or weighted CWT (WCWT) values could be determined.

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Results and discussion

Characteristics of air pollutants and meteorological parameters

Figure 2 shows the time series of air pollutants and meteorological factors in Linfen from December 1, 2019 to February 29, 2020. The mean concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, CO, and MDA$_8$ O$_3$ during the entire study period were 106.2 μg m$^{-3}$, 139.4 μg m$^{-3}$, 47.2 μg m$^{-3}$, 41.0 μg m$^{-3}$, 1.8 mg m$^{-3}$, and 57.0 μg m$^{-3}$, respectively. The overall mean PM$_{2.5}$/PM$_{10}$ ratio was 0.73, which was higher than the ratio observed in winter in Lhasa (0.48) (Yin et al., 2019), Beijing (0.67) (Li et al., 2017a), (Li et al., 2017b), (Rupakheti et al., 2021), demonstrating that PM$_{2.5}$ accounted for a relatively high proportion
of PM$_{10}$ and mainly came from primary and secondary anthropogenic sources. PM$_{2.5}$ was the major pollutant causing air pollution and reduced visibility in Linfen in winter. Qingdao (0.64) (Urumqi (0.70)). The PM$_{2.5}$ concentration level was higher than the 30.5 μg m$^{-3}$ measured in Lhasa (Yin et al., 2019) and 82.0 μg m$^{-3}$ in Beijing (Zhang et al., 2020) but lower than the 115.7 μg m$^{-3}$ in Xi’an (Yang et al., 2019) and 144.6 μg m$^{-3}$ in Urumqi (Rupakheti et al., 2021) during the winter. Pollution days with the daily concentration of PM$_{2.5}$ above 75 μg m$^{-3}$ accounted for about 60% of the total monitored days, and heavily polluted days with the daily concentration of PM$_{2.5}$ above 150 μg m$^{-3}$ accounted for more than 30%, reflecting severe air pollution in this region.

Six heavy air pollution events occurred on December 8–9 and 22, 2019; January 2–10, 15–18, and 23–26, 2020; and February 8, 2020, with the daily PM$_{2.5}$ concentration higher than 150 μg m$^{-3}$. Four of the six events had >2 consecutive days of high pollution and were thus classified as persistent air pollution events; the maximum duration was 9 days. Such pollution events considerably harm the health of residents. Three heavy air pollution events occurred during the Chinese Little New Year (January 17), Spring Festival (January 25), and Lantern Festival (February 8). On these days, the maximum daily mean concentrations of PM$_{2.5}$ and PM$_{10}$ reached 314 μg m$^{-3}$ and 370 μg m$^{-3}$, respectively, which were much higher than the NAAQS’s daily mean concentration limits of 75 μg m$^{-3}$ and 150 μg m$^{-3}$, respectively. The peak hourly values reached up to 378.0 μg m$^{-3}$ and 449.4 μg m$^{-3}$, respectively. These results indicate that fireworks and firecrackers set off to celebrate traditional Chinese festivals, along with unfavorable air pollution-diffusion conditions, may cause the concentration of PM pollutants to spike (Ning, 2018).

The statistical results of air pollutants in Linfen in each month are shown in Fig. 3. The daily mean concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, and CO ranged from 6.3
to 313.7 μg m⁻³, 14.7 to 370 μg m⁻³, 8.1 to 95.2 μg m⁻³, 3.5 to 142.5 μg m⁻³, and 0.4 to 3.9 mg m⁻³, respectively, with the highest concentration in January and the lowest in February. The mean PM₂.₅ and PM₁₀ concentrations in January were the highest, at 158.1 μg m⁻³ and 193.4 μg m⁻³, respectively, which were similar to that measured in Xinjiang (157.42 μg m⁻³ for PM₂.₅ and 219.16 μg m⁻³ for PM₁₀) (Rupakheti et al., 2021) and exceeded the China NAAQS limit by 2.1 and 1.3 times. The mean SO₂ and CO concentrations were also highest in January, at 54.5 μg m⁻³ and 2.3 mg m⁻³, respectively. The mean NO₂ concentrations were similar in December and January, about 54 μg m⁻³, and then dropped to 28.3 μg m⁻³ in February. By contrast, the MDA8 O₃ ranged from 7.5 to 117.8 μg m⁻³, with the maximum found in February and the minimum in January. The mean MDA8 O₃ concentration in February was up to 81.2 μg m⁻³.

