**Spatial Characteristics and Influence of Topography and Synoptic Systems on PM$_{2.5}$ in the Eastern Monsoon Region of China**

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**ABSTRACT**

Based on the PM$_{2.5}$ concentration in the autumn and winter of 2015–2019, the characteristics of urban air pollution in the eastern monsoon region of China were discussed. The spatial distribution and interregional influence of fine particle pollution under different synoptic weather and topography in the eastern monsoon region of China were illustrated. According to synoptic systems, regional PM$_{2.5}$ pollution episodes were classified into three categories, including Uniform Pressure field (UP, 60.00%), Pre-High Pressure (PreHP, 30.91%) and Inverted-Trough (IT, 9.09%). The K-Means algorithm combined with the HYSPLIT backward trajectory clustering analysis indicated four clusters under UP controlled, and under weak pressure field was responsible for the elevation of PM$_{2.5}$ concentration, where the Beijing-Tianjin-Hebei and its surrounding areas were the most polluted region. For PreHP, four clusters eased after cold front. For IT, three clusters were ascertained, and the severe PM$_{2.5}$ pollution area was in the central and southern of the North China Plain. This study provided a scientific basis for the joint prevention of PM$_{2.5}$ pollution based on topographic and meteorological characteristics in Eastern China.

**Keywords**: Eastern monsoon region, PM$_{2.5}$, Synoptic systems, Topographic effect

**1 INTRODUCTION**

Since 2013, China has released the Air Pollution Prevention and Control Action Plan (The State Council of the People’s Republic of China, 2013) and implemented strict air pollution control measures. Although the clean air policy has effectively alleviated air pollution (MEE, 2020), PM$_{2.5}$ pollution in eastern China remains severe in winter (Zhang et al., 2018b). According to the Asian Development Bank report, only about 1% of the 500 largest cities in China were up to the air quality standard recommended by the World Health Organization (10 $\mu$g m$^{-3}$ for annual mean and 25 $\mu$g m$^{-3}$ for 24-hour mean) (Zhang and Cao, 2015; Ji et al., 2019). Serious air pollution has pose deleterious affects on environmental ecosystem security and human health (Xie et al., 2016; Song et al., 2017a; Wang et al., 2017; Wu et al., 2018; Xie et al., 2019; Zhao et al., 2019; Askariyeh et al., 2020; Maji, 2020), especially in most densely populated and developed urban agglomerations, such as the Beijing-Tianjin-Hebei (BTH) and the Yangtze River Delta (YRD) (Yan et al., 2018; Zhang et al., 2019b; Xu et al., 2020).

Fine particulate matter (PM$_{2.5}$) is still a primary air pollutant in China, especially in autumn and...
Due to the lack of ground-level PM$_{2.5}$ monitoring data before 2013, most studies discussed PM$_{2.5}$ pollution from remotely sensed data (Zhao et al., 2019) or short-term observations (less than a year at a national scale). Studies on PM$_{2.5}$ regional transport focused on machine learning model (Chang et al., 2020), numerical modeling (Zhang et al., 2021) and Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) (Tiwari et al., 2012). Trajectory clustering analysis, potential source contribution function analysis (PSCF), and concentration weighted trajectory analysis (CWT) (Zhang et al., 2019a) are commonly used to identify pollutant transport and dispersion characteristics and potential source areas, and have been widely used in the study of transport and dispersion of air pollutants. However, most studies on PM$_{2.5}$ are limited to single-city or lack detailed investigation on spatial variations (Cai et al., 2017). Meanwhile, the influence of different meteorological conditions on PM$_{2.5}$ pollution cannot be ignored (Liu et al., 2019), which can affect the transport and dispersion conditions by changing the wind field, resulting in different PM$_{2.5}$ pollution concentration (Wang et al., 2018). Moreover, topography have different effects on weather systems in different regions and seasons (Lai and Lin, 2020), topography can act as a mechanical barrier or a deflector for the movement of weather systems, while its thermodynamic effects can enhance or weaken high and low pressure systems. A geographical unit enclosed by mountains tends to be affected by the same emission sources and weather systems. However, the studies on PM$_{2.5}$ regional transmission at a large scale were limited, and the division of PM$_{2.5}$ pollution areas (Yao et al., 2020) and joint prevention and control during severe pollution periods and areas were scarce. In addition, studies on temporal PM$_{2.5}$ pollution have focused on seasonal variation, and interannual variation has been neglected. To acquire comprehensive and thorough characteristics of PM$_{2.5}$ pollution in a large area and longtime series, large areas and long-time scales studies are needed, as comparisons between different cities and seasons.

