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Supplementary Material

Spatial Characteristics of $PM_{2.5}$ Pollution among Cities and Policy Implication in the Northern Part of the North China Plain

Yangjun Wang [1,2,†,*], Hongli Li [1,†], Jin Feng [3], Wu Wang [1], Ziyi Liu [1], Ling Huang [1,2], Elly Yaluk [1], Guibin Lu [4], Kasemsan Manomaiphiboon [5,6], Youguo Gong [7], Dramane Traore [1] and Li Li [1,2,*]

[1] School of Environmental and Chemical Engineering, Shanghai University, Shanghai 200444, China; lihongli813@shu.edu.cn (H.L.); wangwu@staff.shu.edu.cn (W.W.); lzy141514@shu.edu.cn (Z.L.); linghuang@shu.edu.cn(L.H.); ken112@shu.edu.cn (E.Y.); dramat74@hotmail.fr (D.T.)
[2] Key Laboratory of Organic Compound Pollution Control Engineering, Shanghai University, Shanghai 200444, China
[3] Institute of Urban Meteorology (IUM), China Meteorological Administration (CMA), Beijing 100089, China; jfeng@ium.cn
[4] School of Economics, Shanghai University, Shanghai 200444, China; guibinlu@shu.edu.cn
[5] The Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok 10140, Thailand; kasemsanm@hotmail.com
[6] Center of Excellence on Energy Technology and Environment, Ministry of Higher Education, Science, Research and Innovation, Bangkok 10140, Thailand
[7] Research Institute of Chemical Defense, Beijing 102205, China; yggong@pku.edu.cn
* Correspondence: yjwang326@shu.edu.cn (Y.W.); lily@shu.edu.cn (L.L.); Tel.: +86-13916761899 (Y.W.); +86-18019005281 (L.L.)
† These two authors contribute equally.

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More description about basic temporal-spatial distribution in the NNCP region

In the NAAQS, the daily average concentration of $PM_{2.5}$ is grouped into six levels: "excellent" (≤35 $\mu g \cdot m^{-3}$); "good" (35-75 $\mu g \cdot m^{-3}$); "lightly polluted" (75-115 $\mu g \cdot m^{-3}$); "moderately polluted" (115-150 $\mu g \cdot m^{-3}$); "heavily polluted" (150-250 $\mu g \cdot m^{-3}$) and "severely polluted" (≥250 $\mu g \cdot m^{-3}$). Therefore, daily average $PM_{2.5}$ concentration exceeding "good" levels are regarded as nonattainment days. As shown in Figure S1, the number of polluted days based on NAAQS definitions, dropped steadily year by year. Notably, the number of excellent days show a considerable increase between 2015-2018 in the 42 cities (precisely, 27%, 1% and 32% compared with the previous year). It is also noteworthy that there was a 70% increase in 2018 relative to 2015. On the other hand, the number of non-excellent days accounted for 39%, 32%, 26% and 20% of the total number of days from 2015 to 2018, respectively.

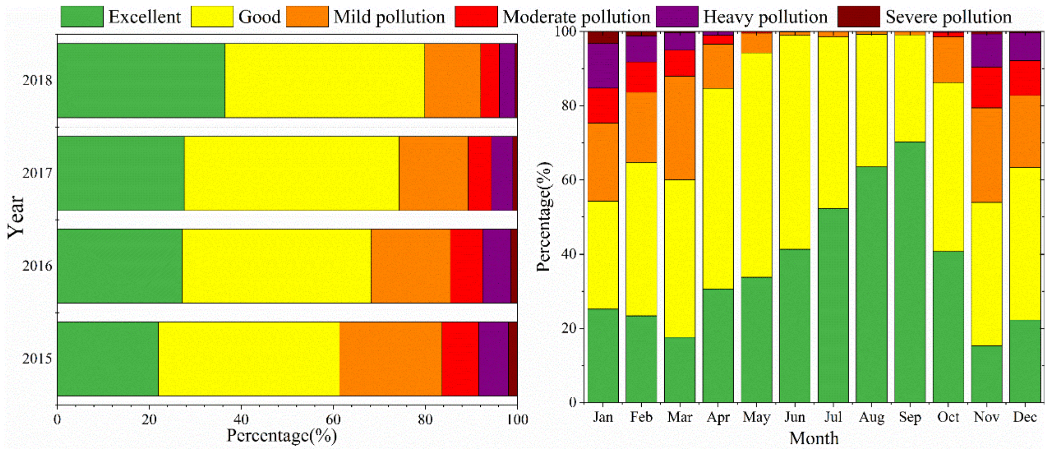

Figure S1. The occurrence frequency of different $PM_{2.5}$ pollution levels in NNCP region year by year during 2015-2018 (left) and month by month in 2018 (right).

