

# The Complex Nonlinear Causal Coupling Patterns between PM2.5 and Meteorological Factors in Tibetan Plateau: A Case Study in Xining

Zhixiao Zou

Key Laboratory of Environmental Change and Natural Disaster, Beijing Normal University, Beijing

Changxiu Cheng (✉ [chengcx@bnu.edu.cn](mailto:chengcx@bnu.edu.cn))

Key Laboratory of Environmental Change and Natural Disaster, Beijing Normal University, Beijing

Shi Shen

Key Laboratory of Environmental Change and Natural Disaster, Beijing Normal University, Beijing

---

## Research Article

**Keywords:** nonlinear state space, coupling, PM2.5, meteorological factors, plateau cities

**Posted Date:** June 25th, 2021

**DOI:** <https://doi.org/10.21203/rs.3.rs-634756/v1>

**License:**  This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

---

---

1      **The complex nonlinear causal coupling patterns between**  
2      **PM2.5 and meteorological factors in Tibetan Plateau: a case**  
3                                    **study in Xining**

4      **Author: Zhixiao Zou<sup>1,2,3</sup>, Changxiu Cheng<sup>1,2,3,4,\*</sup>, Shi Shen<sup>1,2,3</sup>**

5      <sup>1</sup>Key Laboratory of Environmental Change and Natural Disaster, Beijing Normal University, Beijing, China;

6      <sup>2</sup>State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing, China;

7      <sup>3</sup>Faculty of Geographical Science, Center for Geodata and Analysis, Beijing Normal University, Beijing, China;

8      <sup>4</sup>National Tibetan Plateau Data Center, Beijing, China

9      \* Correspondence: [chengcx@bnu.edu.cn](mailto:chengcx@bnu.edu.cn)

10                                    **Abstract**

11      PM2.5 pollution influences the population health and people's daily life. Because  
12      meteorological factors are main factor affecting the formation of PM2.5, the interaction between  
13      PM2.5 and meteorological factors needs to be better understood, both for air quality management  
14      and for PM2.5 projection. Here, we use a nonlinear state space method called the convergent cross  
15      mapping method to identify the complex coupling patterns between PM2.5 and meteorological  
16      factors in a plateau city: Xining. The results prove that PM2.5-meteorological coupling patterns  
17      change with seasons and PM2.5-meteorological coupling patterns are fixed in spring, autumn and  
18      winter. In spring, there is a negative unidirectional effect from precipitation to PM2.5 and a negative  
19      bidirectional effect between relative humidity and PM2.5. In autumn, there are some negative  
20      bidirectional effects between PM2.5 and relative humidity, precipitation, and air pressure, while  
21      solar radiation has a positive bidirectional effect on PM2.5. In winter, there are negative  
22      bidirectional couplings between PM2.5 and wind speed and temperature and a positive bidirectional  
23      coupling between relative humidity and PM2.5. Furthermore, relative humidity is a consistent  
24      driving factor affecting PM2.5. Air quality managers may alleviate PM2.5 by increasing relative

---

25 humidity. Thus, the results provide a meteorological means for improving air quality in plateau cities.

26 Keywords: nonlinear state space; coupling; PM2.5; meteorological factors; plateau cities

## 27 **1. Introduction**

28 PM2.5 pollution pose a serious threat to the health of the population. Long-term or short-term  
29 exposure to PM2.5 concentrations can increase the mortality rate caused by cardiovascular diseases  
30 (especially ischemic heart disease and stroke), the number of respiratory diseases, and the risk of  
31 disability in daily activities among the elderly<sup>1-3</sup>. In addition, PM2.5 pollution also influence  
32 people's life, because PM2.5 concentrations cause serious visibility problems<sup>4</sup>. The poor visibility  
33 may lead to more traffic accidents. Therefore, to solve the PM2.5 pollution is essential for the  
34 prevention of medical accidents due to air pollution.

35 Because atmospheric conditions are one of the main factors affecting the formation of PM2.5  
36 concentrations, Air quality managers may attempt to alleviate PM2.5 through meteorological means.  
37 Meanwhile, some scholars have noted that physical-chemical models such as chemical transport  
38 models were effective for predicting PM2.5 concentrations by PM2.5-meteorological interactions.  
39 However, it is difficult to adjust their parameters for different regions or select proper parameters  
40 for different meteorological factors from first principles<sup>5-6</sup>. In this way, they need more information  
41 to guide parameter adjustment. Therefore, clarifying the complex nonlinear coupling between  
42 multiple meteorological factors and PM2.5 concentrations is of great theoretical significance and  
43 practical value for the PM2.5 prediction and for the decision-making of government for the  
44 environmental management<sup>7-8</sup>.

45 Most studies have emphasized the direct effect of meteorological factors (e.g., temperature,  
46 humidity, wind, precipitation and water vapor pressure) on PM2.5 concentrations. For example,  
47 Tran and Mölder<sup>9</sup> noted that wind, temperature and moisture (water vapor pressure and relative  
48 humidity) could influence PM2.5. Kleine Deters<sup>10</sup> thought that the prediction of PM2.5  
49 concentrations was from wind (speed and direction) and precipitation. Wang<sup>11</sup> believed that wind  
50 direction and relative humidity were the two main meteorological factors affecting PM2.5  
51 concentrations. DeGaetano<sup>12</sup> and Yin<sup>13</sup> reported that temperature, relative humidity and wind speed  
52 were correlated with PM2.5 concentrations. Actually, there are interactions among meteorological

---

53 factors, so that some meteorological factors have indirect influence on PM2.5. However, the  
54 complex nonlinear causal coupling between meteorological factors and PM2.5 concentrations is  
55 unclear.

56 Meanwhile, some scholars<sup>14-16</sup> found that the PM2.5 concentrations had feedbacks to  
57 meteorological factors. Zhong<sup>17</sup> pointed that Elevated PM2.5 concentrations could reduce surface  
58 temperature by back scattering short wave solar radiation. Yang<sup>18</sup> explained how PM2.5 negatively  
59 influenced the formation of winds. Zhao<sup>19</sup> revealed PM in the high-humidity environment tended to  
60 physicochemical reactions, which further affected PM. Therefore, exploring the complex nonlinear  
61 causal coupling patterns is more advantageous to understand the relationship between PM2.5  
62 concentrations and meteorological factors.

63 Previous studies have examined the correlation analysis and attribution analysis between  
64 PM2.5 and meteorological factors<sup>20-22</sup>. However, what we need to explore is a nonlinear coupling  
65 causality. Correlation, regression methods, and GAMs were used to study PM2.5-meteorology  
66 interactions. Among these methods, correlation cannot determine whether there is a causal  
67 relationship between two variables and cannot identify the direction of causation transitivity.  
68 Regression methods, which assume that the data are stationary or in linear space, are often used to  
69 analyze the relationship between PM2.5 and meteorological factors in nature. However, nature is a  
70 typical nonstationary and nonlinear space. Thus, we need a nonlinear state space method to quantify  
71 the coupling between PM2.5 concentrations and meteorological factors. Some studies have noted  
72 that GAMs could solve this problem, but they could not quantify the individual influence of  
73 meteorological factors on PM2.5<sup>23-24</sup>.

74 For causality analysis, Granger causality (GC) is a classic test to identify the causality<sup>25</sup>. Li<sup>26</sup>  
75 found that economic growth, industrialization and urbanization increased PM2.5 concentrations in  
76 the long run using GC. Sfetsos and Vlachogiannis<sup>27</sup> applied GC to quantify the causality between  
77 meteorological factors and PM. Actually, the key requirement of GC is separability, which means  
78 that GC is suitable for the stochastic and linear systems. GC test may fail to detect weak coupling  
79 between meteorological factors and PM2.5 concentrations. Therefore, we could use the convergent  
80 cross-mapping method. Sugihara<sup>28</sup> provided a new method called convergent cross-mapping (CCM)  
81 to reveal the nonlinear coupling causality between multiple meteorological factors. Compared with  
82 the abovementioned methods, this method can quantify the individual influence of meteorological

---

83 factors on PM<sub>2.5</sub> concentrations and describe the coupling between multiple meteorological factors  
84 and PM<sub>2.5</sub> concentrations.