As the most important air pollutant in autumn and winter in China, determining the distribution of PM$_{2.5}$ concentration and the main influencing factors in heavily PM$_{2.5}$ polluted areas are essential. The Hu Huanyong line is a geographic boundary of population (Lu et al., 2016) and a comprehensive ecological boundary, which can be used as a geographical boundary for the PM$_{2.5}$ pollution in China. In autumn and winter, the east area of the Hu Huanyong line was the most polluted area in China (Zhang and Pan, 2020). The PM$_{2.5}$ in the eastern monsoon region is jointly influenced by anthropogenic emissions and seasonal variations of meteorological conditions. In winter, due to the heating demand, the emissions of fossil fuel combustion such as coal increase, while the solar radiation decreases, the atmospheric vertical motion energy reduces, and the mixing layer height decreases accordingly. The atmospheric vertical mixing weakens, and the frequency and intensity of winter inversion layer increase, which are unfavorable for the diffusion and removal of pollutants. Therefore, the PM$_{2.5}$ concentration in the eastern monsoon region is higher in winter and lower in summer, showing significant seasonal variations (Zhang and Cao, 2015; Song et al., 2017b; Wang et al., 2017). Previous studies have shown that urban area, urban population, share of secondary industry, and population density showed positive correlation with PM$_{2.5}$ concentration, and a large population is exposed to high PM$_{2.5}$ concentration above the WHO standard (Wang et al., 2017). Therefore, it is urgent to establish the joint prevention and control of air pollution in the eastern monsoon region of China, east of the Hu Huanyong line.

Due to the high proportion of secondary industries, the coal-based energy structure, the rapid development of transportation, and the rapid urbanization in eastern China, a large population inhabits in the eastern region. Affected by the complex spatial distribution of anthropogenic emissions and the different climatic and meteorological conditions, it is difficult to take effective measures to control air pollution and regional transport in eastern China. It is essential to determine the spatial distribution of PM$_{2.5}$ concentration and the heavily polluted areas, to further strengthen the joint prevention and control of PM$_{2.5}$ pollution. The strong correlation between PM$_{2.5}$ concentration in different cities were related to the similar regional scale meteorological fields (Zhang et al., 2018b). Therefore, the local air prevention and control measures cannot achieve the expected effect. Taking joint prevention and control measures for the similar pollution unit is an effective measure to reduce air pollution. The scientific implementation of joint prevention and control relies on the regional pollution transmission of fine particulate matter impact range and pollution area division. In the present study, the K-Means clustering and HYSPLIT trajectory
clustering analysis were used to investigate the spatial distribution and clustering characteristics of PM$_{2.5}$ pollution under different synoptic weather in the eastern monsoon region east of Hu Huanyong Line in China. Based on the daily average PM$_{2.5}$ concentration in autumn and winter, including 259 cities and a total of 30 months from 2015 to 2019, the possibility of inter-regional pollutant transport in eastern China were clarified, which provide a reference for the joint prevention and control of regional haze under different synoptic weather.