Monthly changes of $PM_{2.5}$ concentrations show a U-shaped pattern (Figure S2). The lowest value in 2015 and 2018 occurred in September, while in 2016 and 2017 it occurred in August. The highest monthly average concentration (139.5 μg·m^{-3}) occurred in December, 2015. In terms of monthly averaged concentrations, the lowest two reduction rates occurred in March and November (5% and 11%, respectively), and the highest rate occurred in December (49%). In general, $PM_{2.5}$ pollution events occur mainly in autumn and winter, and the monthly average concentration of $PM_{2.5}$ generally shows a decreasing trend from year to year. $PM_{2.5}$ concentrations decreased significantly from October to December in 2017 compared to 2015 (decreases of 20%, 33%, and 43%, respectively). One possible reason was that this was the last fall-winter season of the Air Pollution Prevention and Control Action Plan (APPCAP) which was implemented from 2013 to 2017.At that time, cities in the BTH region made greater efforts to control emissions in the end of 2017 to achieve the $PM_{2.5}$ goals of the action plan.

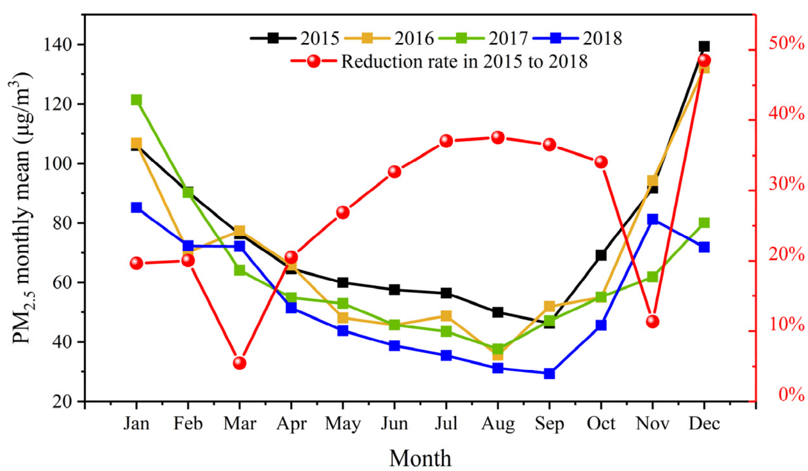

Figure S2. The variations of the monthly average concentration of $PM_{2.5}$ in the NNCP region in different years.

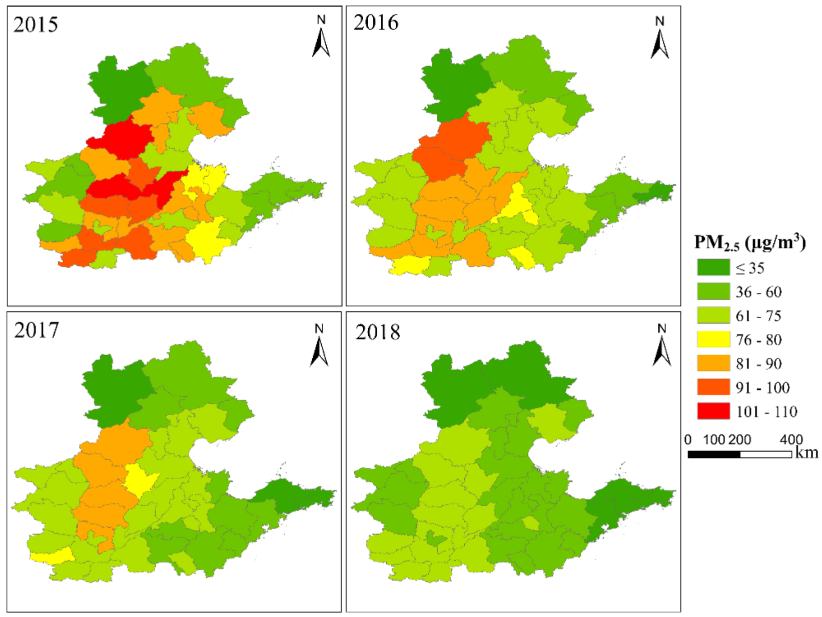

Figure S3. The spatial distribution of $PM_{2.5}$ average annual concentrations in the NNCP region from 2015 to 2018.

The elbow method can help to select the optimal number of clusters by fitting the model with a range of values for K. If the line chart resembles an arm, then the "elbow" (the point of inflection on the curve) is a good indication that the underlying model fits best at that point. Figure S4 shows the elbow method for determining the number of clusters based on two distances.

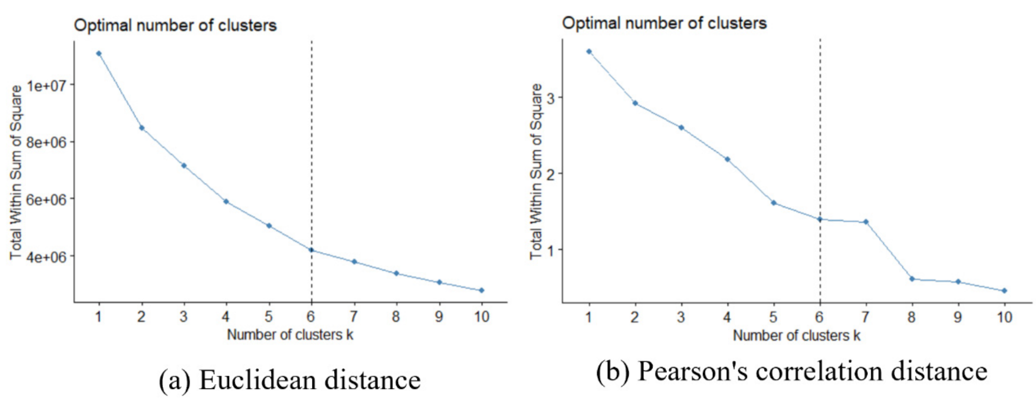

Figure S4. Elbow method for determining the number of clusters based on Euclidean distance (**a**) and Pearson's correlation distance (**b**).