Figure 4 shows the monthly statistics of meteorological factors in Linfen, including temperature, relative humidity, wind speed, visibility, and PBLH. The daily average temperature was between −3.2 and 10.2 °C, with the minimum in December and the maximum in February. The monthly average temperatures in December, January, and February were 1.9 °C, 0.9 °C, and 4.8 °C, respectively. The daily average relative humidity varied from 16.6 to 90.6%. January had the highest monthly average relative humidity of 63.2%, followed by December (49.0%) and February (47.2%). The monthly average wind speed and PBLH in February were the highest at 1.5 m s⁻¹ and 406.7 m, respectively, and the daily maximum reached 4.1 m s⁻¹ and 1168.3 m, respectively, whereas the monthly average wind speed, visibility, and PBLH were the lowest in January at 1.2 m s⁻¹, 4.7 km, and 270.2 m, respectively. A large number of pollutant emissions and unfavorable meteorological conditions in January contributed to higher pollution levels.

Figure 4 Monthly statistics of meteorological parameters in Linfen. The box represents the values from the 25th to 75th percentile. The middle line represents the median. The hollow square represents the mean. The vertical line extends to 1.5 times the interquartile range. Outliers are plotted as solid diamonds. T temperature, RH relative humidity, WS wind speed, V visibility, PBLH planetary boundary layer height

Correlations between air pollutants and meteorological parameters

Spearman’s rank coefficients were used to assess the correlation between the levels of all air pollutants. As shown in Table 1, the hourly concentrations of PM₂.₅

![Box plot of meteorological parameters](image-url)
**Table 1** Spearman’s rank correlations of air pollutants in Linfen based on hourly data for the study period. Correlation coefficients are significant at the 0.01 level

|          | PM$_{10}$ | SO$_2$ | NO$_2$ | O$_3$ | CO    |
|----------|-----------|--------|--------|-------|-------|
| PM$_{2.5}$ | 0.961    | 0.651  | 0.645  | -0.432 | 0.912 |
| PM$_{10}$  | 1         | 0.651  | 0.679  | -0.436 | 0.888 |
| SO$_2$     | 1         | 0.712  | -0.461 | 0.644  |       |
| NO$_2$     | 1         | -0.724 | 0.674  |       |       |
| O$_3$      | 1         | -0.474 |        |       |       |

PM$_{10}$, NO$_2$, SO$_2$, and CO were positively correlated with each other, suggesting that their common origin was the burning of fossil fuels (Wang et al., 2014). Furthermore, O$_3$ had a negative correlation with other pollutants. The most robust relationship was between NO$_2$ and O$_3$, with a correlation coefficient of $-0.724$, reflecting the consumption of precursors and formation of oxidation products (Hamoda et al., 2020).

Meteorological conditions have substantial effects on the formation, diffusion, and removal of air pollutants. The Spearman rank correlation coefficient was applied to evaluate the relationships between air pollutants and meteorological factors, including temperature, wind speed, relative humidity, visibility, and PBLH. As shown in Table 2, the concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, and CO were negatively correlated with temperature. The high surface temperature may reduce the stability of temperature stratification, facilitate the vertical motion of the atmosphere, and result in the dilution and dispersion of air pollutants (Li et al., 2017d). O$_3$ concentrations were positively correlated with the temperature at a correlation coefficient of 0.577, which was due to the strong influence of temperature on the production of O$_3$ by accelerating the rate of chemical reactions and increasing the emission of volatile organic compounds from vegetation (Coates et al., 2016).