2 DATA AND METHODS

2.1 Study Area

The eastern monsoon region of China (EMRC) located east of the Hu Huanyong Line (t), covered a large area east of the Daxinganling-Yinshan-Heilan Mountains-Wuqinling-Nenqing Tanggula Mountains-Transverse Ranges (Huang, 1959). Most terrain pattern of the EMRC is plain, mainly distributed on the third step of China, bordering the Eurasian continent to the north and facing the vast Pacific Ocean. The east area of the Hu Huanyong line accounts for 36% of land area and nearly 96% of the total population (Hu, 1990), and is of great importance to economic development (Ge and Feng, 2010). In winter, under the control of Siberian High, strong cold air activity is frequent with less precipitation. In summer, the Pacific warm air prevails with abundant precipitation (Liu et al., 2009). The average annual temperature varies from above 20°C in southern China to about 0°C in northeast China, and the average annual precipitation ranges from 200 mm to 2200 mm. Rapid urbanization and local pollutant emission were observed in the EMRC over the last two decades (Zhang et al., 2018a), and most pollutants originated from secondary aerosol emission, industrial emission, and vehicle emission (Li et al., 2018; Chen et al., 2019; Yang et al., 2019). Excessive emissions and limited environmental capacity made the east of the Hu Huanyong Line the most polluted area in China.

2.2 Data Collection

Daily average PM$_{2.5}$ concentration, meteorological and digital elevation data in autumn and winter (October 1–March 31) of 2015–2019 in the eastern monsoon region of China were obtained. The PM$_{2.5}$ concentration was obtained from the National Real-Time Urban Air Quality Dissemination Platform (http://113.108.142.147:20035/emcpublish), complied with the China Ambient Air Quality Standard (CAAQS, GB3095-2012) (MEP, 2012) and the Chinese Technical Regulation for Ambient Air Quality Assessment (HJ663-2013) (MEP, 2013).

The meteorological data required for the HYSPLIT model was from the Global Data Assimilation System (GDAS, ftp://arlftp.arlhq.noaa.gov/pub/archives/gdas1) provided online by the National Center for Environmental Prediction (NCEP), with the spatial resolution of 1.0° × 1.0°, and the temporal resolution was 1 h. The synoptic weather chart was provided by the National Meteorological Center (NMC, http://www.nmc.cn/) of China. The digital elevation data were obtained through the NASA/NIMA Shuttle Radar Topography Mission (SRTM) with a resolution of 90 m.

The original PM$_{2.5}$ data from 2015–2019 were preprocessed, and the missing data were complemented by the linear interpolation method. In the present study, heavy pollution was defined as the daily PM$_{2.5}$ mass concentration > 75 µg m$^{-3}$ for three consecutive days and a peak value > 200 µg m$^{-3}$ (Wei et al., 2020). To classify the main synoptic weather system in the EMRC area, the 6-hour weather charts of the regional heavy pollution process were analyzed based on the pressure field and wind circulation characteristics (Peng et al., 2015; Zhang et al., 2018c; Dai et al., 2020). Finally, the heavy pollution process in the EMRC were classified into Uniform Pressure field (UP), Pre-High Pressure (PreHP), and Inverted-Trough (IT) (Fig. 2).

2.3 Methods

2.3.1 Empirical bayesian kriging

The Empirical Bayesian Kriging (EBK) is a geostatistical technique that permits accurate interpolation of spatially intensive data (Roberts et al., 2014; Zhang et al., 2016). The EBK is more accurate in interpolating PM$_{2.5}$ than the Ordinary Kriging. The monthly average PM$_{2.5}$ concentration in autumn and winter of 2015–2019 was estimated using the EBK method. Spatial interpolation
was conducted in ArcGIS 10.7 (Krivoruchko, 2012) using empirical Bayesian kriging (EBK) for 259 cities in the study area to clarify the spatial and temporal distribution patterns of PM$_{2.5}$ concentration.

2.3.2 K-Means clustering

The K-Means clustering algorithm has been widely used in the spatial analysis of air pollutants (Liu et al., 2020), which is a data mining technique in machine learning that seeks to partition M points in N dimensions into k clusters. The algorithm allows data to be grouped into clusters so that the objects within a cluster are similar, but objects in the other groups are different, and the algorithm can help to reveal hidden information in the large dataset (Franceschi et al., 2018). The selection of the appropriate number of clusters is one of the most influential factors on the results of k-means algorithm.