85 Convergent cross-mapping (CCM) has been successfully applied in PM<sub>2.5</sub>-meteorological  
86 interactions. Some studies<sup>29-30</sup> filtered the original dataset and extracted the predictors through CCM  
87 for forecasting the PM<sub>2.5</sub> concentrations. Furthermore, Chen used CCM to examine the causal  
88 relationship between PM<sub>2.5</sub> and meteorological factors in the Jing-Jin-Ji region<sup>31</sup> and some  
89 megacities across China<sup>32</sup>. They mainly compared the individual influence of meteorological factors  
90 on PM<sub>2.5</sub> in different scales and find the main meteorological factors in different regions and  
91 seasons. As mentioned above, the quantitative coupling patterns between meteorological factors and  
92 PM<sub>2.5</sub> concentrations is unclear. In this study, based on CCM, we mainly identify the complex  
93 nonlinear coupling networks in different seasons.

94 Additionally, most studies on the PM<sub>2.5</sub> have focused on the non-plateau areas and not on the  
95 Tibetan Plateau (TP)<sup>33-34</sup>. Recently, the Tibetan Plateau has also been impacted by aerosol  
96 pollution<sup>35-36</sup>. The main resources are biomass burning and the transport of pollution from the nearby  
97 regions of Southeast Asia and the northern part of the Indian Peninsula. As the largest-scale and  
98 most populated city on TP, Xining also have experienced PM<sub>2.5</sub> pollution and faced with critical  
99 public health challenge due to the relative high PM<sub>2.5</sub> concentrations, population exposure,  
100 vulnerability, slight awareness and high altitude conditions.

101 In this paper, we used a nonlinear state space method called CCM. Based on this method, we  
102 obtained the coupling patterns between meteorological factors and PM<sub>2.5</sub> in Xining. The main  
103 results we acquired were (a) the temporal and spatial characteristics of PM<sub>2.5</sub> concentration in  
104 Xining in 2019, (b) the individual influence of meteorological factors on PM<sub>2.5</sub> in Xining in 2019,  
105 and (c) the coupling pattern between PM<sub>2.5</sub> and meteorological factors in different seasons in  
106 Xining in 2019.

107 Specifically, section 2 introduces the study area, defines the data sources and explains the  
108 research methods. Section 3 presents our results. Section 4 discusses some uncertainties. Finally,  
109 chapter 5 presents the conclusions and prospects.

---

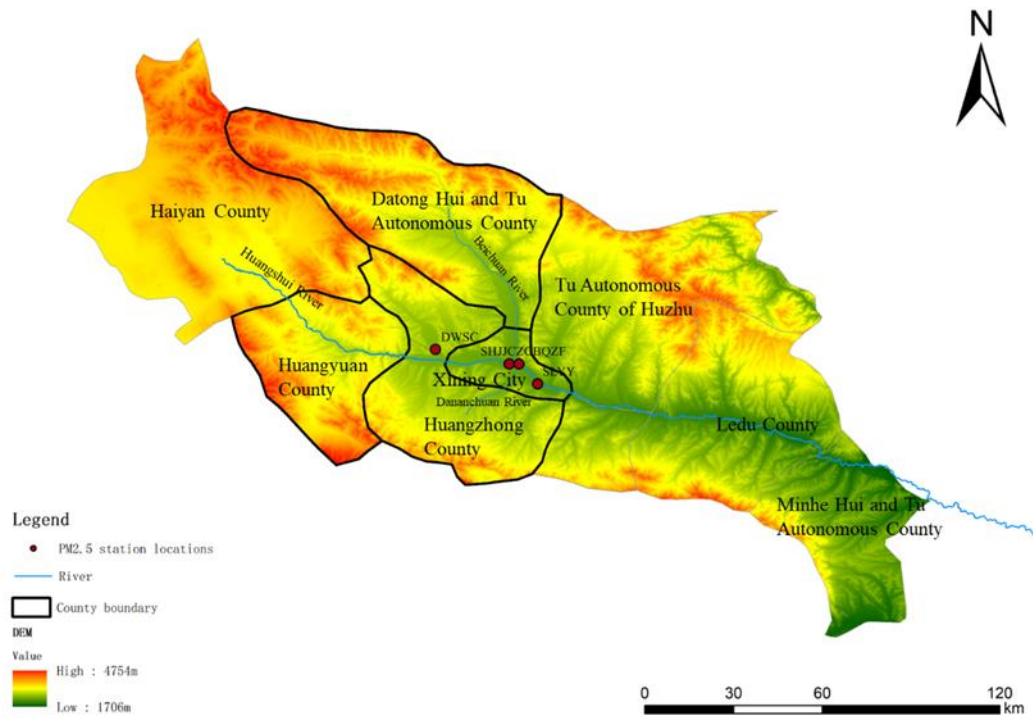
## 2. Materials and Methods

110

### 111 2.1 Study area

112 Xining, the capital city of Qinghai Province, is located in the northeastern part of the Tibetan  
113 Plateau, with an average altitude of 2,261.2 m. It belongs to the plateau continental climate, with  
114 low air pressure, a large day-night temperature difference, less rainfall, long sunshine, and strong  
115 solar radiation. It is the largest city in the region and hosts the main economic and social activities  
116 on the Tibetan Plateau. With a permanent resident population of 2,387,000, it is the only central city  
117 on the Tibetan Plateau with a population greater than one million. The urban area of Xining is  
118 located at the confluence of the Huangshui River, Nanchuan River, and Beichuan River. It is  
119 surrounded by mountains and forms a cross valley. In general, the terrain is high in the northwest  
120 and low in the southeast.

121 As Fig. 1 demonstrates, the four meteorological stations in this study are all located in  
122 southeastern Xining, among which three stations (Municipal Environmental Monitoring Station  
123 (SHJJCZ), Chengbei District Government (CBQZF) and Silu Hospital (SLYY)) are located in the  
124 urban area of Xining, and one station (Fifth Water Plant, DWSC) is located in the suburbs.



125

Figure 1. Geographical locations of PM2.5 stations and DEM in Xining

126 **2.2 Data collection**

127 As Table 1 shows, meteorological data were acquired from the China Meteorological Data  
 128 Sharing Service System (<http://data.cma.cn/>). We studied eight kinds of meteorological factors:  
 129 precipitation (PRE), wind speed (WS), wind direction (WD), pressure (PRS), temperature (TEM),  
 130 water vapor pressure (e), sunshine duration (SSD), and relative humidity (RH). These factors were  
 131 further categorized into subfactors. Precipitation is the total precipitation from 20 pm–20 pm. Wind  
 132 speed includes the extreme wind speed (WSex), maximum wind speed (WSmax), wind speed and  
 133 an average maximum wind speed of 2 minutes (WSmean2mins). The wind direction includes the  
 134 maximum wind speed of the wind direction (WDex) and the maximum wind speed direction  
 135 (WDmax). Pressure includes the daily mean pressure (PRSmean), daily maximum pressure  
 136 (PRSmax), and daily minimum pressure (PRSmin). Temperature includes the daily mean  
 137 temperature (TEMmean), daily maximum temperature (TEMmax) and daily minimum temperature  
 138 (TEMmin). Water vapor pressure is the mean water vapor pressure. Solar radiation is represented  
 139 by the daily sunshine duration (SSD). Relative humidity includes the daily mean relative humidity  
 140 (RHmean) and daily minimum relative humidity (RHmin).

Data	Data type	Data source	Factors
Meteorological data	Station data	China Meteorological Data Sharing Service System ( <a href="http://data.cma.cn/">http://data.cma.cn/</a> )	Precipitation (PRE), wind speed (WS), wind direction (WD), pressure (PRS), temperature (TEM), water vapor pressure (e), sunshine duration (SSD), relative humidity (RH)
Daily PM2.5 concentration data	Station data	Qingyue Open Environmental Data Center ( <a href="https://data.epmap.org">https://data.epmap.org</a> )	PM2.5 concentrations

