Migration and diffusion characteristics of air pollutants and meteorological influences in Northwest China: a case study of four mining areas

Jia Su1 · Guangqiu Huang1 · Zhixia Zhang1

Received: 15 November 2021 / Accepted: 10 March 2022 / Published online: 21 March 2022 © The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2022

Abstract
In the process of exploiting mineral resources, dust enters the environment through air suspended particles and surface runoff, which has a serious impact on the atmospheric environment and human health. From all-year and seasonal scenarios, the migration trajectories and cumulative concentration based on the secondary development of Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) in four mining areas (SF, BC, SJZ, and MJT) in Northwest China are studied. The convergent cross mapping (CCM) method is used to study the causal relationship between concentration and meteorological factors. In this process, the problem of missing non-station meteorological data is solved with the help of the inverse distance weighted interpolation method, and the problem in which the convergence requirements of the CCM algorithm cannot meet the requirements is solved with the bootstrap method. The results indicated that the short path has the characteristics of slow movement, short migration path, low altitude (<1 km), and high contribution rate, while the long path has the opposite characteristics. Furthermore, the results demonstrated that the concentration is centered on the pollution source and diffuses around, with a diffusion radius of 220–270 km, showing a serious pollution center and slight gradient settlement on the edge, but the overall distribution of accumulated concentration is uneven. The results also show that temperature (TEMP and S_TEMP), evaporation, and air pressure are the main meteorological factors affecting the all-year concentration. The concentration and meteorological factors in the four mining areas also show significant seasonal characteristics, and the correlation in spring, summer, and autumn is stronger than that in winter. This study not only provides a reference for the green and sustainable exploitation of mineral resources but also provides theoretical support for the joint prevention and control of transboundary pollution.

Keywords Transboundary pollution · Pollutant migration · Secondary development of HYSPLIT · Meteorological factors · Convergent cross mapping method

Introduction
With the rapid development of China’s industrialization process, environmental problems caused by human activities such as industrial and agricultural emissions have become increasingly prominent (Wang et al. 2020). China has become an important source of global anthropogenic emissions of pollutants (Xiao et al. 2020). Especially in the process of mining mineral resources, the waste discharged from mineral dust enters the environment through surface runoff and air suspended particles (Su et al. 2019; Zhang et al. 2018). This has a serious impact on the atmospheric environment and human health. These factors not only provide a reference for the green and sustainable mining of mineral resources but also provide a theoretical basis for the...
joint prevention and control of the atmospheric environment in the northwestern arid area (Wang et al. 2020).

At present, there have been many studies on the spatial and temporal distribution characteristics of pollutants. According to the different ways of obtaining data, they can be divided into three categories. (i) Historical observation data: Whether the static historical data of environmental monitoring are combined with statistical methods and spatial geographic information systems (Liu et al. 2018; Tian et al. 2019; Yu et al. 2019) or the grid points are generated by the orthogonal decomposition basis function in interpolation data (Bisquert et al. 2017), it is impossible to clarify the emission status and geographic distribution of pollution sources. It is not helpful to track the spatiotemporal evolutionary process of emissions and the cross-domain flow of pollution sources. Therefore, it is impossible to explore the quantitative relationship between the cross-domain flow of air pollution and the pollution degree of recipient cities. (ii) Activity level data: Based on field investigation, the activity level of typical industrial pollution sources and emission factors were obtained (Gao et al. 2019), and a high-resolution atmospheric emission inventory was established based on the tree hierarchy method of the network (Hua et al. 2019). However, the compilation of an emission inventory relies only on national environmental statistical data and general emission factor data, and does not consider the actual characteristics of a region’s pollution emissions (Wang et al. 2020). Therefore, the characteristics of the interregional flow of emissions from industrial sources under the influence of meteorological factors are also ignored. (iii) Interpolation of experimental sample data: The experimental interpolation method takes the distance as the interpolation basis and does not consider the terrain and meteorological factors of the polluted area; therefore, there is a large error. Limited by experimental sampling, it has little operability in obtaining data over multiple years.

Considering the shortcomings of the above research, it has become a trend to simulate the temporal and spatial distribution characteristics of pollutant flow across regions based on meteorological data. The existing research on the cross-domain flow of pollutants mainly focuses on pollutant path tracking and quantitative analysis of transport. Based on the HYSPLIT model, the main transport routes, potential sources and contribution of dust to PM$_{10}$ in the Hexi Corridor were studied (Guan et al. 2019). Ngan et al. (2019) simulated tracer tracing of the diffusion and migration paths of chemically inert trace gases released five times in 5 days. Air mass simulations and concentration weighted trajectory (CWT) based on backward trajectories obtained from the HYSPLIT model and in situ measurements were used to identify the potential sources of air pollutants at the monitoring site (Yin et al. 2021). In regard to path tracking, the HYSPLIT model is undoubtedly one of the most widely used models for atmospheric trajectory diffusion paths (Asadzadeh et al. 2015). In terms of transmission quantitative analysis, the existing research methods are more diversified. Chang et al. (2019) used a regional multiscale air quality model to study the all-year average local contribution rate of 13 cities in the Beijing-Tianjin-Hebei region (BTH) in 2014, which ranged from 32 to 63%. Based on the Weather Research and Forecasting coupled with Chemistry (WRF-Chem) model, the transport budget characteristics of PM2.5 in a haze pollution process in Nanjing were analyzed by using the calculation method of atmospheric transport flux (Tang et al. 2018). Su et al. (2019) took four mining areas as research objects. Based on the Eulerian method of the HYSPLIT model, they simulated the concentration of pollutants in the long-distance migration of mineral dust to other counties to quantify the regional flow concentration of pollutants. In addition, the HYSPLIT model is not only used to calculate pollutant concentrations but is also used as an important estimation method to identify the degree of transboundary air pollution. Du et al. (2020) provided a global estimate of the degree of transboundary air pollution caused by coal-fired power generation. Sulaymon et al. (2021) investigated the impact of transboundary air pollution on air quality in some parts of China, including Anhui Province. Many studies have shown that the HYSPLIT model can not only simulate the long-distance migration path of pollutants with the characteristics of air flow (Lin et al. 2009) but can also simulate concentration diffusion and pollutant deposition with the Euler method for pollutant emissions (Omidvar et al. 2014). Therefore, the HYSPLIT model has good applicability for simulating the characteristics of path migration and diffusion.