The daily PM$_{2.5}$ concentration data of the heavy pollution process under three synoptic systems were grouped separately using the K-Means algorithm with the following steps.

a. Specify the number of clusters (k), set the cluster centre to arbitrary

b. Calculate the distance of each data centre cluster using the Eq. (1), where $d_{ik}$ is the Euclidean distance from the i-th data point to the k-th cluster center, $c_{ij}$ is the value of the i-th data point on the j-th dimension, $c_{kj}$ is the value of the k-th cluster center on the j-th dimension, and m is the number of dimensions:

$$d_{ik} = \sqrt{\sum_{j=1}^{m} (c_{ij} - c_{kj})^2}$$  

(1)

c. Group data into cluster with the shortest distance using the Eq. (2):

$$\text{Min} \sum_{k=1}^{k} d_{ik} = \sqrt{\sum_{j=1}^{m} (c_{ij} - c_{kj})^2}$$  

(2)

d. Calculate the new cluster center using the Eq. (3), where $x_{ij}$ is the value of the i-th data point on the j-th dimension, and p is the number of data points in the k-th cluster:

$$c_{kj} = \frac{\sum_{i=1}^{p} x_{ij}}{p}$$  

(3)

Repeat steps two through four until no more data move to another cluster and use the spatial distribution map to represent the clustering results. The algorithm searches for a local solution that minimizes the Euclidean distance between the observations and the cluster centers. The maximum number of iterations was set to 100 applying this algorithm, and the selection of the initial center of mass was randomized. In this study, the distance refers to the difference between the PM$_{2.5}$ concentration of each city and the PM$_{2.5}$ concentration of the cluster center, which is used to measure the similarity of PM$_{2.5}$ pollution levels among cities. This method can effectively divide different pollution regions with similar concentration levels and changes, which are more influenced by common external factors such as terrain and weather systems. Mathematics and experience were combined in selecting the optimal number of clusters due to the significant difference in PM$_{2.5}$ concentration of cities in the EMRC (Lv et al., 2015).

2.3.3 HYSPLIT model

The TrajStat-Trajectory Statistics program in MeteoInfo was used to calculate the backward trajectories of air mass during heavy pollution to determine the source of air mass and the regional transport (Wang et al., 2009). The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model was used to calculate the trajectories (Wang et al., 2016). The Euclidean distance clustering and GIS technology was performed for air mass trajectory visualization and statistical
analysis. In the present study, the city clusters in the K-Means clustering results were under the control of a uniform pressure field and were influenced by the same or similar air flow paths. To represent the spatial distribution characteristics of the cities in each cluster, we selected the center city of K-Means clustering of typical pollution process of three synoptic system as the starting point by using the mean centroid method, with the top height of the model set at 10,000 m, and the 36-h backward trajectory of 500 m height was simulated by using the HYSPLIT model. The backward trajectories of air masses in the center city of K-Means clustering qualitatively indicated the source of atmospheric pollutants as well as the direction path and influence range of long-range transport dispersion. In the clustering analysis, 3168, 1632 and 480 trajectories were used for the UP, the PreHP and the IT, respectively.

3 RESULT

3.1 Spatiotemporal Variation of Monthly Average PM$_{2.5}$ Concentration

Table 1 presents the descriptive statistics of PM$_{2.5}$ concentration for 259 cities in the EMRC during autumn and winter from 2015 to 2019. The monthly average concentration varied from 35.2 µg m$^{-3}$ to 84.9 µg m$^{-3}$, with the highest standard deviation of 41.6 µg m$^{-3}$ in December 2015. The most polluted cities were Baoding, Shijiazhuang, and Anyang, which were located in the