142

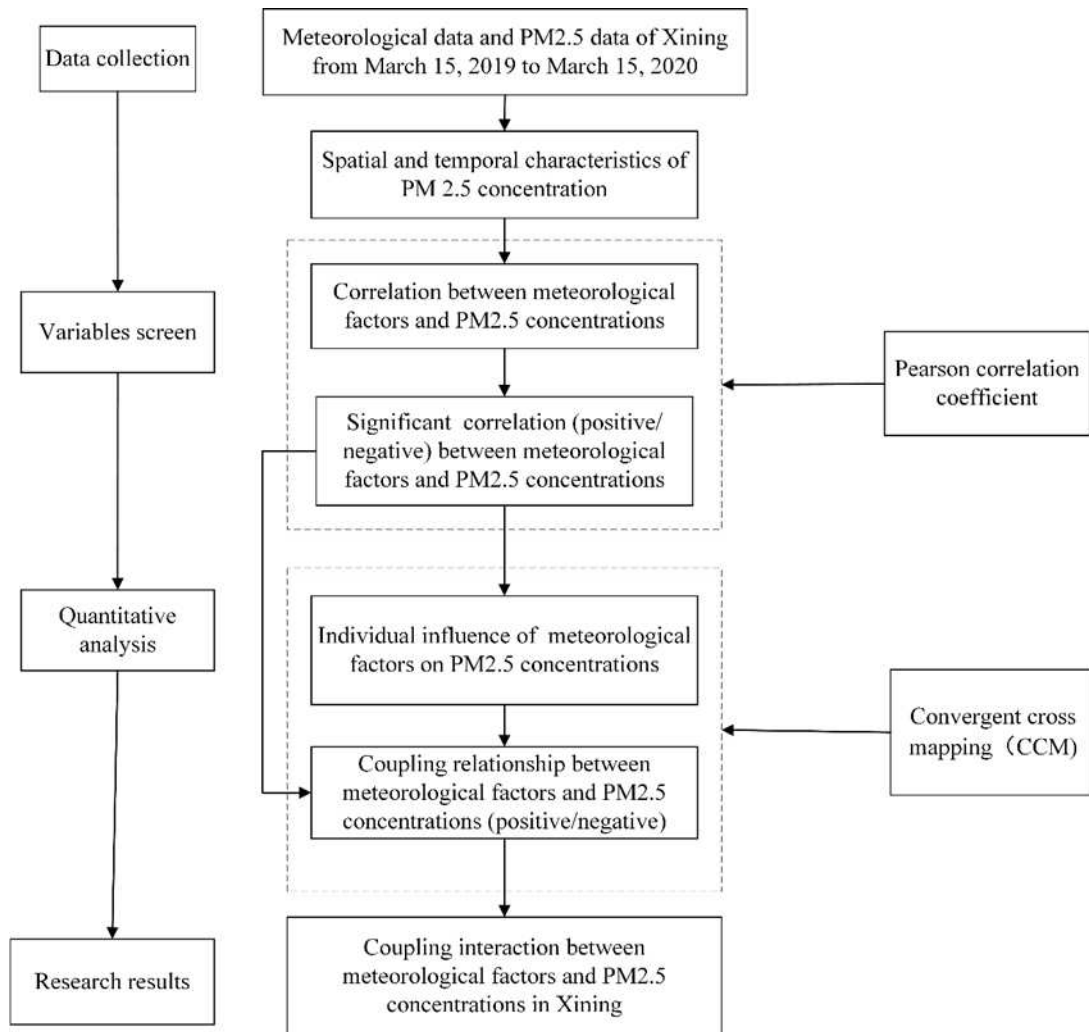
143 Daily PM2.5 concentration data were obtained from Qingyue Open Environmental Data Center  
 144 (<https://data.epmap.org>) from March 15, 2019, to March 15, 2020 (Table 1). This website provided  
 145 PM2.5 data for each city by station in China. This study extracted PM2.5 data from four country-  
 146 controlled stations in Xining (Chengbei District Government, PM2.5\_CBQZF; Silu Hospital,  
 147 PM2.5\_SLYY; Municipal Environmental Monitoring Station, PM2.5\_SHJJCZ; and Fifth Water  
 148 Plant, PM2.5\_DWSC).

## 149 2.3 Methods

150 This paper focuses on the key scientific problem of coupling patterns between PM2.5  
 151 concentrations and meteorological factors in different seasons in Xining. First, we obtained the  
 152 PM2.5 station data and meteorological data in Xining and illustrated the spatiotemporal  
 153 characteristics of PM2.5 concentrations in Xining in 2019. Second, based on the Pearson correlation  
 154 coefficient, we screened the significant meteorological subfactors and acquired positive or negative  
 155 correlations. Third, we used the causality CCM method to distinguish the spatiotemporal individual  
 156 influence of meteorological factors on PM2.5 in Xining in 2019 and identified the coupling patterns  
 157 between PM2.5 concentrations and meteorological factors in different seasons, which is beneficial



158 for providing a scientific basis and theoretical suggestions for improving the air quality of Xining  
159 (Fig. 2).



160 Figure 2 Framework of the study

### 161 2.3.1 Correlation analysis

162 The Pearson correlation coefficient was used to measure the correlation between  
163 meteorological factors and PM2.5 concentrations<sup>37</sup>. There were two problems to solve: the first was  
164 whether there was a correlation between each meteorological factor and the PM2.5 concentrations,  
165 and the second was what kind of correlation it was, that is, a positive or a negative correlation.

### 166 2.3.2 Convergent cross-mapping (CCM)

167 After finding the correlations, we needed a nonlinear state space method to identify the

168 coupling between PM2.5 and meteorological factors. Fortunately, Sugihara (Sugihara et al., 2012)  
 169 proposed the convergent cross-mapping (CCM) method. This is a method that can identify the  
 170 coupling relationships (network) among individual variables in a complex system. The main  
 171 algorithm of CCM is as follows. Consider two time series of length  $L$ ,  $\{X\} = \{X(1), X(2), \dots, X(L)\}$ ,  
 172  $\{Y\} = \{Y(1), Y(2), \dots, Y(L)\}$ . In this study, there were temporal variations in the meteorological  
 173 factors and PM2.5 concentrations. The goal was to determine the causality between  $\{X\}$  and  $\{Y\}$   
 174 and identify what direction the coupling was (unidirectional causality/bidirectional causality). Take  
 175 cross-mapping from  $X$  to  $Y$  as an example. First, we formed the lagged-coordinate vectors  $\underline{x}(t) =$   
 176  $\langle X(t), X(t - \tau), X(t - 2\tau), \dots, X(t - (E - 1)\tau) \rangle$  for  $t=1+(E-1)$  to  $t=L$ . This set of vectors was  
 177 defined as the “reconstructed manifold” or “shadow manifold”  $M_X$ . Next, we needed to generate a  
 178 cross-mapped estimate of  $Y(t)$ , denoted by  $\hat{Y}(t)|_{M_X}$ , by locating the contemporaneous lagged-  
 179 coordinate vector on  $M_X$  and finding its  $E+1$  nearest neighbors.  $E+1$  is the minimum number of  
 180 points needed for a bounding simplex in an  $E$ -dimensional space. We used the distance  $w_i$ ,  
 181 generated by the  $E+1$  nearest neighbors on  $M_X$ , to weight  $Y(t_i)$  and obtain the estimate  $\hat{Y}(t)|_{M_X}$ .  
 182 Finally, the skill of the cross-map estimate (indicated by the correlation coefficient  $\rho$  value between  
 183 observed and predicted), which ranged from 0 to 1, revealed the quantitative causality of  $X$  on  $Y$ .  
 184 After obtaining the  $\rho$  value among multiple factors, we drew the coupling network among them. In  
 185 this way, we acquired the coupling pattern between PM2.5 and meteorological factors.

$$186 \quad \hat{Y}(t)|_{M_X} = \sum w_i Y(t_i); \quad i = 1 \dots E + 1$$

187 where  $w_i = u_i / \sum_{j=1 \dots E+1} u_j$ ,  $u_i = \exp\{-d[\underline{x}(t), \underline{x}(t_i)] / d[\underline{x}(t), \underline{x}(t_1)]\}$ .  $d[\underline{x}(t), \underline{x}(t_i)]$   
 188 represents the Euclidean distance between two vectors.