With the continuous study of pollution cross-domain flow, it has been found that there are great differences in its concentration on time scales and spatial scales (Xu et al. 2019; Tian et al. 2019). To explore the reasons for this difference, many scholars have studied the correlation between meteorological conditions and pollutant concentrations. Shmool et al. (2014) designed a spatial saturation monitoring study and combined it with GIS analytical tools to study the spatial variability of multiple pollutants in Pittsburgh, USA. The research results showed the effects of meteorological factors such as season, temperature, and altitude on the change in pollutant concentration. Cross-correlation analysis was performed with air temperature, solar radiation, wind direction, and velocity (Battista and Vollaro 2017). It is noted out that weather changes are strongly coupled with pollutant concentrations in most cases. After further study, the concentration of pollutants and complex meteorological factors constitute a nonlinear system (Chen et al. 2020; Liu and Lei 2019). Nonlinear variables usually show unstable correlation states. This indicates that there is causality between seemingly
unrelated, weakly coupled variables. The traditional Granger causality test has an important premise that the time series must be stable, that is, the curve fitted by the time series of sample data has not changed significantly and there is no significant difference between the variance of any sample data. On the other hand, Granger causality test is suitable for the identification of causality between strongly coupled variables (Liu and Lei 2019). There is no way to identify the causal relationship between weakly coupled variables (Liu and Lei 2019). To make up for the shortcomings of the Granger causality test, Sugihara et al. (2012) proposed a convergent cross mapping algorithm for the first time. This algorithm has good applicability for the identification of causal relationships between weakly coupled variables in nonlinear systems and has been widely used in ecology, environmental science, geography, and other research fields (Chen et al. 2020; Liu and Lei 2019).

Therefore, based on the HYSPLIT model to simulate the forward trajectory of pollutants, the transmission trajectories of pollutants in four mining areas are obtained by seasonal scenarios. Seasonal scenarios of cumulative concentration are simulated by the secondary development of HYSPLIT. The causal relationships between seasonal concentration and various meteorological factors are traced by using the convergent cross mapping model. The structure of this paper is shown in Fig. 1.

**Materials**

**Study areas**

In this study, four mining areas in Northwest China (Shaanxi, Gansu, and Ningxia) in national mineral
resources planning (2016–2020) are taken as the research cases (Shenfu, Binchang, Majiatan, and Shajingzi mining areas) and as the starting point of pollution. The Shenfu mining area (38°52′–39°27′N, 110°05′–110°50′E) is located in Shenmu and Fugu counties (Tao et al. 2010). It is the largest proven coalfield in China, with Pb, Zn, and Cu as the main heavy metals in mine dust and gangue. The Binchang mining area is located in the gully region of the Loess Plateau, northeast of Xianyang city, Shaanxi Province, and the main heavy metal pollution includes chromium, Zn, and Pb (Liu et al. 2016). The Majiatan mining area is located in the southeast part of Wuzhong city, Ningxia, and its administrative division is under the jurisdiction of Fengjigou Township, Yanchi County, Wuzhong city. The Shajingzi mining area is located in Qingyang city, Gansu Province, and the main heavy metals in the two mining areas include polluted Zn, Cu, and Cr. The four mining areas are typical industrial emission enterprises. Four mining areas are selected as the research object to comprehensively consider the contribution of the mining area to emissions and the geographic location of the mining area. For details and reasons, refer to Su et al. (2019). Therefore, tracking the transmission trajectory, simulating the concentration distribution of pollutants and studying the influence of meteorological factors are of great significance to study the cross regional flow of pollutants.

### Data sources

There are 77 monitoring stations in Shaanxi, Gansu, and Ningxia, which are located in different regions of the three provinces (Fig. 2). This study takes four mining areas as the research center and selects 11 monitoring stations. The detailed locations of 11 stations (Shenmu, Qindu, Jinghe, Wugong, Guyuan, Xiji, Haiyuan, Huanxian, Tongxin, Zhongning, and Wuzhong) are shown in Table S1 in the Appendix A supplementary data. The location and distribution of these four mining areas and monitoring stations are shown in Fig. 2. The data of 77 monitoring stations, including the meteorological data of the 11 monitoring stations used in the article, are from the National Meteorological Science Data Center (http://data.cma.cn/). The daily value dataset of China’s surface climate data is from 2016 to 2017 (V3.0). A set of comprehensive meteorological elements, including mean temperature (TEMP), mean relative humidity (RH), mean wind speed (WS), wind direction (WDIR), sunshine hours (SSD), evaporation (EVAP), mean atmospheric pressure (PRS), and mean surface temperature (S_TEMP), is selected. It is worth mentioning that the mean temperature (TEMP) is the mean temperature of the vertical profile, and the mean surface temperature (S_TEMP) is the ground temperature at 0 cm. The meteorological data from non-monitoring stations (four mining areas) come from the inverse distance weighted interpolation method of the...
monitoring stations. The concentration data of the four mining areas are calculated as follows.

The general situation of the four mining areas comes from the national information publicity system for exploration and mining of mining owners (http://kyqgs.mlr.gov.cn/index.jhtml). The selection of the four mining areas comes from the national mineral resources planning (2016–2020). The initial meteorological data of the HYSPLIT model are from the Global Data Assimilation System (GDAS) (ftp: Supplementary material/arftp.arlhq.noaa.gov/pub/archives/gdas1/). Google Earth and ArcGIS 10.2 are used for image data. Other data are from published articles. Micro Visual Studio 2012 is used for model calculation.

Methods

HYSPLIT model

The HYSPLIT model is a professional model developed by the Air Resources Laboratory of the National Oceanic and Atmospheric Administration (NOAA) and the Australian meteorological service in the past 20 years, which is used to calculate and analyze the transport, diffusion trajectory, and dry–wet deposition of atmospheric pollutants (Shan et al. 2017). Based on the hybrid single event Lagrange trajectory model, it is one of the most widely used models in atmospheric trajectory diffusion and subsidence simulation (Rolph et al. 2017; Stein et al. 2016). The model has the ability of forward calculation and backward calculation. The model cannot only simulate the long-distance migration path of pollutants by using air flow characteristics (Li and Zhang 2012) but can also simulate concentration diffusion and pollutant deposition by using the Eulerian method for pollutant emissions (Chen et al. 2018; Dare et al. 2016; Draxler et al. 2012a, b).

Forward trajectory based on HYSPLIT

According to the HYSPLIT model, the forward trajectory is simulated. In view of the uncertainty of a single trajectory and its limited meaning, a method based on total spatial variance (TVS) was proposed (Draxler et al. 2012a, b). According to the principle of minimizing interclass differences and maximizing intraclass differences, 694, 724, 722, and 720 forward trajectories of Shenu (38.83 N, 110.5 E), Binchang (34.32 N, 108.73 E), Shajingzi (36.33 N, 106.47 E), and Majiatan (37.36 N, 106.51 E) are clustered, respectively. There are two scenarios migration trajectories of pollutants in the four mining areas, including seasonal and all-year trajectories, which are simulated.

In the process of trajectory simulation, some parameters of the HYSPLIT 4.0 model are set as follows: from March 1, 2016, to February 28, 2017, 00:00 (UTC) is selected as the starting time point, 36 h is set as the time of the forward track, and the trajectory starting height is selected as 10 m from the ground. The selection of this height is considered to be near the ground (Qiu et al. 2009).