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<th>Period</th>
<th>Minimum PM$_{2.5}$</th>
<th>City name</th>
<th>Maximum PM$_{2.5}$</th>
<th>City name</th>
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Table 1. The descriptive statistics of PM$_{2.5}$ concentration for 259 cities in the EMRC during autumn and winter, 2015–2019 (µg m$^{-3}$).
North China Plain and surrounded by mountains on three sides (Fig. 1). In the early stage of air pollution, the North China Plain was typically affected by low-pressure weather systems, and the near-surface southeast wind transported pollutants to the northwest (An et al., 2019). The Taihang Mountains and the east of Loess Plateau blocked the moving air flow, and therefore air pollutants were accumulated. Affected by the high-pressure system, the northwest air flow form a rolling down circulation on the leeward slope due to the terrain effect, which strengthened the upslope wind and vertical upward air flow over the plain. Pollutants were diffused to the high-altitude areas, and then were brought back to the plain by the north wind, resulting in pollutants lingering and gathering (Liu et al., 2023), with mean PM$_{2.5}$ concentrations exceeding 100 µg m$^{-3}$. The cities such as Lijiang, Puer, and Sanya were observed lower PM$_{2.5}$ concentrations of less than 20 µg m$^{-3}$, mostly located in the south and coastal areas of China and the terrain was mainly hilly and relatively open. In winter, these cities were affected by air flows from northwest and northeast (Chen et al., 2020), and were greatly influenced by the marine air mass, which was conducive to the diffusion and dissipation of pollutants. The maximum PM$_{2.5}$ concentration recorded was 727.0 µg m$^{-3}$ at Xingtai, Hebei province, in November 2016, which was more than tenfold the national air quality standard. The minimum PM$_{2.5}$ concentration recorded was 6.6 µg m$^{-3}$ at Lijiang, Yunnan province, in February 2019. The PM$_{2.5}$ pollution was more severe during winter than other months, with mean PM$_{2.5}$ concentration above the national secondary standard (75 µg m$^{-3}$).

3.2 Synoptic System Analysis of Heavy Pollution Process

The EMRC was mainly influenced by the periodic activity of the Siberian High, and the three typical synoptic systems were Uniform Pressure field (UP), Pre-High Pressure (PreHP) and Inverted-Trough (IT) (Fig. 2), which accounted for 60.00%, 30.91% and 9.09%, respectively (Table 2). The UP was a weather system that occurred before the Siberian high pressure moved southward and affected the eastern monsoon region. The UP system was characterized by sparse isobars, weak pressure gradient, low wind speed, and unfavorable conditions for pollutant dispersion, which aggravated the accumulation of particulate matter, and further intensifying the accumulation of PM$_{2.5}$ and causing the greatest impact and longest duration. The PreHP weather was typically followed by the UP, and PM$_{2.5}$ pollution in the EMRC was serious, the airflow from the northwest gathered air pollutants in the east with the passing cold front, the clean air will accelerate the diffusion of...
particulate matter and dilute the pollutant concentration, thus reducing the PM$_{2.5}$ concentration significantly and easing air pollution (Fig. 3). The duration of IT was the shortest, and the moderate PM$_{2.5}$ pollution was generally observed. Fig. 4 shows the classification and integration of the heavy PM$_{2.5}$ pollution in the EMRC during the autumn and winter of 2015–2019 under different synoptic systems. The heavy PM$_{2.5}$ pollution is mainly concentrated in January or December, with December 2016 having the largest frequency (24 days). The PM$_{2.5}$ heavy pollution days is decreasing from 2015 to 2019, which indicated that air pollution in eastern China had gradually alleviated.

3.3 Spatial Clustering Pattern and Backward Trajectory under Different Synoptic Systems

A significant difference was found between coastal and inland cities under the control of different weather systems in regional PM$_{2.5}$ heavy pollution. Moreover, topography aggravated the complexity of spatial clustering (Fig. 5).
3.3.1 Uniform Pressure field (UP)

Under the uniform pressure, eastern China was divided into four clusters (Fig. 6). Cluster I was located in northeast, northwest and south China, at the outer edge of the uniform pressure field; Cluster II was mainly in the middle and lower reaches of the Yangtze River and the northeast plain, outside the heavily polluted area and near the cleaner Cluster I area; Cluster III was mainly in the central part of the north China plain, Henan-Shandong, near the heavily polluted Cluster IV area; Cluster IV was mainly in the east of Taihang Mountains, near Beijing-Tianjin-Hebei city cluster and central Shaanxi-Jinan. Due to the influence of meteorological flow field, the PM$_{2.5}$ concentration significantly varied among clusters. Generally, neighboring cities in the similar topographic or airflow area belonged to the same cluster. Cluster IV was near the eastern side of Taihang Mountains.
Table 2. The summary of pollution characteristics of different synoptic systems in the EMRC.