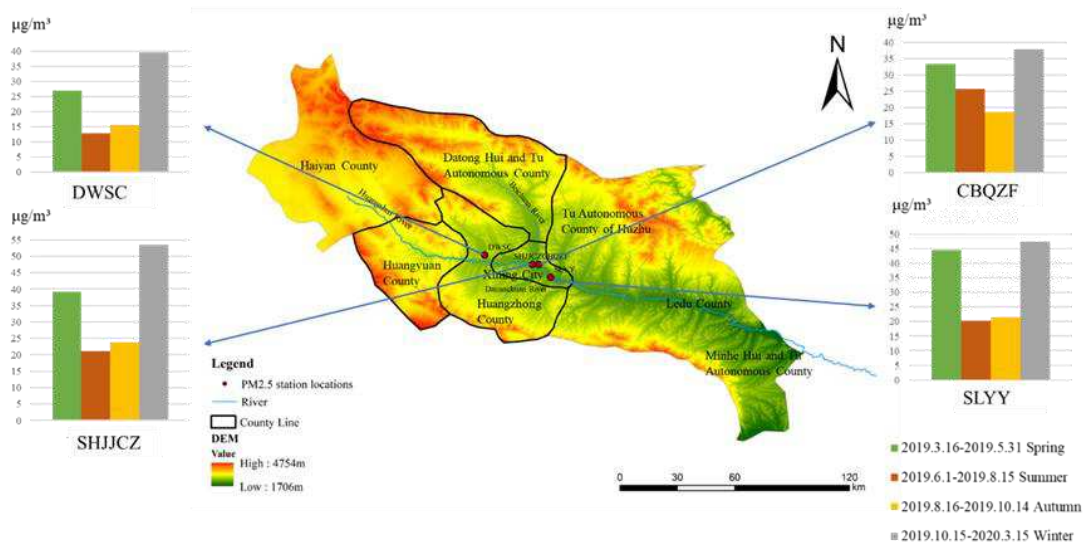
189 The convergent cross-mapping algorithm is a backward-looking pattern. It examines the  
 190 relationship between the current states and predicts the current  $Y$  rather than predicting the future  
 191 value of  $Y$  based on the current  $X$ . To summarize, if variable  $Y$  from variable  $X$  by using the  
 192 historical data is more reliable, the quantitative causality of variable  $X$  on the variable  $Y$  will be the  
 193 stronger result.

### 3. Results

194

#### 195 3.1 Spatial and temporal characteristics of PM 2.5

196 We used daily PM<sub>2.5</sub> concentration data for the study period from March 15, 2019, to March  
197 15, 2020, from the four state-controlled stations in Xining for analysis. Previous studies proved that  
198 PM<sub>2.5</sub> in China has spatial and seasonal variations<sup>38-40</sup>. According to the high temperature, the  
199 period from June 1 to August 15 was defined as summer. Spring was defined from March 15 to May  
200 31. Autumn was defined from August 16 to October 14. Winter was defined from October 15 to  
201 March 14. Therefore, we calculated the average daily PM<sub>2.5</sub> concentrations of each season at the 4  
202 stations and visualized them in Fig. 3.



203

Figure 3 Spatial and seasonal characteristics of PM 2.5 concentration in Xining

204

205 Fig. 3 shows that at the four stations, the average PM<sub>2.5</sub> concentrations in winter were the  
206 highest (over 35µg/m<sup>3</sup>), followed by those in spring, because central heating occurs from October  
207 15 to April 15 of the following year and burns coal, releasing more air pollutants. Compared with  
208 different stations, the mean PM<sub>2.5</sub> concentrations at the suburban site Fifth Water Plant (DWSC)  
were the lowest in spring, summer, and autumn.

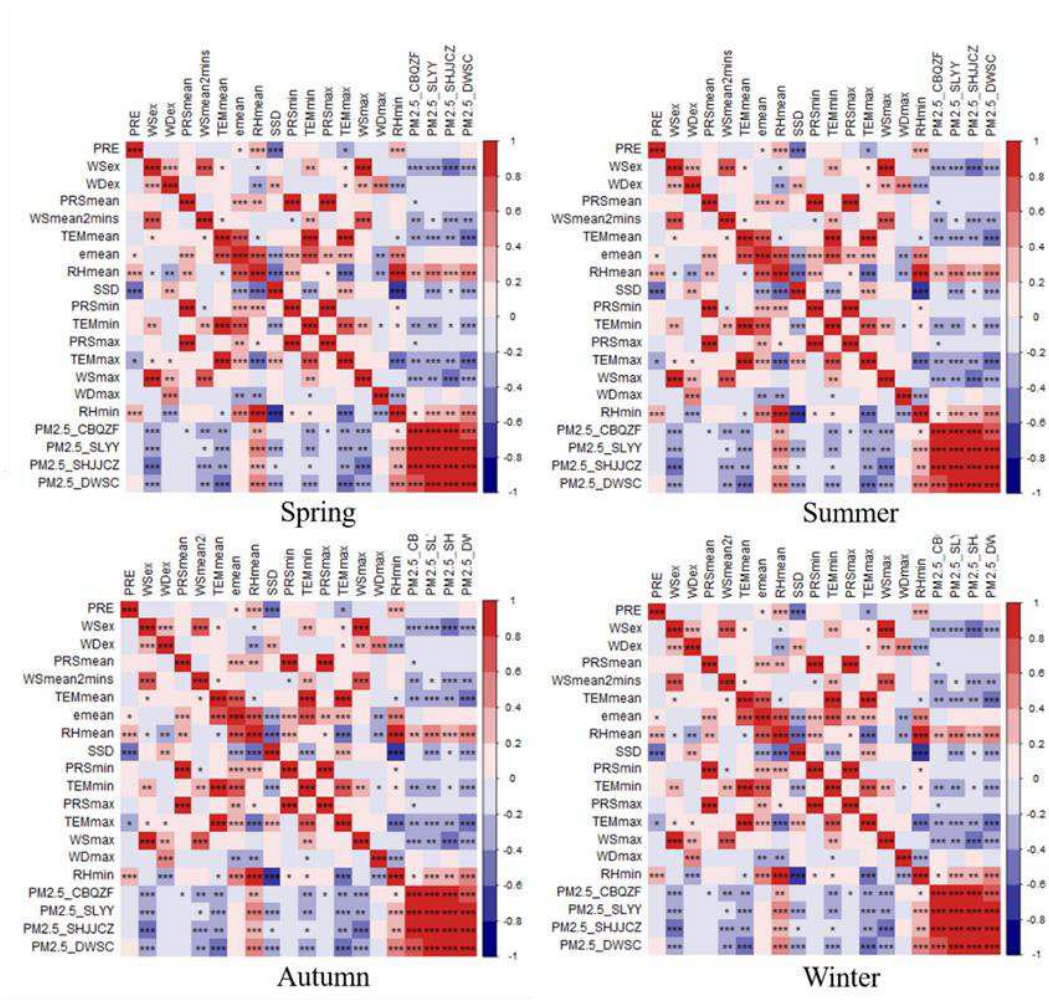
209

#### 3.2 Correlation between meteorological factors and PM2.5

210

Some studies have noted that precipitation, relative humidity, and temperature were related to

211 air quality in Xining<sup>41</sup>. In addition, previous studies<sup>31, 42-44</sup> have shown some influences of radiation,  
 212 air pressure, wind speed, wind direction and water vapor pressure on PM2.5. To more  
 213 comprehensively analyze the impact of meteorological factors on PM2.5, we examined precipitation,  
 214 relative humidity, temperature, radiation, air pressure, wind speed, wind direction and water vapor  
 215 pressure. In the last chapter, these factors were further categorized into subfactors: precipitation,  
 216 wind speed (extreme wind speed, maximum wind speed wind speed, an average of 2 minutes  
 217 maximum wind speed), wind direction (maximum wind speed of the wind direction, the maximum  
 218 wind speed direction), pressure (average pressure, low pressure, high pressure), temperature (mean  
 219 temperature, maximum temperature and minimum temperature), water vapor pressure, solar  
 220 radiation (daily sunshine duration) and relative humidity (average relative humidity, minimum  
 221 relative humidity).



222 Figure 4 Seasonal correlations between individual meteorological factors and PM2.5 concentrations for different stations.  
 223 \*\*Correlation is significant at the 0.01 level (2 tailed); \*Correlation is significant at the 0.05 level (2 tailed). Red squares show positive  
 224 correlations, and blue squares show negative correlations.

225 According to the division of seasons, we obtained the correlation analysis results in Fig. 4. The  
 226 meteorological factors strongly correlated with PM2.5 concentrations were extracted from each  
 227 station. The correlation between meteorological factors and PM2.5 daily concentrations changed  
 228 with season and station. The correlation between PM2.5 concentration and meteorological factors  
 229 was strong in autumn and winter but weak in spring and summer. In addition, there was a correlation  
 230 between meteorological factors, which varied by season. The correlation significance between  
 231 PM2.5 concentrations at different stations was vital in all seasons except spring. Finally, the  
 232 significant meteorological factors were screened, providing the foundation for causal analysis.

### 233 3.3 Causality between meteorological factors and PM 2.5

234 For the significant variables in Fig. 4, we adopted the CCM method to obtain the individual  
 235 influence of meteorological factors on PM2.5 concentrations. According to different seasons, we  
 236 could calculate the seasonal causality for each station. Despite multiple subfactors affecting PM2.5,  
 237 the most significant p-value of subfactors represented the meteorological factors for each station.  
 238 The  $\rho$  values between meteorological factors and PM2.5 are shown in Table 2. The value of  
 239 prediction skill (p-value) ranged from 0 to 1, indicating the influence of one variable on another  
 240 variable.