Cumulative concentration based on the secondary development of HYSPLIT

Since the daily concentration value can be simulated by HYSPLIT, it cannot calculate the accumulated concentration in the time period, such as a whole year or a season. In this paper, we first simulate the daily concentration value 365 times, and then the 365 simulation values of concentration at the same latitude and longitude are summed. Thus, the sum of the annual accumulated concentrations can be obtained. However, because the function of the HYSPLIT concentration setup needs to be manually input, there are more than 30 pieces of data each time (e.g., the cumulative concentration in the year needs to be manually input to 30 × 365 pieces of data), which is too complex and redundant. Therefore, step (1) of generating HYSPLIT concentration setup () is designed in this paper. The fixed three-dimensional grid is used to simulate the daily concentration by HYSPLIT to form a map of the plane concentration distribution. The annual cumulative concentration is used to obtain the concentration of longitude and latitude at the same time or similar grid points 365 times. The process involves the selection of the grid range and the size of the grid density; therefore, step (3) of calculating the annual or seasonal cumulative concentration () is designed in this paper. The results of step (3) are points composed of longitude, latitude and concentration, which need to be transformed into faces through ArcGIS; therefore, step (4) of rasterizing the annual or seasonal accumulated concentrations () is needed. The software interface for calculating cumulative concentration based on HYSPLIT secondary development and pseudocodes of each function are shown in Fig. S1 in the Appendix A supplementary data. The accumulated concentration of multiple pollution sources is calculated. Thus, the daily concentration accumulation of pollutants in the process of diffusion and migration in the four mining areas is simulated by seasonal and all-year scenarios. It is worth noting that no matter what the conditions are, the model is always calculated in terms of unit concentration. When the unit concentration is multiplied by the measured emission rate of pollutants, the predicted concentration of each region can be obtained.

The basic parameters such as the pollution starting point and simulation time are the same as those in Section 3.1.1. The parameters that need to be added as follows: when both dry and wet deposition exist, the resolution is 0.01° × 0.01°, the pollutant release rate is 1.0 kg/h, and the vertical height is 0, that is, the surface level.
Convergent cross-mapping (CCM)

Under the influence of complex meteorological factors, pollutants migrate and diffuse from the pollution source to the surrounding areas. There is a weakly coupled causality between the meteorological factors and pollutant concentration, which constitutes a nonlinear system. In this paper, the convergent cross mapping algorithm is used to quantify the causal relationship between each meteorological factor and pollutant concentration. The key meteorological factors of pollutant migration and diffusion are identified, which provides a reference for the emission reduction of pollutants.

The idea of the convergent cross-mapping algorithm is based on embedding theory and state space reconstruction technology (Sugihara et al. 2012). Two time series variables, meteorological factor (8 meteorological factors in Section 2.2) and pollutant daily concentration step (2) of cumulative concentration based on the secondary development of HYSPLIT in Appendix A) \( Y \), with the period length of \( L \), are set. Suppose that the dimension of reconstructed shadow manifolds is \( E \); then \( \tau > 0 \) is lagged-time and depends on the availability of data in actual situations. By generating lagged-coordinate embeddings of \( X \) and \( Y \), shadow manifolds of \( M_x \) (Formula (1)) and \( M_y \) (Formula (2)) are reconstructed:

\[
M_x : x(t) = \langle X(t), X(t-\tau), \ldots, X(t-(E-1)\tau) \rangle \quad (1)
\]

\[
M_y : y(t) = \langle Y(t), Y(t-\tau), \ldots, Y(t-(E-1)\tau) \rangle \quad (2)
\]

where \( t \in [1+(E-1), L] \). Lagged-coordinate embeddings \( g(t) \) in the same period and the nearest \( E+1 \) points can be found on \( M_y \). The weighted \( w_i \) is constructed by these points, and then the real value of \( X \) is a locally weighted average. Then, a cross-mapping estimation of \( X(t) \) is created in Formula (3), as well as the cross-mapping estimation of \( Y(t) \) in Formula (4):

\[
\hat{X}(t)|_{M_y,i} = \sum w_i X(t_i), i = 1, 2, \ldots, E + 1 \quad (3)
\]

\[
\hat{Y}(t)|_{M_x,i} = \sum w_i Y(t_i), i = 1, 2, \ldots, E + 1 \quad (4)
\]

That is, meteorological factor \( X \) is the cause of the daily concentration \( Y \) of pollutants. The calculation of the weighted \( w_i \) and CCM algorithm are from previous studies (Chen et al. 2019; Liu and Lei 2019; Sugihara et al. 2012).

Results

Simulation of the temporal and spatial distributions of the pollution load based on the HYSPLIT model

To determine the temporal and spatial distribution characteristics in the process of multisource pollutants emissions, the forward trajectory and concentration of pollutants were simulated based on the HYSPLIT model by seasonal and all-year scenarios, respectively. The simulation process was divided into four sections, and then one by one was simulated.

All-year forward clustering trajectories

Four pollution sources in 74 national planning mining areas in arid areas of Northwest China were selected as the starting points of pollution. Based on the HYSPLIT model, 694, 724, 722, and 720 forward trajectories of Shenfu, Binchang, Shajingzi, and Majiatan were clustered into 5, 6, and 6 forward trajectories, respectively (details of determining the number of clusters based on total spatial variance are provided in the Appendix A supplementary data). The clustering trajectory is shown in Fig. 3 (a) Shenfu, (b) Binchang, (c) Shajingzi, and (d) Majiatan.

Figure 3(a) shows that the air mass in the Shenfu mining area at the starting point of the simulation was divided into five paths (Table 1): The first and second routes passed through the Yellow River northeast of the pollution source. The former passed through northern Shanxi Province and reached the junction of Zhangjiakou and Baoding in Hebei Province (short-range, contribution rate accounting for 26% of the total path). The latter crossed Hohhot city in Inner Mongolia, Zhangjiakou city in Hebei, and Chengde city in Northeast China (long-range, accounting for 10%). The third route passed through southern Shanxi from the southeastern direction of pollutants to Jincheng city, accounting for 24% of the total path. The fourth route was from the southwestern pollution source through the Yulin area of the province to southern Inner Mongolia, which is a short range, accounting for 16%. The fifth route directly reaches the central part of Inner Mongolia from the northern pollution source, accounting for 16%.

The short-range route of the air mass in the Binchang and Shajingzi mining areas was mainly concentrated in the provinces where the pollutants were located and the surrounding northeastern and southeastern provinces, while the long path was mainly concentrated in the northeast (Fig. 3(b) (c) and Table 1), which was consistent with the Shenfu mining area. The long path of the Majiatan mining area was in the southeast, and the short path was relatively scattered.

All-year cumulative concentration of pollutants

The concentration of pollutants in 2016–2017 was accumulated and summed, and the calculation process and step of cumulative concentration in the year and seasons based on the secondary development of HYSPLIT are shown in Section 3.1.2 and Appendix A. supplementary data. The
accumulated concentrations of the four mining areas over 365 days from 2016 to 2017 were visualized by ArcGIS 10.2, as shown in Fig. 4.