<table>
<thead>
<tr>
<th>Pattern</th>
<th>Frequency</th>
<th>Some typical periods</th>
<th>characteristics</th>
<th>Max. concentration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform Pressure field (UP)</td>
<td>60.00%</td>
<td>2015.12.06–2015.12.08; 2016.12.15–2016.12.18; 2017.02.12–2017.02.15; 2018.11.27–2018.12.01; 2019.01.09–2019.01.12</td>
<td>Eastern monsoon area under the control of uniform pressure field. The isobars are thin, surface wind speed is small, atmospheric diffusion ability is weak. Blocked by Taihang Mountains, air pollutants accumulate in the North China Plain.</td>
<td>727 µg m⁻³</td>
</tr>
<tr>
<td>Pre-High Pressure (PreHP)</td>
<td>30.91%</td>
<td>2015.12.09–2015.12.10; 2016.11.18–2016.11.02; 2017.01.07–2017.01.08; 2018.12.02–2018.12.03; 2019.01.03–2019.01.06</td>
<td>Pre-High pressure weather systems weaken the topographic effect. The cold high pressure usually extends to the southeast, the isobars in the southern region are thin, pollutants are easy to accumulate before cold fronts arrival. Cold fronts usually bring northwest clean air mass to dissipate the heavy pollution.</td>
<td>644 µg m⁻³</td>
</tr>
<tr>
<td>Inverted-Trough (IT)</td>
<td>9.09%</td>
<td>2015.01.25–2015.01.26; 2016.11.12–2016.11.14; 2017.01.27–2017.01.29; 2018.01.15–2018.01.16; 2019.12.22–2019.12.25</td>
<td>Air mass underground inverted-trough control is governed by low pressure. The trough opens to the south or southwest, the bottom of the trough extends to the north or northeast, moving to the northeast from the southwest of China. The IT weather system has weak influence on heavy pollution.</td>
<td>542 µg m⁻³</td>
</tr>
</tbody>
</table>

Fig. 4. Frequency distribution of heavy pollution days under three weather systems of PM$_{2.5}$ in autumn and winter from 2015 to 2019.
Fig. 5. PM$_{2.5}$ clustering and box line diagrams of prefecture-level cities in the eastern monsoon region during the study period under the control of different weather systems.

and had the maximum PM$_{2.5}$ concentration due to the influence of the converging airflow caused by the topography (Fig. 6), with an average concentration of 161.3 µg m$^{-3}$, followed by Cluster III, which was second to Cluster IV with a concentration of 134.8 µg m$^{-3}$. The average and median
concentration in the peripheral area Cluster I were lower than the national secondary standard. In general, under the control of the uniform pressure field, the low wind speed caused by the weak pressure gradients, as well as the occurrence of near-surface inversions due to the warm surface currents that normally accompany them, led to disadvantageous conditions for particulate matter diffusion and increased concentration accumulation. Weak wind fields led to slow air mass movement, which aggravated the pollution. In addition, particulate matter emission increased in autumn and winter due to winter heating. Once the uniform pressure field weather was encountered, which might lead to a rapid deterioration of air quality and a significant increase in PM$_{2.5}$ concentration and an outbreak of large-scale air pollution.

Backward trajectory of air mass at 500 m height is shown in Fig. 6. Under the uniform pressure field control, Cluster I (e.g., Yichun) was affected by the trajectory airflow in six directions, among which the most frequent influence was from the inland airflow in two directions, northwest (32.83%) and northeast (31.06%), with low air mass temperature and relatively less pollution. Cluster II (e.g., Suizhou) was driven by the trajectory airflow in three directions, among which the highest frequency is from northeast (50.66%) and southwest (41.45%) inland airflow in two directions, the air mass have slightly lower temperature and less pollution. Cluster III (e.g., Heze) was subject to the influence of trajectory airflow in four directions, primarily by inland airflow in the southeast (37.59%) and southwest (29.58%). The air mass from southern area was slightly warmer and more polluted and passed the economically developed area and had relatively high-emission pollution. Cluster IV (e.g., Xingtai) was influenced by the trajectory airflow in three orientations, among which the influence frequency was the airflow from the eastern of the province from local area (42.80%), and the air mass had low temperature and serious pollution (Wang et al., 2018). Regional severe pollution episodes mainly occur in the Yellow-Huaihai Plain and Fenwei Basin owing to the influence of topography. Neighboring cities located in the similar topographic or airflow area constantly interact with each other, thus these cities had similar characteristics and were classified into the same clusters.