241 Table 2 Seasonal causality between individual meteorological factors and PM2.5 concentrations for different stations.

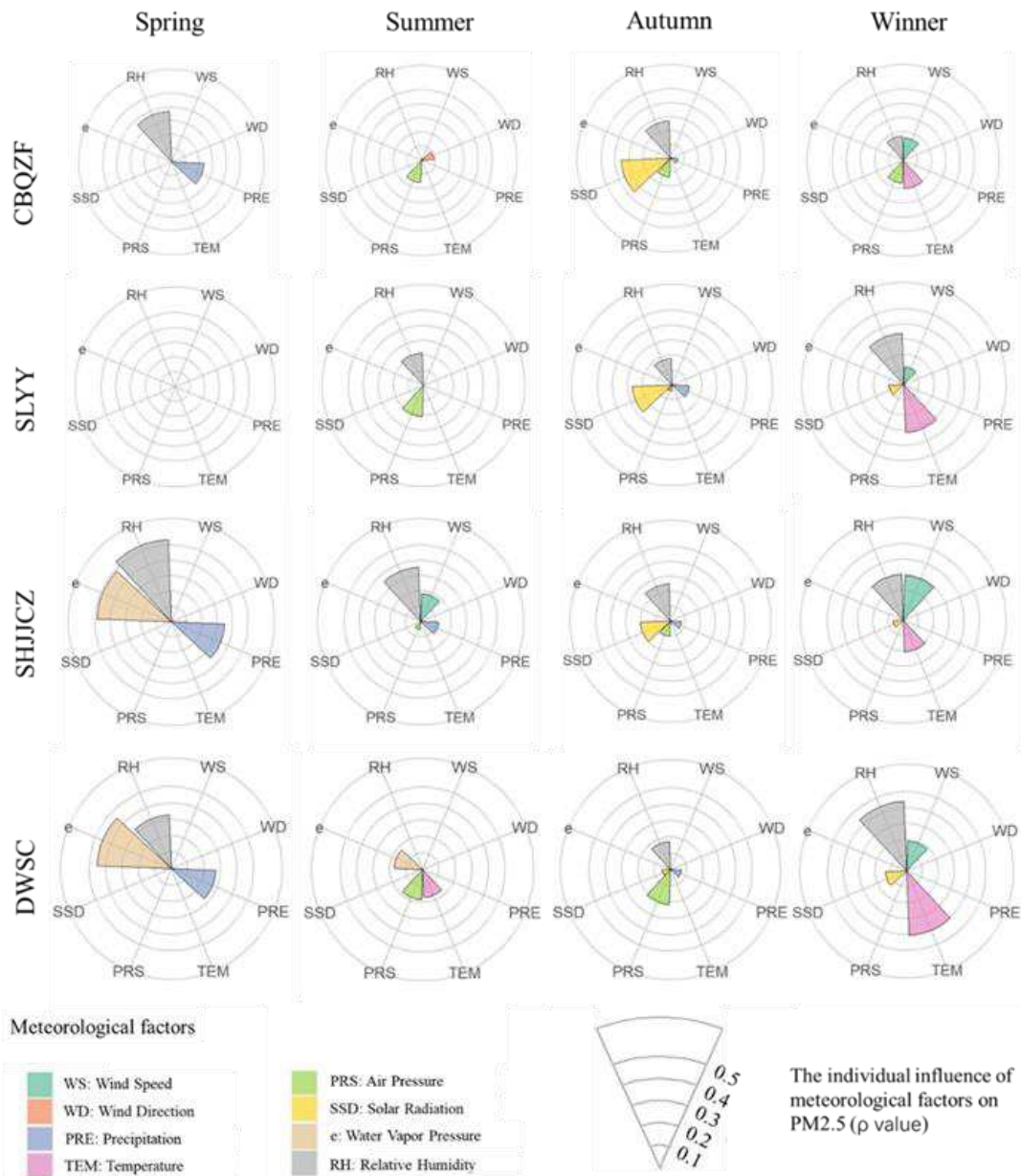
	Spring	$\rho$ value	Summer	$\rho$ value	Autumn	$\rho$ value	Winter	$\rho$ value
CBQZF	PRE	0.237	PRSm <sub>max</sub>	0.156	PRE	0.056	WSex	0.158
	RH <sub>min</sub>	0.368	WSex	0.015	RH <sub>mean</sub>	0.268	PRSm <sub>max</sub>	0.16
			WD <sub>ex</sub>	0.088	SSD	0.356	RH <sub>mean</sub>	0.17
					TEM <sub>max</sub>	0	TEM <sub>max</sub>	0.2
					PRSm <sub>max</sub>	0.136		
SLYY			RH <sub>mean</sub>	0.217	PRE	0.117	WSex	0.118
			PRSm <sub>max</sub>	0.209	PRSm <sub>mean</sub>	0.042	RH <sub>mean</sub>	0.338
					RH <sub>mean</sub>	0.177	SSD	0.097
					SSD	0.267	TEM <sub>max</sub>	0.315
					TEM <sub>max</sub>	0		
SHJJCZ	PRE	0.348	WSex	0.182	PRE	0.075	WSex	0.294
	e	0.487	PRE	0.118	PRSm <sub>mean</sub>	0.102	RH <sub>mean</sub>	0.301
	RH <sub>mean</sub>	0.535	PRSm <sub>mean</sub>	0.053	RH <sub>mean</sub>	0.25	TEM <sub>max</sub>	0.208
			RH <sub>mean</sub>	0.354	SSD	0.202	SSD	0.067
					TEM <sub>max</sub>	0		

DWSC	PRE	0.271	TEMmin	0.17	PRE	0.067	WSex	0.189
	RHmean	0.327	PRSmax	0.183	RHmean	0.171	RHmean	0.439
			e	0.173	SSD	0.054	SSD	0.135
					PRSmax	0.214	TEMmax	0.406
				TEMmax	0			

242

243 **3.3.1. Individual influence of different meteorological factors on the PM2.5**

244 To better explain the individual influence ( $\rho$  value) of different meteorological factors on the PM2.5  
 245 concentrations, a rose wind map was drawn by R programming, as shown in Fig. 5. Each wind rose  
 246 petal demonstrates a kind of meteorological factor, and the size represents the maximum value of  
 247 all subfactors.



248

Figure 5 Seasonal and spatial causality between individual meteorological factors and PM2.5 concentrations for different stations.

249

The individual influences of meteorological factors in the four seasons were different. However, the meteorological factors of different stations in spring, autumn, and winter were similar. In spring, PM2.5 was mainly affected by precipitation and relative humidity. In summer, different stations had different main meteorological factors. The factors differed at different stations. In autumn, relative humidity, precipitation, air pressure, and sunshine duration largely influenced PM2.5. In winter, relative humidity, wind speed, and temperature were the dominant meteorological factors affecting PM2.5. Based on the main meteorological factors in spring, autumn and winter, we used them to analyze the coupling patterns of PM2.5 and meteorological factors.