According to the results, the accumulated concentration of pollution sources in the Shenfu mining area was 0.16–154 g/m³, Binchang mining area is 2.1–210 g/m³, and Shajingzi and Majiatan mining areas were 0.2–134 g/m³. Figure 4(a), (c), and (d) shows that the pollution range of the Shenfu, Shajingzi, and Majiatan mining areas was wide and the pollution load was relatively scattered, while Fig. 4(b) shows that the pollution range of the Binchang mining area was relatively concentrated. In addition, Fig. 4 shows that the area with a serious pollution load was around the four pollution sources. It was not uniformly distributed but distributed in the area where the air mass trajectory passed in Fig. 3. Taking Fig. 4(a) as an example, we find...
that the pollution load in the Shanxi area far from the pollution source was more serious than that in the area near the pollution source between Shanxi and Inner Mongolia in the first air mass path in Fig. 4(a) and so is Fig. 4(d).

Table 1: Results of cluster means in different four mining area

| Starting points   | Number | E/S (26%) | E/S (50%) | S/S (14%) | SE/S (21%) |
|-------------------|--------|-----------|-----------|-----------|------------|
| Binchang          | (34.32 N, 108.73E) | NE/L (10%) | N/S (29%) | E/S (12%) | E/S (12%) |
| Shajingzi         | (36.33 N, 106.47E) | SE/S (24%) | SE/M (6%) | N/S (29%) | NE/S (23%) |
| Majiatan          | (37.36 N, 106.51E) | W/S (16%) | NW/M (11%) | SE/S (13%) | SE/L (1%) |
| Shenfu            | (38.83 N, 110.50) | W/S (24%) | NE/L (2%) | W/S (27%) | W/S (37%) |
| Binchang          | (34.32 N, 108.73E) | NE/L (2%) | W/N/M (4%) | W/N/M (7%) |           |
| Shajingzi         | (36.33 N, 106.47E) | NE/L (1%) |           |           |            |

The threshold for distinguishing long and short trajectories is 3000 km (Li et al. 2010). Based on the above, a path less than 1000 m is defined as a short path, and the rest is defined as a medium path. E, eastern; N, northern; S, southern; W, western; S, short-range; M, medium-range; L, long-range.

Fig. 4: Cumulative pollution load map of four pollution sources and surrounding areas under dry and wet deposition (g/m³)
Seasonal variation forward clustering trajectories

Starting from the four mining areas in Section 4.1.1, the migration trajectory of pollutants in the mining area was simulated in different seasons. The research period from March 2016 to February 2017 was divided into four seasons. March to May 2016 was divided into spring; June to August 2016 was divided into summer; September to November 2016 was divided into autumn; and December 2016 to February 2017 was divided into winter, respectively. The simulation parameters were the same as those in Section 4.1.1. The simulation results of the seasonal variation in the pollutant migration trajectories of the four mining areas are shown in Fig. 5.

According to the simulation results in Fig. 5(a), the clustering trajectories of pollutants in the Shenfu mining area were mostly concentrated in the northeastern and southeastern directions in spring, and only the fifth path appeared in the western direction, accounting for 12% of the total number of paths. In autumn and winter, the clustering path direction was more single and concentrated, which was also distributed in the northeast and southeast. Compared with spring and summer, most of the pollutant migration paths in these two seasons were short-range paths and long-range paths. In summer, the path length of pollutant clusters in the Shenfu mining area was mostly the medium-range path, and the path proportion was relatively uniform.

The clustering trajectories of pollutants in the Binchang mining area in the four seasons were mainly concentrated in the northwestern and southeastern directions (Fig. 5(b)). Approximately 10% of the paths in spring and summer were distributed in the northeastern direction, and the long paths all migrated to the northeastern direction, but the proportion was small. The spring and winter paths of the Binchang mining area were similar. In the Binchang mining area, there were single paths in autumn, and there were fewer long-range paths. The short paths were concentrated in the north and southeast, and the distribution of the paths in summer was more uniform.

The four seasonal clustering trajectories of pollutants in the Shajingzi mining area were mostly distributed in northwestern and southeastern directions (Fig. 5(c)), which was similar to the Binchang mining area. The migration paths of pollutants in spring, autumn, and summer were very similar, and only 2% of long paths migrated to the northeast in spring. In winter, in addition to the northwest and southeast, 32% of the paths migrated to the southwest.

According to the simulation results in Fig. 5(d), the distribution of pollutant clustering trajectories in the Majiatan mining area is relatively uniform, and the distribution is in four directions. In winter, the clustering trajectories of pollutants were mainly short paths, and only 2% of them were long paths. In spring and autumn, the clustering trajectories of pollutants were mostly short paths and medium paths, while the long path is less, while in summer, there were more medium and longer paths.

Seasonal variation of pollutant concentration

Taking the four mining areas in Section 4.1.1 as the starting point, the concentration of pollutants in the mining area was simulated in different seasons. The research period was from March 2016 to February 2017, and the simulation parameters were the same as those in Section 4.1.2. The simulation results of the pollutant concentration of the four mining areas are shown in Fig. 6, and the legend is the same as the legend in Fig. 4.

In Fig. 6(a), the concentration distribution of the Shenfu mining area in autumn and winter was relatively uniform around the pollution source. The high concentration areas were mainly concentrated in the northern part of Shaanxi, the northern part of Shanxi Province, and the central region, showing regional pollution. In the Northern Shaanxi area around the pollution source, the concentration of pollutants in autumn was higher than that in winter, while the concentration in other areas was more obvious in winter. In spring, the pollutant concentration was distributed in spots. It rarely migrates and diffused outwards, and the pollutant concentration was not obvious (Fig. 6(a)). It mainly concentrated around the pollution source and the northeastern area of Shaanxi Province, which was quite different from the other three seasons. In summer, the high concentration area of pollutants in the Shenfu mining area mainly migrates and diffuses from the pollution source, but the diffusion range was narrow, which was limited to northern Shaanxi and Datong city of Shanxi Province.

Compared with Figs. 6(a) and (b), the concentration distributions of the Binchang and Shenfu mining areas were quite different. The latter concentration spatial distribution was relatively concentrated and distributed around the Binchang mining area. Although the concentration distributions in autumn and winter were relatively similar, the concentration distribution in autumn was more dispersed than that in winter. The high concentration areas in autumn included not only central Shaanxi and eastern Gansu as in winter but also southern and northern Shaanxi and the junction of Inner Mongolia and Shaanxi. In spring, the concentration distribution of pollutants was concentrated, and the diffusion was less. This was the same as the Shenfu mining area. In summer, except for a small amount of migration to Northwest China’s Gansu Province, most of them were concentrated around the pollution sources.