|          | PM$_{2.5}$ | PM$_{10}$ | SO$_2$ | NO$_2$ | O$_3$ | CO |
|----------|------------|-----------|--------|--------|-------|----|
| T        | -0.184     | -0.139    | -0.155 | -0.252 | 0.577 | -0.150 |
| RH       | 0.617      | 0.549     | 0.178  | 0.319  | -0.537 | 0.553 |
| WS       | -0.245     | -0.233    | -0.232 | -0.391 | 0.389 | -0.242 |
| V        | -0.930     | -0.876    | -0.479 | -0.533 | 0.458 | -0.844 |
| PBLH     | -0.297     | -0.291    | -0.319 | -0.491 | 0.518 | -0.232 |

PM$_{10}$, NO$_2$, SO$_2$, and CO were positively correlated with relative humidity, and the correlation coefficients were 0.617, 0.549, 0.319, 0.178, and 0.553, respectively. High relative humidity increases the concentration of PM by facilitating the partitioning of semivolatile substances into the aerosol phase, and a moister atmosphere normally accompanies the lower boundary layer, thereby further increasing the concentrations of pollutants dominated by those primary sources (Hoshino et al., 2015). Simultaneously, this study found that all air pollutants other than O$_3$ were negatively correlated with wind speed, visibility, and PBLH. Light winds and low PBLH were the cause of weak dilution of primary pollutants and increased formation of secondary PM (Wang et al., 2014), and the accumulation of pollutants further contributed to the decline in visibility. Strong winds enhance the intensity of atmospheric dispersion and dilution, flushing primary and PM pollutants out of the city. Subsequently, enhanced visibility and solar radiation increase the O$_3$ formed by the photochemical reaction (Li et al., 2017c), explaining the positive correlation observed between O$_3$ level, wind speed, and visibility.

$T$ temperature, $RH$ relative humidity, $WS$ wind speed, $V$ visibility, $PBLH$ planetary boundary layer height

**Diurnal variations of air pollutants**

The diurnal variations of air pollutants for each month were investigated in this study using hourly data to determine potential emission sources. The monthly average diurnal variations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, CO, and O$_3$ concentrations in Linfen are shown in Fig. 5. The diurnal variations of SO$_2$ and CO concentrations had two peaks around 10:00 and 22:00. Coal burning, steelmaking, coking, and electricity production were the main sources of SO$_2$ (Lu et al., 2010). CO is a product of the incomplete combustion of fuel. The main sources of CO were...
steelmaking, coal burning, and vehicle emissions (Streets et al., 2003). The diurnal variations of NO$_2$ concentrations were bimodal, with peaks appearing in the morning rush hour and evening, which indicated that vehicle emissions were the principal source. Steelmaking and electricity production may also contribute to NO$_2$ emissions (Ma & Jia, 2016).

The diurnal variations of PM$_{2.5}$ and PM$_{10}$ had bimodal distributions similar to NO$_2$, SO$_2$, and CO, indicating that primary emissions such as coal burning, steelmaking, coking, electricity production, and vehicle emissions, as well as the secondary formation of sulfates and nitrates, made essential contributions to PM. Generally, the lower levels of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, and CO in the afternoon were caused by higher temperature, wind speed, and PBLH (Fig. 5), which enhanced the dispersion and dilution of air pollutants (Li et al., 2017d). In addition, the higher levels before noon and in the evening were mainly attributed to a low PBLH. The diurnal variations of O$_3$ were different from those of other pollutants with a unimodal pattern. The concentration of O$_3$ began to increase rapidly after 8:00 and reached a peak around 16:00. This coincided with the increase in solar radiation and the decrease in NO$_2$, indicating the photochemical reaction and secondary formation of O$_3$.

The concentrations of PM$_{2.5}$, PM$_{10}$, SO$_2$, and CO increased sharply in January, followed by December and February. The mean hourly concentrations of PM$_{2.5}$ and PM$_{10}$ in January were above 140 µg m$^{-3}$ and 170 µg m$^{-3}$, respectively. The concentrations of NO$_2$ were similar in December and January and higher than that in February. O$_3$ concentration was highest in February, followed by January and December. Business and social activities were suspended to prevent the spread of COVID-19 (Anchordoqui et al., 2020). The decline
Fig. 6 Air mass back trajectory clusters in Linfen in December (a), January (b), and February (c)
of anthropogenic emissions, mainly from industry and transportation, led to a reduction in air pollutants except for O₃ in February.