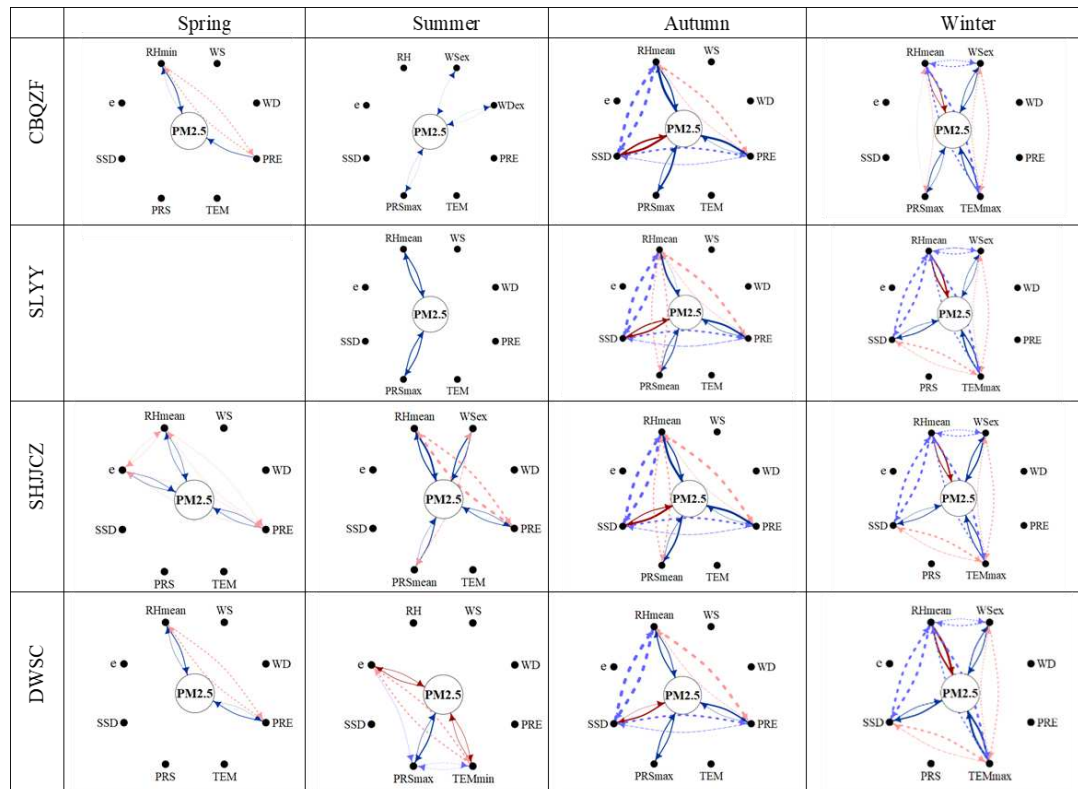
257

### 3.3.2 Coupling pattern of PM2.5 and meteorological factors

258

According to the wind rose map, the network diagram of meteorological factors and PM2.5 was drawn and is shown in Fig. 6. These four stations in spring, autumn, and winter had different PM2.5-meteorological coupling patterns, but there was a similar PM2.5-meteorological coupling pattern for the three seasons. There was no fixed coupling pattern in summer. The PM2.5-meteorological coupling pattern in spring and summer was simple, while the PM2.5-meteorological coupling pattern in autumn and winter was complicated. Meanwhile, the feedback effects of PM2.5 concentrations on individual meteorological factors were explained<sup>43</sup> (Li et al., 2015a). Next, we

264



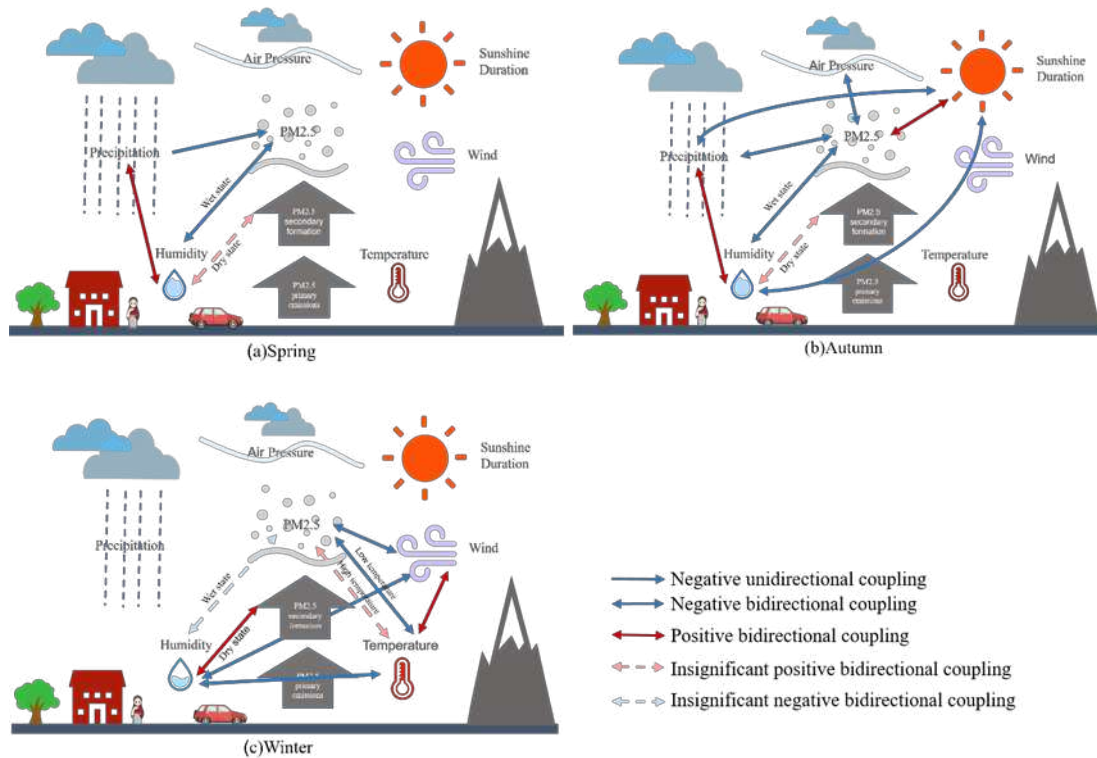
---

265 Figure 6 Seasonal and spatial coupling between individual meteorological factors and PM2.5 concentrations for different  
266 stations. Red represents a positive influence, and blue represents a negative influence. The solid line arrows show the causality  
267 between meteorological factors and PM2.5, while the dotted line arrows show the causality between meteorological factors. Two-  
268 way arrows show bidirectional causality, and one-way arrows show unidirectional causality. The thickness of the line arrows  
269 indicates the proportional size of the  $p$  value.

270 extracted the common meteorological factors from different stations in each season and analyzed  
271 the coupling patterns between these meteorological factors and PM2.5 to determine the coupling  
272 pattern of each season.

273 In spring, precipitation and humidity were the most influential meteorological factors affecting  
274 the PM2.5 concentrations. Both relative humidity and precipitation had a negative effect on PM2.5.  
275 Higher precipitation led to lower PM2.5 concentrations because of wet deposition. When  
276 precipitation increased, relative humidity increased. Similarly, when relative humidity increased,  
277 precipitation increased. In a wet environment, there was bidirectional coupling between PM2.5 and  
278 humidity. This result means that high humidity led to low PM2.5 concentrations and that feedback  
279 from low PM2.5 concentrations could increase the humidity. In this way, strong negative  
280 bidirectional PM2.5-humidity coupling would strengthen the effects of humidity on PM2.5  
281 concentrations. At the same time, the increased precipitation caused increased relative humidity,  
282 which would also indirectly influence the PM2.5 concentrations (Fig. 7(a)).





283 Figure 7 (a) Coupling pattern of meteorological factors and PM 2.5 concentration in spring (b) Coupling pattern of meteorological factors  
 284 and PM 2.5 concentration in autumn (c) Coupling pattern of meteorological factors and PM 2.5 concentration in winter.

285 In autumn, relative humidity, precipitation and air pressure all had negative effects on PM<sub>2.5</sub>,  
 286 while sunshine duration had a positive effect on PM<sub>2.5</sub>. The influence of air pressure on PM<sub>2.5</sub> was  
 287 relatively independent. That is, it did not affect the PM<sub>2.5</sub> concentrations indirectly through the  
 288 influence of meteorological factors. Precipitation had a strong positive influence on relative  
 289 humidity, which increased the negative influence on PM<sub>2.5</sub>. Precipitation had a negative effect on  
 290 sunshine hours, which also strengthened the negative effect on PM<sub>2.5</sub> concentrations. There was a  
 291 negative bidirectional coupling between relative humidity and sunshine hours (Fig. 7(b)).

292 In winter, in a dry state, there was a positive coupling between PM<sub>2.5</sub> and relative humidity.  
 293 Temperature had a negative effect on relative humidity. Wind speed and temperature had a negative  
 294 bidirectional coupling on PM<sub>2.5</sub>. As the temperature increased, the saturated water vapor pressure  
 295 increased, and the relative humidity decreased. This result means that temperature not only directly  
 296 affected PM<sub>2.5</sub> but also indirectly influenced PM<sub>2.5</sub> by affecting relative humidity. Temperature  
 297 positively impacted wind speed, so it strengthened the negative impact on PM<sub>2.5</sub> (Fig. 7(c)).

---

## 4. Discussion

299 Previous studies put more emphasis on the relationship between individual meteorological  
300 factors and PM<sub>2.5</sub> concentrations<sup>33</sup>. We obtained the coupling patterns between PM<sub>2.5</sub>  
301 concentrations and meteorological factors. Based on these coupling patterns, we can design or adjust  
302 physical-chemical models for PM<sub>2.5</sub> simulation or prediction.