3.3.2 Pre-High Pressure (PreHP)

Eastern monsoon region was divided into four clusters under the pre-high pressure weather system (Fig. S1). Cluster I mainly included the northeast and south China, which were at the edge of the cold high-pressure march. Cluster II consisted primarily of the middle and lower reaches of the Yangtze River, which was outside the heavily polluted area and close to the cleaner Cluster I area. Cluster III mainly contained the Beijing-Tianjin-Hebei area in the northern of the North China Plain, which was close to the severe polluted Cluster IV area. Cluster IV was primarily located south of the Taihang Mountains, near the Central Plains urban cluster. However, cluster IV had the highest PM$_{2.5}$ concentration (Fig. 6), with an average concentration of 155.8 $\mu$g m$^{-3}$, which was affected by the topography and heavy air mass from the north. Due to the proximity to the Taihang Mountains, the cluster IV area were frequently located in front of the cold high pressure. Cluster III and Cluster IV have similar characteristics, with PM$_{2.5}$ concentration of 143.2 $\mu$g m$^{-3}$ (Fig. S1).

The backward trajectory clustering of pre-high pressure is indicated in Fig. S1. Cluster I (e.g., Siping) was affected by trajectory airflow in five directions, among which the highest frequency was from inland northwest (30.33%) and southwest (23.04%) airflow, with low temperature and less pollution. Cluster II (e.g., Xinyang) was affected by six directional air currents, of which the most frequent were inland air currents from the southeast (32.11%) and northwest (21.51%), with low air mass temperature and slightly heavier pollution. Cluster III (e.g., Zhengzhou) was impacted by trajectory airflow in four directions, primarily by inland southeast (42.83%) and northwest (27.57%) airflow, with slightly higher air mass temperature and heavy pollution from the southeast, and severe pollution from the northwest due to the air mass from more polluted Hebei and Shanxi province. Cluster IV (such as Hengshui) including five directional track airflow were mainly affected by airflow from the eastern of the province form local emission (35.54%), and inland northwest airflow (24.57%), air mass with low temperature and severe pollution. As the Mongolia-Siberia cold high pressure was active and southward in autumn and winter, air pollutants were accumulated in North China at first, and with the cold front southward could remove the atmospheric pollutants in North China rapidly. The cold front was the gathering zone of atmospheric pollutants, when the gathering zone was pushed to a certain area, the pollutant concentration raised sharply, and then
Fig. 6. Backward trajectories of air mass of different spatial patterns under different synoptic systems controlled. ((a) Uniform Pressure field (UP)).
the air quality in the area before the front deteriorated rapidly (Kang et al., 2019). Affected by the Mongolian-Siberian cold high pressure, the intense weather system weakened the topographic effect and most of the clusters had a relatively similar backward trajectory. When the high pressure kept moving southward, the dominant airflow changed, originating in the Siberian and Mongolian regions, air mass cross the North China Plain, passing through the middle and lower reaches of the Yangtze River, and reaching the southern part of the eastern monsoon region, with most of the clusters mainly were influenced by the north or northwest airflow.

3.3.3 Inverted-Trough (IT)

Under the inverted-trough weather system, the eastern monsoon region of China was divided into three clusters (Fig. S1). Cluster I included South China and coastal areas, which were far from the low-pressure center controlling the surface inversion trough. Cluster II included the outer part of the North China Plain, the Sichuan Basin and the Northeast Plain, which were in the transition area of heavy pollution. Cluster III was in the south-central part of the North China Plain and the central Shaanxi-Jinan region (Fig. S1). Cluster III was located at the bottom of the inversion trough of the ground, where the isobars were sparse and blocked by the Taihang Mountains, and air pollutants were accumulated, with an average concentration of 166.9 µg m⁻³ (Fig. S1).