### Pollution pathways and source regions

Back trajectory clustering has been widely used to illustrate the transport pathway of air masses, and the cluster pathways for each month are shown in Fig. 6. In December, the back trajectories were grouped into five clusters (Fig. 6a). Clusters 1, 2, 3, 4, and 5 accounted for 16.13%, 20.16%, 8.06%, 38.71%, and 16.94% of the total trajectories, respectively. Cluster 1 was characterized by trajectories from Mongolia, crossing Inner Mongolia and Shaanxi Province, and then reaching Linfen. Cluster 2 was from Inner Mongolia, passing through Shanxi and Hebei provinces before arriving at Linfen. Cluster 4 gathered trajectories from Xinjiang and Gansu provinces; subsequently, cluster 4, together with cluster 3, passed through Inner Mongolia, Ningxia, and Shaanxi provinces to Linfen. Mean PM₂.₅ concentrations related to clusters 2, 3, and 4 were 94.76 μg m⁻³, 83.98 μg m⁻³, and 90.82 μg m⁻³, respectively. Cluster 5 originated from Ningxia Province, passed through Gansu and Shaanxi provinces to Linfen. The mean PM₂.₅ concentration related to cluster 5 was the highest among all clusters at 126.98 μg m⁻³.

In January, the back trajectories were divided into four clusters (Fig. 6b). Clusters 1, 2, 3, and 4 accounted for 31.45%, 8.06%, 14.52%, and 45.97% of all the trajectories, respectively. Cluster 1 had the highest mean PM₂.₅ concentration of 188.19 μg m⁻³, which was derived from Hebei Province to Linfen. Cluster 2 began from the south of Shanxi Province with a short transport pattern. Clusters 3 and 4 were from Inner Mongolia, passing through Shaanxi Province before arriving at Linfen. Mean PM₂.₅ loadings related to clusters 2, 3, and 4 were 153.98 μg m⁻³, 155.96 μg m⁻³, and 135.88 μg m⁻³, respectively.

In February, the back trajectories were grouped into five clusters (Fig. 6c). Clusters 1, 2, 3, 4, and 5 accounted for 17.24%, 37.93%, 16.38%, 18.97%, and 9.48% of all the trajectories, respectively. Clusters 1 and 2 came from Inner Mongolia, passing through Ningxia and Shaanxi Provinces, and then reached Linfen. Cluster 3 began in Beijing; traveled through Tianjin, Hebei, Shandong, and Henan provinces; and finally reached Linfen. Cluster 4 was from Hebei and Henan provinces to Linfen, and the mean PM₂.₅ concentration was the highest, at 85.94 μg m⁻³. Cluster 5 represented long-range transport and fast-moving trajectories. It originated in Russia and reached Linfen.

### Table 3 Mean PM₂.₅ concentrations for each cluster

| Cluster | December (μg m⁻³) | January (μg m⁻³) | February (μg m⁻³) |
|---------|------------------|-----------------|------------------|
| 1       | 54.07            | 188.19          | 72.51            |
| 2       | 94.76            | 153.98          | 70.69            |
| 3       | 83.98            | 155.96          | 59.47            |
| 4       | 90.82            | 135.88          | 85.94            |
| 5       | 126.98           | –               | 19.08            |

### Fig. 7

Weighted potential source contribution function (WPSCF) and weighted concentration weighted trajectory (WCWT) maps of PM₂.₅ in December (a, b), January (c, d), and February (e, f).
after passing through Mongolia, Inner Mongolia, and Shaanxi Province (Table 3).