303 According to the coupling patterns in different seasons, individual meteorological factors can  
304 influence local PM<sub>2.5</sub> concentrations indirectly by interacting with other meteorological factors.  
305 Managers can take meteorological measures in different seasons to reduce the PM<sub>2.5</sub> concentrations.  
306 In spring, they could reduce PM<sub>2.5</sub> concentrations by increasing precipitation and relative humidity.  
307 In autumn, controlling precipitation, air pressure, relative humidity or solar radiation could mitigate  
308 the PM<sub>2.5</sub> concentrations. In winter, they could adjust the temperature, relative humidity and wind  
309 speed to decrease the PM<sub>2.5</sub> concentrations. In general, managing the relative humidity is the most  
310 effective method.

311 In terms of different seasons, as shown in Fig. 7, the negative influence of meteorological  
312 factors on PM<sub>2.5</sub> was greater than the positive influence on seasonal coupling patterns. This may  
313 be make PM<sub>2.5</sub> concentrations unstable. It means it will not continue to increase or decrease. The  
314 weather conditions are different every day. Higher precipitation leads to lower PM<sub>2.5</sub> concentrations  
315 and lower precipitation in the same coupling pattern, leading to more PM<sub>2.5</sub>. In this way, the  
316 variation in weather causes fluctuations in PM<sub>2.5</sub> concentrations. PM<sub>2.5</sub> concentrations were  
317 dynamically stable over time. Compared with different seasons or coupling patterns, there is a  
318 critical value for the same meteorological factor. This result means that the influence of the same  
319 meteorological factor on PM<sub>2.5</sub> in different states is different (e.g., relative humidity). In a wet state,  
320 the increased precipitation increased relative humidity. In a dry state, there was a positive coupling  
321 between PM<sub>2.5</sub> and relative humidity.

322 It is worth noting that the PM<sub>2.5</sub> concentrations at the Fifth Water Plant station were lower  
323 than those at other stations. On the one hand, the land-use type of Chengbei District Government,  
324 Silu Hospital, Municipal Environmental Monitoring Station is urban land, but the Fifth Water Plant  
325 in the suburban area is irrigated land (a kind of dry land). Urban land creates more dust than irrigated

---

326 land. Additionally, it may be because there is less traffic in the suburbs than that in the cities, and  
327 PM2.5 partly comes from the exhaust gas discharged into the atmosphere when vehicles use fuel on  
328 the roads.

329 This paper takes a plateau city as an example, but the method can be extended to other cities  
330 or regions. It can discover the PM2.5-meteorological patterns in different cities or regions.  
331 Meanwhile, it can also be extended to a larger time scale. It can find the PM2.5-meteorological  
332 patterns of different years or the seasonal PM2.5-meteorological patterns in different years.

## 333 5. Conclusions

334 In this paper, we analyzed the temporal and spatial characteristics of PM2.5 concentrations in  
335 Xining in 2019. More importantly, based on CCM, we revealed the temporal and spatial individual  
336 influences of meteorological factors on PM2.5 and identified coupling patterns between PM2.5 and  
337 meteorological factors in different seasons in 2019 in Xining. The key findings were as follows.

338 Based on a seasonal comparison, the PM2.5-meteorological coupling patterns were different  
339 in the four seasons in Xining. In spring, autumn and winter, there was a similar PM2.5-  
340 meteorological coupling pattern. There was no fixed coupling pattern in summer. The PM2.5-  
341 meteorological coupling pattern in spring and summer was simple, while the PM2.5-meteorological  
342 coupling pattern in autumn and winter was complicated.

343 The research suggests that individual meteorological factors can influence local PM2.5  
344 concentrations indirectly by interacting with other meteorological factors. In spring, higher  
345 precipitation leads to lower PM2.5 concentrations, and higher relative humidity in the wet  
346 environment leads to lower PM2.5 concentrations. There is positive bidirectional coupling between  
347 precipitation and humidity. In autumn, relative humidity in the wet environment, precipitation and  
348 air pressure all negatively influence PM2.5, while sunshine duration positively influences PM2.5 In  
349 comparison, the influence of air pressure on PM2.5 is relatively independent. In winter, wind speed  
350 and low temperatures have a negative bidirectional coupling on PM2.5. There is a positive coupling  
351 between PM2.5 and relative humidity in a wet environment. Due to the coupling among relative  
352 humidity, wind speed and temperature, one of them can indirectly affect PM2.5.

353 The meteorological influence on PM2.5 concentrations was seasonally similar in Xining. In

---

354 spring, PM<sub>2.5</sub> was mainly affected by precipitation and relative humidity. In autumn, relative  
355 humidity, precipitation, air pressure, and sunshine duration mainly influenced PM<sub>2.5</sub>. In winter,  
356 relative humidity, wind speed and temperature were the dominant meteorological factors affecting  
357 PM<sub>2.5</sub>. Generally, relative humidity was the most important influencing factor affecting PM<sub>2.5</sub>  
358 concentrations.

359 According to the coupling pattern in different seasons, managers could take different measures  
360 in different seasons to reduce the PM<sub>2.5</sub> concentrations. It would be the most advantageous to  
361 reduce PM<sub>2.5</sub> concentrations by decreasing relative humidity. In the future, we can extend this  
362 method to larger temporal and spatial scales; for example, we can analyze it for more years and  
363 expand it nationwide. Therefore, a PM<sub>2.5</sub>-meteorological coupling pattern at a larger scale could be  
364 acquired.

365

## 6. References

- 366 1. Brook, R. D., Newby, D. E. & Rajagopalan, S. Air Pollution and Cardiometabolic Disease: An  
367 Update and Call for Clinical Trials. *AM J HYPERTENS.* 31, 1-10 (2017).
- 368 2. Hayes, R. B. et al. PM<sub>2.5</sub> Air Pollution and Cause-Specific Cardiovascular Disease Mortality.  
369 *INT J EPIDEMIOL.* 49, 25-35 (2020).
- 370 3. Lv, Y. et al. Long-Term Exposure to PM<sub>2.5</sub> and Incidence of Disability in Activities of Daily  
371 Living Among Oldest Old. *ENVIRON POLLUT.* 259, 113910 (2020).
- 372 4. Pui, D. Y. H., Chen, S. & Zuo, Z. PM 2.5 in China: Measurements, Sources, Visibility and  
373 Health Effects, and Mitigation. *PARTICUOLOGY.* 13, 1-26 (2014).
- 374 5. Reichstein, M. et al. Deep Learning and Process Understanding for Data-Driven Earth System  
375 Science. *Nature (London).* 566, 195-204 (2019).
- 376 6. Sharma, A. et al. WRF-Chem Simulated Surface Ozone Over South Asia During the Pre-  
377 Monsoon: Effects of Emission Inventories and Chemical Mechanisms. *ATMOS CHEM PHYS.*  
378 17, 14393-14413 (2017).
- 379 7. Chen, G. et al. A Machine Learning Method to Estimate PM<sub>2.5</sub> Concentrations Across China  
380 with Remote Sensing, Meteorological and Land Use Information. *SCI TOTAL ENVIRON.* 636,  
381 52-60 (2018).