Figure 6(c) shows that the spatial distribution of high concentrations of pollutants in the Shajingzi mining area was similar in autumn and winter, showing a north–south zonal distribution. In autumn, the high concentration pollutants...
also diffused to Weinan, Xi’an, and other areas in central Shaanxi Province. In addition to the same distribution as autumn, the concentration distribution in winter also included Tianshui and Pingliang in eastern Gansu Province. In spring, the pollutant concentration was distributed in spots and rarely migrated and diffused outwards, which was...
the opposite of summer. The pollutants were more dispersed, and outward diffusion from the pollution source presented a star distribution in summer.

Figure 6(d) shows that the high concentration areas of pollutants in the Majiatan mining area were mainly concentrated in the Ningxia Hui Autonomous Region, where the pollution...
source was located. Only in winter, did they migrate to Xi'an and other places in the central part of Shaanxi Province. In autumn and summer, pollutants moved to the beginning of the border between Inner Mongolia and Ningxia. Pollutants were dispersed in Inner Mongolia in autumn and concentrated in summer. In spring, the areas with high concentrations of pollutants were mainly concentrated around the pollution source and rarely migrated and diffused to other areas. The pollutant concentration was distributed in spots in spring, which was consistent with Shenfu (Fig. 6(a)), BinChang (Fig. 6(b)) and Shajingzi (Fig. 6(c)).

**Analysis of key factors affecting pollutant migration based on CCM**

**Parameter selection and astringency of the CCM algorithm**

Although the CCM algorithm was not sensitive to the selection of parameters (Van Nes et al. 2015), for the sake of
precision, this paper must give the determination method of key parameters. The value of lagged time $\tau$ and dimension of reconstructed shadow manifolds $E$ are two key parameters of CCM. Because the meteorological data and pollutant concentration are collected according to the daily value, the $\tau$ value of lagged-time is 1. Four mining areas (SF, BC, SJZ,
Fig. 6 (continued)
and MJT) for correlation analysis between daily concentration and mean temperature (TEMP) with dimensions of shadow manifolds $E$ from 1 to 12 (step = 1) were simulated and calculated, respectively, in Fig. 7.

Figure 7 shows the correlation coefficient curve of the iterations $t$ with the concentration and TEMP of the four mining areas, where $\tau = 1$ and $E$ from 1 to 12 (step = 1). As shown in Fig. 7, with increasing $E$, the correlation coefficient in the four mining areas showed a trend of first increasing and then stabilizing. That is, when the dimension of the reconstructed shadow manifolds $E \in [1, 6]$, the greater $E$ was, the greater the strength of causality between concentration and TEMP. When the dimension of the reconstructed shadow manifolds $E \in [7, 12]$, the strength of causality tended to be stable. Therefore, in the time series of concentration and TEMP in the four mining areas, the strength of their causality was basically linear with the dimension of reconstructed shadow manifolds. In general, the curve of the correlation between concentration and average temperature in Fig. 7 converged to approximately $t = 175$, but it cannot be concluded from the curve that $E$ was related to the convergence rate. In addition, according to the description of the CCM algorithm in Sect. 3.2, as $E$ increases from 1 to 12, the simulation data indicated that the time series of the initial value of $t$ was from 1 to 12 (Fig. 7(a)) and the final value was the period length of $L = 365$. That is, for each mining area, the larger the value of the dimension of reconstructed shadow manifolds $E$ was, the smaller the time series of the

![Fig. 6 (continued)](image-url)
correlation coefficient. Considering the accuracy and efficiency of the CCM algorithm, the value of $E$ should be set as 7 in the time series of concentration and meteorological factors in the four mining areas.

CCM causality test between all-year concentration and meteorological factors

The causal relationship between the concentration of pollutants around the four mining areas and meteorological factors was studied based on the inverse distance weighted interpolation method. This method was based on the similarity principle. Each sampling point has a certain influence on the interpolation points, that is, the weight. The weight decreases with increasing distance between the sampling point and the interpolation point (Hu et al. 2021; Zhang et al. 2012). The meteorological data of the four mining areas were obtained through multiple monitoring stations around the four mining areas. The monitoring stations near the four mining areas were selected (Table S1 in the Appendix A. supplementary data).

The daily concentration of the monitoring station can be obtained by the secondary development of HYSPLIT. The calculation process and procedure are shown in the Appendix A of the supplementary data. Therefore, according to the convergent cross-mapping algorithm in Section 3.2, the causal relationship between the eight meteorological factors in the daily value data of China’s surface climate data and the daily concentration of pollutant migration was calculated. The calculation results are shown in Fig. 8.

Figure 8 is a curve of the correlation coefficient over time with $\tau = 1$ and $E = 7$ in the four mining areas. The curve as a whole fluctuated first and then stabilized, and the correlation coefficients between concentration and individual meteorological factors are concentrated in a range of $[-0.2, 0.7]$. Figure 8(a), (b), (c), and (d) showed that the correlation

![Fig. 7 Correlations between daily concentration and TEMP with $\tau = 1$ and $E$ from 1 to 12 (step = 1) in the four mining areas](image-url)
curve of concentration and individual meteorological factors in the SF mining area converges earlier than that in the other three mining areas, converged at approximately \( t = 75 \). The BC and SJZ mining areas converge at approximately \( t = 175 \), and MJT converging at approximately \( t = 150 \). For the individual meteorological factors (Fig. 8(f)), there is an obvious correlation between concentration and temperature, including mean temperature (TEMP) and mean surface temperature (S_TEMP), evaporation (EVAP), and mean atmospheric pressure (PRS). There was no significant correlation between other meteorological factors and concentration. It was worth noting that for the four mining areas in Fig. 8(e) and (f), the correlation between the mean surface temperature (S_TEMP) and concentration was more obvious than the mean temperature (TEMP). For the four mining areas (Fig. 8(e)), the correlation between concentration and temperature was obvious in the SF, SJZ, and MJT mining areas, while the concentration in the BC mining area was closely related to EVAP. According to the all-year cumulative concentration of BC pollutants in Fig. 4(b), its spatial distribution was different from that of the other three mining areas. This was consistent with the difference between BC meteorological factors and the other three mining areas. In addition, the correlation between concentration and meteorological factors was more obvious in the SF mining area than in the other three mining areas, which may be related to the fact that the monitoring stations around the other three mining areas were far away from the mining area, which made it difficult to obtain accurate meteorological factors in the mining area.

**CCM causality test between seasonal concentration and meteorological factors**

The conclusions in Sections 4.2.1 and 4.2.2 showed that the correlation curves of concentration and meteorological factors in the four mining areas converged at approximately \( t = 75 \), \( t = 175 \), \( t = 175 \), and \( t = 150 \), respectively, but the period length of \( L \) of seasonal data was at most 92, which did not meet the convergence requirements of correlation curves. Therefore, causality tests of BC, SJZ, and MJT used bootstrapping to leverage spatial information to solve the problem in which short time series cannot meet the convergence requirements (Clark et al. 2015). The impact of individual meteorological factors on seasonal concentrations in the four mining areas with \( r = 1, E = 7 \), and \( L = 184 \) in spring and summer; \( L = 182 \) in autumn; and \( L = 180 \) in winter is shown in Fig. 9.