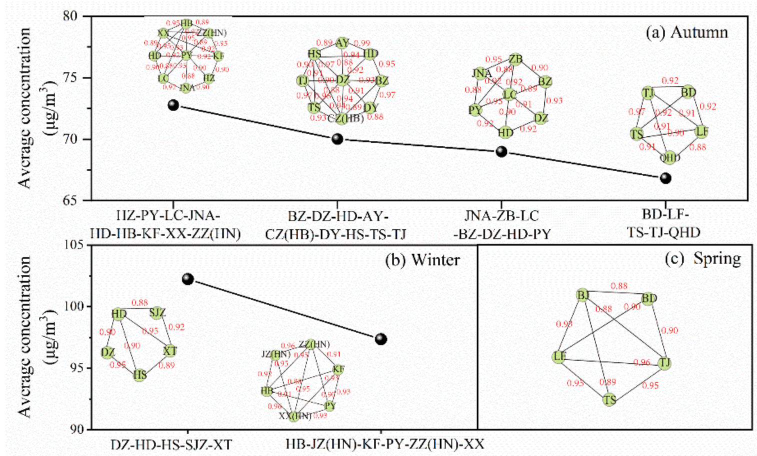

Figure S5. The city-clusters with their average $PM_{2.5}$ concentrations and ϱ values for the third-level in seasons (**a**): Autumn, (**b**): Winter, (**c**): Spring.

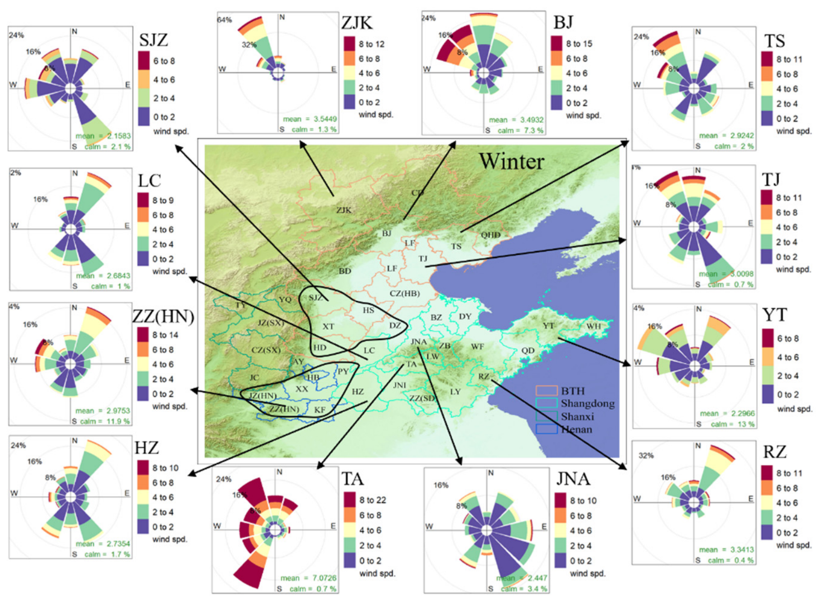

Figure S6. Topographic map and winds rose diagrams of some cities for the winter of in 2018 in the NNCP region.

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Table S1. The COD values for six sub-regions based on Euclidean distance clustering.

City	Yantai	Langfang	Taian	Jinzhong	Xinxiang	Handan
Yantai	0	0.38	0.34	0.40	0.44	0.45
Langfang	0.38	0	0.28	0.24	0.27	0.28
Taian	0.34	0.28	0	0.25	0.23	0.25
Jinzhong	0.40	0.24	0.25	0	0.21	0.23
Xinxiang	0.44	0.27	0.23	0.21	0	0.14
Handan	0.45	0.28	0.25	0.23	0.14	0

Table S2. The COD values for six sub-regions based on Pearson's correlation distance clustering.

City	Zhangjiakou	Rizhao	Langfang	Jinzhong	Xinxiang	Hengshui
Zhangjiakou	0	0.39	0.47	0.37	0.39	0.42
Rizhao	0.39	0	0.36	0.34	0.34	0.34
Langfang	0.47	0.36	0	0.24	0.27	0.24
Jinzhong	0.37	0.34	0.24	0	0.21	0.21
Xinxiang	0.39	0.34	0.27	0.21	0	0.17
Hengshui	0.42	0.34	0.24	0.21	0.17	0