- 
- 382 8. Pérez P, T. A. R. J. Prediction of PM Concentrations Several Hours in Advance Using Neural  
383 Networks in Santiago, Chile. *ATMOS ENVIRON.* (2000).
- 384 9. Tran, H. N. Q. & Mölders, N. Investigations On Meteorological Conditions for Elevated PM2.5  
385 in Fairbanks, Alaska. *ATMOS RES.* 99, 39-49 (2011).
- 386 10. Kleine Deters, J., Zalakeviciute, R., Gonzalez, M. & Rybarczyk, Y. Modeling PM2.5  
387 Urban Pollution Using Machine Learning and Selected Meteorological Parameters. *Journal of*  
388 *Electrical and Computer Engineering.* 2017, 1-14 (2017).
- 389 11. Wang, S., Zhou, C., Wang, Z., Feng, K. & Hubacek, K. The Characteristics and Drivers of Fine  
390 Particulate Matter (PM2.5) Distribution in China. *J CLEAN PROD.* 142, 1800-1809 (2017).
- 391 12. DeGaetano, A. T. & Doherty, O. M. Temporal, Spatial and Meteorological Variations in Hourly  
392 PM2.5 Concentration Extremes in New York City. *ATMOS ENVIRON.* 38, 1547-1558 (2004).
- 393 13. Yin, Q., Wang, J., Hu, M. & Wong, H. Estimation of Daily PM 2.5 Concentration and its  
394 Relationship with Meteorological Conditions in Beijing. *J ENVIRON SCI-CHINA.* 48, 161-168  
395 (2016).
- 396 14. Bister, M. & Kulmala, M. Anthropogenic Aerosols May Have Increased Upper Tropospheric  
397 Humidity in the 20Th Century. *ATMOS CHEM PHYS.* 11, 4577-4586 (2011).
- 398 15. Huang, Y., Dickinson, R. E. & Chameides, W. L. Impact of Aerosol Indirect Effect On Surface  
399 Temperature Over East Asia. *Proceedings of the National Academy of Sciences - PNAS.* 103,  
400 4371-4376 (2006).
- 401 16. Rosenfeld, D. et al. Global Observations of Aerosol-Cloud-Precipitation-Climate Interactions.  
402 *REV GEOPHYS.* 52, 750-808 (2014).
- 403 17. Zhong, J., Zhang, X., Dong, Y., Wang, Y., Wang, J., Zhang, Y. & Che, H. Feedback effects of  
404 boundary-layer meteorological factors on explosive growth of PM2.5 during winter heavy  
405 pollution episodes in Beijing from 2013 to 2016. *Atmos. Chem. Phys.* 2017, 1–25 (2017).
- 406 18. Yang, Y. R. et al. Characteristics and Formation Mechanism of Continuous Hazes in China: A  
407 Case Study During the Autumn of 2014 in the North China Plain. *ATMOS CHEM PHYS.* 15,  
408 8165-8178 (2015).
- 409 19. Zhao, Z. et al. Chemical composition of PM2.5 at a high–altitude regional background site over  
410 Northeast of Tibet Plateau. *Atmos. Pollut. Res.* 6(5), 815-823 (2015).
- 411 20. Li X, F. Y. J. L. The Impact of Meteorological Factors On PM2.5 Variations in Hong Kong. *IOP*

- 
- 412 *Conference Series: Earth and Environmental Science*. (2017).
- 413 21. Lin, G. et al. Spatial Variation of the Relationship Between PM<sub>2.5</sub> Concentrations and  
414 Meteorological Parameters in China. *BIOMED RES INT*. 2015, 1-15 (2015).
- 415 22. Pu, W., Zhao, X., Zhang, X. & Ma, Z. Effect of Meteorological Factors On PM<sub>2.5</sub> During July  
416 to September of Beijing. *Procedia Earth and Planetary Science*. 2, 272-277 (2011).
- 417 23. Huang, F. et al. PM<sub>2.5</sub> Spatiotemporal Variations and the Relationship with Meteorological  
418 Factors During 2013-2014 in Beijing, China. *PLOS ONE*. 10, e141642 (2015).
- 419 24. Pearce, J. L., Beringer, J., Nicholls, N., Hyndman, R. J. & Tapper, N. J. Quantifying the  
420 Influence of Local Meteorology On Air Quality Using Generalized Additive Models. *ATMOS*  
421 *ENVIRON*. 45, 1328-1336 (2011).
- 422 25. Granger, C.W.J. Investigating causal relations by econometric models and cross-spectral  
423 methods. *Econometrica*. 37 (3), 424-438 (1969).
- 424 26. Li, G., Fang, C., Wang, S. & Sun, S. The Effect of Economic Growth, Urbanization, and  
425 Industrialization on Fine Particulate Matter PM<sub>2.5</sub> Concentrations in China. *Environ. Sci.*  
426 *Technol*. 50 (21), 11452-11459 (2016).
- 427 27. Sfetsos, A. & Vlachogiannis, D. A new approach to discovering the causal relationship between  
428 meteorological patterns and PM<sub>10</sub> exceedances. *Atmos. Res*. 98 (2-4), 500-511 (2010).
- 429 28. Sugihara, G. et al. Detecting Causality in Complex Ecosystems. *Science (American Association*  
430 *for the Advancement of Science)*. 338, 496-500 (2012).
- 431 29. Xu, X. & Ren, W. Application of a Hybrid Model Based on Echo State Network and Improved  
432 Particle Swarm Optimization in PM<sub>2.5</sub> Concentration Forecasting: A Case Study of Beijing,  
433 China. *Sustainability-Basel*. 11 (11), 3096 (2019).
- 434 30. Sethi, J.K. & Mittal, M. A new feature selection method based on machine learning technique  
435 for air quality dataset. *Journal of Statistics and Management Systems*. 22 (4), 697-705 (2019).
- 436 31. Chen, Z. et al. Detecting the Causality Influence of Individual Meteorological Factors On Local  
437 PM<sub>2.5</sub> Concentration in the Jing-Jin-Ji Region. *SCI REP-UK*. 7, (2017).
- 438 32. Chen, Z. et al. Understanding meteorological influences on PM<sub>2.5</sub> concentrations across China:  
439 a temporal and spatial perspective. *ATMOS CHEM PHYS*. 18, 5343-5358 (2018).
- 440 33. Chen, Z. et al. Influence of Meteorological Conditions On PM<sub>2.5</sub> Concentrations Across China:  
441 A Review of Methodology and Mechanism. *ENVIRON INT*. 139, 105558 (2020).

- 
- 442 34. Hu, X. et al. Temporal and Spatial Variation of PM<sub>2.5</sub> in Xining, Northeast of the Qinghai–  
443 Xizang (Tibet) Plateau. *ATMOSPHERE-BASEL*. 11, 953 (2020).
- 444 35. Engling, G. et al. Characterization and sources of aerosol particles over the southeastern Tibetan  
445 Plateau during the Southeast Asia biomass-burning season. *Tellus Ser. B Chem. Phys. Meteorol.*  
446 63, 117–128 (2011).
- 447 36. Zhuzi Zhao, J. C. Z. S. Chemical Composition of PM<sub>2.5</sub> at a High–Altitude Regional  
448 Background Site Over Northeast of Tibet Plateau. *ATMOS POLLUT RES*. 5, 815-823 (2015).
- 449 37. Chen, L., Zhu, J., Liao, H., Yang, Y. & Yue, X. Meteorological Influences On PM<sub>2.5</sub> and O<sub>3</sub>  
450 Trends and Associated Health Burden Since China's Clean Air Actions. *SCI TOTAL ENVIRON*.  
451 744, 140837 (2020).
- 452 38. Zhang, X., Gu, X., Cheng, C. & Yang, D. Spatiotemporal Heterogeneity of PM<sub>2.5</sub> and its  
453 Relationship with Urbanization in North China From 2000 to 2017. *SCI TOTAL ENVIRON*. 744,  
454 140925 (2020).
- 455 39. Yang, Q., Yuan, Q., Li, T., Shen, H. & Zhang, L. The Relationships Between PM<sub>2.5</sub> and  
456 Meteorological Factors in China: Seasonal and Regional Variations. *INT J ENV RES PUB HE*.  
457 14, 1510 (2017).
- 458 40. Wu, X., Cheng, C., Zurita-Milla, R. & Song, C. An Overview of Clustering Methods for Geo-  
459 Referenced Time Series: From One-Way Clustering to Co- and Tri-Clustering. *International*  
460 *journal of geographical information science : IJGIS*. 34, 1822-1848 (2020).
- 461 41. Dong-Lin, Q. I. et al. Characteristics of Air Quality and its Relationship with Meteorological  
462 Factors From 2001 to 2011 in Xining. *Journal of Meteorology and Environment*. (2014).
- 463 42. Chen, T., He, J., Lu, X., She, J. & Guan, Z. Spatial and Temporal Variations of PM<sub>2.5</sub> and its  
464 Relation to Meteorological Factors in the Urban Area of Nanjing, China. *INT J ENV RES PUB*  
465 *HE*. 13, 921 (2016).
- 466 43. Li, Y., Chen, Q., Zhao, H., Wang, L. & Tao, R. Variations in PM<sub>10</sub>, PM<sub>2.5</sub> and PM<sub>1.0</sub> in an  
467 Urban Area of the Sichuan Basin and their Relation to Meteorological Factors. *ATMOSPHERE-*  
468 *BASEL*. 6, 150-163 (2015).
- 469 44. Lin, G. et al. Spatial Variation of the Relationship Between PM<sub>2.5</sub> Concentrations and  
470 Meteorological Parameters in China. *BIOMED RES INT*. 2015, 1-15 (2015).