The WPSCF and WCWT maps describe the potential source areas of PM$_{2.5}$. In December (Fig. 7a, b), the main pollution source areas include Xinjiang Province, the middle and east of Gansu Province, the south of Inner Mongolia, the middle of Shaanxi Province, the south of Shanxi Province, the south of Hebei Province, and the north of Henan Province. The WPSCF and WCWT values of these areas were higher than 0.6 and 95 μg m$^{-3}$, respectively. In January (Fig. 7c, d), the critical pollution source regions with WPSCF values exceeding 0.8 and WCWT values exceeding 130 μg m$^{-3}$ included the south of Inner Mongolia, the north of Shaanxi Province, the south of Shanxi Province, and the southwest of Hebei Province. In February (Fig. 7e, f), the north of Gansu Province, the middle of Shaanxi Province, the south of Shanxi Province, and the northeast of Henan Province were the central source regions. The WPSCF values were higher than 0.5, and the WCWT values were higher than 75 μg m$^{-3}$.

**Conclusion**

This study investigated the variations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, CO, and O$_3$ in Linfen from December 1, 2019 to February 29, 2020. PM$_{2.5}$ was the major pollutant causing air pollution during the study period. Six heavy air pollution events occurred with the daily PM$_{2.5}$ concentration exceeded 150 μg m$^{-3}$, which reflects the severe air pollution in Linfen during winter and the potential threat to the health of residents. The maximum daily mean PM$_{2.5}$ concentrations reached 314 μg m$^{-3}$, and the peak hourly values were up to 378.0 μg m$^{-3}$. Fireworks and firecrackers set off to celebrate traditional Chinese festivals may cause the concentration of PM pollutants to spike. The Spearman rank correlation coefficient was used to assess the relationships between air pollutants and meteorological factors. Except for O$_3$, the concentrations of PM$_{2.5}$, PM$_{10}$, NO$_2$, SO$_2$, and CO were negatively correlated with temperature, wind speed, visibility, and PBLH but positively correlated with relative humidity. Large concentrations of pollutant emissions and unfavorable weather conditions, such as lower temperature, weaker wind, higher relative humidity, and reduced PBLH, led to higher pollution levels. Suspensions of social and business activities due to COVID-19 helped reduce anthropogenic emissions, mainly from industry and transportation, and reduced air pollutants other than O$_3$. Air mass back trajectory clusters, PSCF, and CWT analyses demonstrated that PM$_{2.5}$ pollution mainly comes from local emissions in Shanxi Province and regional transport from Inner Mongolia, Shaanxi, Hebei, Henan, and Gansu provinces.

The industrial structure of Linfen is heavy—with coal, coke, steel, and electricity being the leading industries—causing vast quantities of industrial emissions. Such heavy industry must urgently transition to ultra-low emission processes to significantly reduce the air pollutants in the flue gas and improve its environmental management standards (Cui, 2020). The energy structure is dominated by coal, and improvements to the level of clean utilization and structural adjustments toward clean alternative energy are necessary. Coal and coke are mainly transported by road, and the problem of vehicle emissions is prominent. Measures should be taken to eliminate the use of heavy diesel vehicles, develop clean-energy vehicles, strengthen the control of large-scale transportation, and increase the proportion of railway transportation to reduce traffic emissions (Abdulkareem et al., 2020; Angelevska et al., 2021). Moreover, more effective emission reduction measures should be adopted in Shanxi and surrounding provinces to reduce regional emissions. These findings will help policy-makers draft plans and policies to reduce air pollution in Linfe.

**Author contribution** Conceptualization: Lei Liu. Formal analysis and investigation: Lei Liu. Writing-original draft preparation: Lei Liu. Writing-review and editing: Xin Ma, Wei Wen, Chang Sun, Jiao Jiao. Funding acquisition: Lei Liu, Wei Wen.

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**Data availability** The data analyzed in this study were obtained from the Urban Air Quality Real-time Publishing Platform of China (http://106.37.208.233:20035/) and the Chinese National Meteorological Science Data Center (http://data.cma.cn).
Declarations

Conflicts of interest The authors declare that they have no competing 386 interests.

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