Figure 9 showed that the correlation between the all-year concentration and meteorological factors was obviously stronger than the seasonal concentration, but generally speaking, the relationship between the concentration and meteorological factors in the four mining areas presented obvious seasonal characteristics and the correlation between the concentration and meteorological factors in spring, summer, and autumn was stronger than that in winter. For the SF mining area, meteorological factors had a greater impact in autumn and spring. Among them, temperature (S_TEMP and TEMP), PRS, and RH were the main factors affecting seasonal concentration. EVAP, S_TEMP, and RH were the key factors affecting the concentration in summer. In addition to temperature (S_TEMP and TEMP) and RH, the correlation in winter with other meteorological factors was not significant. For BC, summer and spring were more affected by meteorological factors than autumn and winter, among which WS and PRS in summer; RH and PRS in spring were not obvious, respectively. For SJZ, temperature (S_TEMP and TEMP) and WS were obvious in spring and summer, EVAP and SSD were obvious in autumn, and SSD and WS were obvious in winter. For MJT, temperature was still the main factor affecting concentration. In addition, EVAP was obvious in summer, autumn, and winter, while WS was obvious in spring, summer, and autumn.

Since the relationship between concentration and meteorological factors had obvious seasonal characteristics, a statistical study was carried out to determine whether the correlation between concentration and meteorological factors in the four mining areas was significant (as shown in Table 2). Correlations and their stability were very different at the mining area scale. Taking SF, for example, meteorological factors had a relatively stable impact. Specifically, temperature (S_TEMP and TEMP), PRS, and RH produced significant and stable impacts; WS and WDIR produced stable but not significant effects. For BC, the correlation of meteorological factors and concentration was not as stable (the CV was larger). On the scale of meteorological factors, WS had a relatively consistent impact on the concentration in each mining area, while the correlation and stability between PRS, RH, S_TEMP, and the concentration in different mining areas had large variations.

**Discussion**

**Temporal and spatial distribution characteristics of pollution load**

According to the results, the pollutants were discharged locally at high concentrations and flowed across the region to other surrounding provinces. As a whole, it presented a cascade diffusion law with the pollution source as the center and spreading around, the diffusion radius range was 220–270 km, the pollution center was serious, and the edge was slight (Fig. 4). There were some differences in that the concentration of pollutants was decreasing and
the pollution range was expanding over time (Lei et al. 2010). The reason for this is that the pollution source in this paper was simulated under the condition of continuous emission of pollutants, and the release time of pollutants was set at 36 h, which was also in line with the actual situation of mine dust emissions. Lei et al. (2010) simulated...
a pollutant emergency and set the pollutant release time to 1 h.

In this study, Guanzhong Basin in central Shaanxi, especially in winter and autumn, was undoubtedly one of the areas most polluted by local emission accumulation of pollution sources (Fig. 4(b)). There are two reasons for this. In terms of pollution emissions, a large number of heavy industries, especially coal, oil, and other energy related industries, are located in Xianyang, Tongchuan, Weinan, and other places, resulting in too much dust and other particles, and the emission from heating in winter would be more serious. Topographically, the Guanzhong Basin is located in an east–west direction and is surrounded by the Qinling Mountains and Loess Plateau. Less than 20% of the weather is conducive to the diffusion of air pollutants, and other meteorological conditions lead to the accumulation of local pollutants and the input of external sources. The days of heavy pollution in autumn and winter in Guanzhong Basin in Shaanxi Province account for almost 90% of the incidence of haze in the whole year, which may be related
to the above reasons. At the same time, Guanzhong Basin is also affected by the cross-regional flow from foreign sources. From the results in Fig. 4(c) and (d), the exogenous pollutants in the northwestern parts of the Shajingzi and Majiatan mining areas flowed to the Guanzhong Basin in winter. In addition, the contribution rate of regional transport from Shanxi and Henan to the pollution of Guanzhong Basin was 22.2%, and with the increase in PM$_{2.5}$ concentration, the contribution of regional transport continued to increase (Li et al. 2021a, b; Bei et al. 2017). It can also be concluded that Datong in northern Shanxi and Taiyuan in central Shanxi were seriously polluted all year round, which may also be related to the pollution emission source in northern Shaanxi (Fig. 4(a)).

This also showed that the cumulative concentration of pollutants presented an uneven cascade diffusion law. However, there was a large difference between this and the results of the statistical and geographic analysis of the point kriging method in Battista and Vollaro (2017). The threshold friction velocity dependent on surface roughness was considered in the simulation of concentration diffusion and pollutant deposition based on the HYSPLIT Eulerian method (Draxler et al. 2012a). In other words, it was related to the geological and soil properties of pollution receptors; therefore, the distribution of pollution settlement was not uniform. This also shows that strengthening the coordination and joint prevention and control between Fenwei Plain cities was an important means and main direction to solve China’s air pollution prevention and control. However, the pollution control effect was not obvious. In recent years, heavy pollution weather has occurred in autumn and winter. Therefore, based on meteorological big data, studying the temporal and spatial characteristics of the cross-regional flow of pollutants, finely dividing pollution related areas, and establishing a network-related model of regional joint prevention and control can provide a solution for pollution prevention and control on the Fenwei Plain.

**Analysis of influencing factors of pollutant migration**

As previously mentioned, the correlation between the all-year concentration and meteorological factors was obviously stronger than the seasonal concentration. This was consistent with previous study (Chen et al. 2019). The reason for this is related to the parameter of the period length $L$ of the CCM algorithm, and the correlation coefficient increases with increasing $L$. In turn, it also showed that it was effective in increasing the length of the short sequence by the bootstrap method when the convergence length of the CCM algorithm did not meet the convergence requirements of the original short sequence. Different original sequences had different requirements for the dimension of reconstructed shadow manifolds $E$, but basically the correlation coefficient increased with the increase of the $E$ value. It has not been found that $E$ is related to the convergence speed.

The emission of particulate matter, such as coal combustion in winter in Guanzhong area, was the main cause of pollution, and the inversion layer phenomenon was a favorable meteorological factor for the formation of heavily polluted weather. In the inversion layer phenomenon, the low temperature near the surface was pressed by the high temperature (TEMP) at high altitude, which hindered the upward movement of the air, resulting in the continuous accumulation of pollution emissions on the surface and aggravating air pollution. This conclusion was confirmed in this study. Meteorological factors of the mean surface temperature(S_TEMP) and mean temperature (TEMP) were used. It was concluded that the correlation between S_TEMP and concentration was more significant than TEMP and S_TEMP was significantly higher than TEMP in winter and autumn, which also showed that the mean surface temperature could not be ignored in the selection of meteorological factor indicators. In addition, the difference between the mean surface temperature and mean temperature might be more reasonable than a single index.