The backward trajectory air mass of representative cities under Inverted-Trough weather systems are analyzed in Fig. S1. Cluster I (e.g., Huangshi) was subject to six trajectory airflow, and the most frequently influenced airflow was from trajectory 4 (38.54%) and trajectory 1 (23.96%) in the inland area form southwest. The air mass was warmer and less polluted. Cluster II (e.g., Jinan) was influenced by six airflow, primarily from the eastern of Shandong province (50.00%), with heavy pollution. Cluster III (e.g., Jiaozuo) was affected by six directional air mass, mostly affected by air-mass from the inland area form west (41.25%) and northwest (22.08%), with low air temperature and severe pollution. Duration of the surface inversion trough was usually short and initiated in the southern area and moved in the north-east, with thin isobars, small pressure gradients, and weak surface wind. The weak prevailing southerly wind was not beneficial for pollutant diffusion, e.g., under the control of the surface inversion trough, atmospheric pollutants near Beijing converged and formed aggregates in front of Taihang Mountains, thereby causing regional severe pollution episodes (Yu et al., 2020).

4 CONCLUSION AND IMPLICATION

4.1 Conclusion

The autumn and winter PM₂.₅ concentration in the eastern monsoon region of China from 2015–2019 were investigated in the present study. The spatial pattern of severe air pollution was closely related to the synoptic system and the topographic effect. The pollution weather types can be classified as uniform pressure field (60.00%), pre-high pressure (30.91%) and inverted-trough (9.09%). K-Means algorithm combined with HYSPLIT backward trajectory clustering was used to analyze the regional classification and regional transport of PM₂.₅ pollution under the three synoptic systems. The results showed that under the control of a uniform pressure field, the weak wind speed caused by the low-pressure gradient and the complex topography made the prevailing wind direction unstable and the regional differences were significant. The neighboring cities situated in the same topographic area or airflow path often had similar characteristics. Affected by pre-high pressure, the advance of the cold front in front of the intense cold high pressure weakened the influence of the topography. Under the influence of surface inversion trough, the small pressure gradient, low surface wind speed, and the weak southerly wind were available for air pollutants accumulation. Therefore, in regional PM₂.₅ severe pollution, it was necessary to carry out detailed prevention and control methods according to the synoptic weather systems and the distribution pattern of the corresponding regional influence clusters.

4.2 Policy Suggestions

According to the aforementioned results, the eastern monsoon region in China should establish a regional joint prevention and control mechanism for air pollution, and actively promote regional
cooperation for the overall haze control in the eastern monsoon region. The main suggestions were as follows.

1. Under severe pollution, to establish joint prevention and regional control units based on different weather systems with long influence time and develop different pollution prevention and control policies for different areas, implement differentiated emergency management was necessary. In most heavy pollution, the eastern monsoon area was controlled in the Uniform Pressure field, and the east of the Taihang Mountains, Beijing, Tianjin and Hebei urban agglomeration should be used as a focus control unit. From the Central North China Plain to Henan, Shandong should be used as a secondary priority control unit, other areas with low pollution levels can be used as a general control unit.

2. To improve the monitoring and forecasting and early warning system for weather system with short impact time. The duration of pre-high pressure and inverted-trough control of severe pollution was usually short. Therefore, the corresponding environmental pollution monitoring and early warning platform should be established, implementation of regional environmental information sharing, joint warning and demonstration effect mechanism, accurate forecasting of the pollution process weather situation and the dominant airflow, to further take targeted joint control measures.

3. Strengthen the construction of a joint regional environmental law enforcement and regulatory system. Establish a coordinated regional linkage environmental management mechanism and explore the linked management system of cities outside the Beijing-Tianjin-Hebei corridor.

ADDITIONAL INFORMATION AND DECLARATIONS

Declaration of Competing Interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary Material

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220393

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