Low wind speed and static weather in Shaanxi, Gansu, and Ningxia, especially in the Guanzhong region, were important reasons for the difficult diffusion of pollutants. This conclusion was also confirmed in this study. Therefore, strengthening the relocation and transformation of heavily polluting enterprises from the source and effectively using meteorological means to improve urban land layout and strengthening air duct construction were promising solutions to solve serious local pollution. The former removed polluting factories from the city through geographic methods, resulting in the degradation of the environment in its suburbs and rural areas. Environmental spread and backwash effects might help explain the severe intraregional environmental and economic disparities and environmental injustice (Liu 2013). Environmental co-governance effectively avoided possible pollution transfer due to the differences in environmental control intensity in different regions (Li et al. 2021a, b). The latter would boost and accelerate the depletion of pollution by transforming the urban air duct of Xi’an in the Guanzhong area and improving the air duct system to improve the low-level atmospheric circulation between urban and rural areas and accelerate the discharge and digestion of air pollutants (Huang et al. 2019).

**Conclusions**

Taking four mining areas in Northwest China as an example, this paper studied the migration trajectory and concentration in the process of mine dust discharge during the
period from March 2016 to February 2017. We revealed the temporal and spatial distribution characteristics of pollutant migration and diffusion and traced the causal relationship between pollutant concentration and meteorological factors. In terms of the pollutant migration trajectory, the short-range path had the characteristics of slow movement of air mass, short migration path, low altitude (less than 1 km), high contribution rate of air mass path, and easy intersection to short-range path, which was just opposite to the long-range path. From the perspective of pollutant concentration, the pollution concentration was concentrated on the pollution source and diffuses to the surrounding area, with a diffusion radius of 220–270 km, showing the law of a serious pollution center and slight settlement of edge steps, but the overall distribution of cumulative concentration was uneven. In addition, the air mass trajectory and concentration distribution of SJZ and MJT had similar characteristics. For CCM algorithm parameters, the greater $E$ was, the greater the strength of causality between concentration and meteorological factors. Considering the accuracy and efficiency of the CCM algorithm, the value of $E$ should be set as 7 in the time series of the four mining areas. The longer the period length $L$ was, the stronger the correlation. At $t = 150$, the sequence begins to converge. It was not found that $E$ was related to the convergence rate. In terms of pollution influencing factors, temperature (TEMP and S_TEMP), evaporation, and air pressure are the main meteorological factors affecting the all-year concentration. The correlation between the mean surface temperature and concentration was more significant than that between the mean temperature and concentration. The concentration and meteorological factors in the four mining areas also showed significant seasonal characteristics, and the correlation in spring, summer, and autumn was stronger than that in winter. This paper not only provides a reference for the green and sustainable exploitation of mineral resources but also provides theoretical support for the joint prevention and control of the atmospheric environment in the northwestern arid area. Future work includes (1) taking multiple pollution sources of cities as the research object, using a new cross domain model to obtain pollutant concentrations, determining the quantitative relationship between exogenous inputs and local outputs of pollutants, and comparing the results of the HYSPLIT model in this paper and (2) considering the impact of COVID-19 on city pollutant emissions, how to design the experiment and compare the changes in the cumulative concentration of pollutants in the city before and after the outbreak of the epidemic.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-19706-w.

Acknowledgements The article is supported by the National Natural Science Foundation of China (No.71874134), Humanity and Social Science Youth foundation of Ministry of Education of China (No. 21YJCZH138), China Postdoctoral Science Foundation (No. 2020M683433), Social Science Foundation of Shaanxi Province (No. 2019S046), the Key Project of Natural Science Basic Research Plan in Shaanxi Province (No. 2019JZ-30), Natural Science Foundation of Shaanxi Province (No. 2021JQ-517), Foundation of Shaanxi Province Educational Commission (21JK0729), Shaanxi Provincial Department of Education serving the Special Project of Local Enterprises (No. 19JC015), and Social Science Foundation of Shaanxi Province under Grant (No.2020F014).

Author contribution Jia Su: conceptualization, software, writing—original draft preparation, visualization, writing—revising and editing, sujia9108@163.com. Guangqiu Huang: supervision, huangnan93@163.com. Zhixia Zhang: methodology, 1079353791@qq.com.

Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Ethical approval and consent to participate. Not applicable.

Consent for publication All authors consent to the publication of the manuscript.

Competing interests The authors declare no competing interests.

References

Asadzadeh A, Kötter T, Zebardast E (2015) An augmented approach for measurement of disaster resilience using connective factor analysis and analytic network process (FANP) model. Int J Disaster Risk Reduct 14(04):504–518

Battista G, Vollaro RDL (2017) Correlation between air pollution and weather data in urban areas: assessment of the city of Rome (Italy) as spatially and temporally independent regarding pollutants. Atmos Environ 165:240–247

Bei NF, Zhao LN, Xiao B et al (2017) Impacts of local circulations on the wintertime air pollution in the Guanzhong Basin, China. Sci Total Environ 592:373–390

Bisquert DS, Castejón JM, Fernández GG (2017) The impact of atmospheric dust deposition and trace elements levels on the villages surrounding the former mining areas in a semi-arid environment (SE Spain). Atmos Environ 152:256–269

Chang X, Wang SX, Zhao B et al (2019) Contributions of inter-city and regional transport to PM$_{2.5}$ concentrations in the Beijing-Tianjin-Hebei region and its implications on regional joint air pollution control. Sci Total Environ 660:1191–1200

Chen L, Li Y, Liu C et al (2018) Wet deposition of mercury in Qingdao, a coastal urban city in China: concentrations, fluxes, and influencing factors. Atmos Environ 174:204–213

Chen ZY, Zhuang Y, Xie X et al (2019) Understanding long-term variations of meteorological influences on ground ozone concentrations in Beijing During 2006–2016. Environ Pollut 245(02):29–37

Chen Z Y, Chen D, Zhao C . et al. Influence of meteorological conditions on PM$_{2.5}$ concentrations across China: a review of
methodology and mechanism. Environment International, 2020,139:105558.

Clark AT, Ye H et al (2015) Spatial convergent cross mapping to detect causal relationships from short time series. Ecology 96(5):1174–1181.

Dare RA, Potts RJ, Wain AG (2016) Modelling wet deposition in simulations of volcanic ash dispersion from hypothetical eruptions of Merapi, Indonesia. Atmos Environ 143:190–201.

Draxler RR, Stunder B, Rolph G et al (2012a) HYSPLIT_4 user’s guide. Silver Spring, Maryland, USA: NOAA Air Resources Laboratory; (Available at http://www.arl.noaa.gov/documents/reports/hysplit_user_guide.pdf).

Draxler RR, Stunder B, Rolph G et al (2012) HYSPLIT tutorial. NOAA Air Resources Laboratory, Silver Spring.

Du X, Jin X, Zucker N et al (2020) Transboundary air pollution from coal-fired power generation. J Environ Manag 270:110862.

Ngan F, Loughner CP, Stein A (2019) The evaluation of mixing methods in HYSPLIT using measurements from controlled tracer experiments. Atmos Environ 219:117043.

Gao W, Jiang W, Zhou M (2019) The spatial and temporal characteristics of mercury emission from coal combustion in China during the year 2015. Atmos Pollut Res 10(3):776–783.

Guan Q, Luo H, Pan N et al (2019) Contribution of dust in northern China to PM10 concentrations over the Hexi corridor. Sci Total Environ 660:947–958.

Hu WL, Xin XK, Zou XB et al (2021) Application of production splitting method based on inverse distance weighted interpolation in X Oilfield. Energy Rep 07:850–855.

Hua H, Jiang SY, She HZ et al (2019) A high spatial-temporal resolution emission inventory of multi-type air pollutants for Wuxi city. J Clean Prod 229:278–288.

Huang Q, Xue L, Tian S (2019) Preliminary study on methods and strategies of urban air system planning [A]. Proceedings of 2019 China urban planning annual conference (08 urban ecological planning) [C]. Chongqing, China Construction Industry Press.

Lei ZC, Zhang B, Zang KZ et al (2010) Study on emergency response system of atmospheric pollution diffusion in Changzhou City based on HYSPLIT 4.8. J Anhui Agric Sci 38(24):13527–13530.

Li X, Zhang L (2012) Analysis of aerosol sources and optical properties of based on backward trajectory model over SACOL. Acta Physica Sinica 61(2):238–246.

Li C, Krotkov NA, Dickerson RR et al (2010) Transport and evolution of a pollution plume from northern China: a satellite-based case study. J Geophys Res Atmos 115:D00K03.

Li M, Du W, Tang S (2021a) Assessing the impact of environmental regulation and environmental co-governance on pollution transfer: Micro-evidence from China. Environ Impact Assess Rev 86:106467.

Li X, Bei NF, Tie XX et al (2021b) Local and transboundary transport contributions to the wintertime particulate pollution in the Guanzhong Basin (GZB), China: A case study. Sci Total Environ 797:148876.

Lin T, Lin JY, Cui SH et al (2009) Using a network framework to quantitatively select ecological indicators. Ecol Ind 9(06):1114–1120.

Liu L (2013) Geographic approaches to resolving environmental problems in search of the path to sustainability: the case of polluting plant relocation in China. Appl Geogr 45:138–146.

Liu HJ, Lei MY (2019) The Causality between traffic congestion and smog pollution—an empirical study using convergent cross mapping. Stat Res 36(10):43–57.

Liu X, Ge M, Yuan LN et al (2016) Ecological risk assessment of heavy metals in soil based on entropy weight fuzzy model. J Saf Environ 16(5):384–389.

Liu YJ, Li Y, Miao SG (2018) Spatial-temporal characteristics and meteorological factors analysis of air pollution in Fangshang District of Beijing. Meteorol Environ Sci 41(4):60–69.

Omidvar B, HojjatiMalekshah M, Omidvar H (2014) Failure risk assessment of interdependent infrastructures against earthquake, a Petri net approach: case study—power and water distribution networks. Nat Hazards 71(03):1971–1993.

Qiu M, Shi C, Zhang H et al (2009) Variation characteristics and influencing factors of acid rain in Hefei. J Environ Sci 06:1329–1338.

Rolph G, Stein A, Stunder B (2017) Real-time environmental applications and display system: READY. Environ Model Softw 95:210–228.

Shan YC, Zhang JX, Wang KN et al (2017) Application of HYSPLIT software in water vapor transport analysis in Western Jilin. Meteorol Disaster Prev 24(3):19–23.

Shmool JL, Michanowicz DR, Cambal L et al (2014) Saturation sampling for spatial variation in multiple air pollutants across an inversion-prone metropolitan area of complex terrain. Environ Health 13(1):28.

Stein AF, Draxler RR, Rolph GD et al (2016) NOAA’s HYSPLIT atmospheric transport and dispersion modeling system. Bull Am Meteor Soc 96(12):2059–2077.

Sugihara G, May R, Ye H et al (2012) Detecting causality in complex ecosystems. Science 338(6106):496–500.

Sulaymon I, Zhang Y, Hople P et al (2021) Influence of transboundary air pollution and meteorology on air quality in three major cities of Anhui Province, China. J Clean Prod 329:129641.

Su J, Huang G, Cao L et al (2019) Evaluation and analysis of cascading spread caused by multisource dust migration in a pollution-related ecosystem. Sci Total Environ 686(10):10–25.

Tang Z, Wu X, Gao S et al (2018) Analysis of PM2.5 regional transmigration budget of a heavy haze pollution event in Nanjing in winter. J Environ Sci 38(12):4605–4611.

Tao H, Li C, Chai XB et al (2010) Environmental geological problems and causes of Shenfu coalfield in Shaanxi Province. Geol Resour 19(3):249–252.

Tian Y, Yao X, Chen L (2019) Analysis of spatial and seasonal distributions of air pollutants by incorporating urban morphological characteristics. Comput Environ Urban Syst 658:280–293.

Van Nes EH, Scheffer M, Brockvink V et al (2015) Causal feedbacks in climate change. Nat Clim Chang 5(5):445–448.

Wang D, Wan K, Song X et al (2020) Understanding coal miners’ livelihood vulnerability to declining coal demand: Negative impact and coping strategies. Energy Policy 138:111199.

Xiao C, Chang M, Guo P et al (2019) Characteristics analysis of industrial atmospheric emission sources in Beijing–Tianjin–Hebei and surrounding areas using data mining and statistics on different time scales. Atmos Pollut Res 11:11–26.

Xu H, Xiao Z, Chen K et al (2019) Spatial and temporal distribution, chemical characteristics, and sources of ambient particulate matter in the Beijing-Tianjin-Hebei region. Sci Total Environ 658:280–293.
Yin X, Kang S, Rupakheti M et al (2021) Influence of transboundary air pollution on air quality in southwestern China. Geosci Front 12(6):101239

Yu H, Yang W, Wang X et al (2019) A seriously sand storm mixed air-polluted area in the margin of Tarim Basin: temporal-spatial distribution and potential sources. Sci Total Environ 676:436–446

Zhang JM, Guo LP, Zhang XD (2012) Influence of interpolation parameters on DEM Interpolation Error in inverse distance weighted interpolation algorithm. J Survey Map Sci Technol 29(01):51–56

Zhang X, Yang H, Cui Z (2018) Evaluation and analysis of soil migration and distribution characteristics of heavy metals in iron tailings. J Clean Prod 172:475–480

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.