Supporting Information for

Spatial and temporal differentiation of air quality and its influence factors in 16 cities in Shandong Province in 2019-2020

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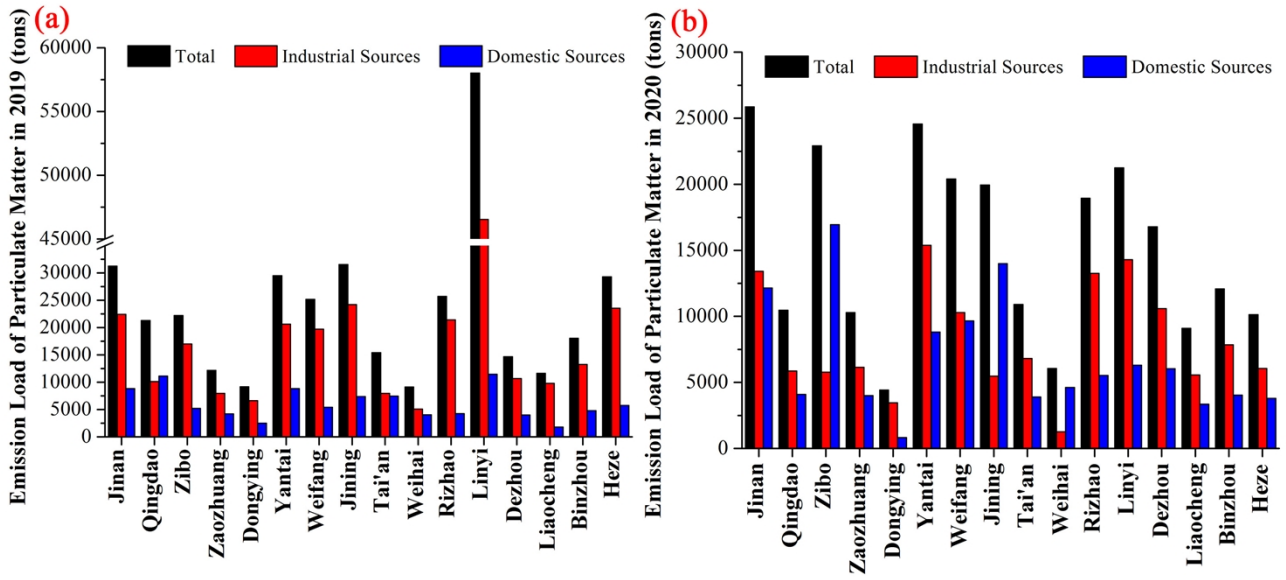

Fig. S1 Emission load of particulate matter in Shandong Province in 2019 (a) and 2020 (b)

The emission of particulate matter in different years and cities varies greatly. In 2019, the total emission of particulate matter in Linyi was the largest, among which the emissions of particulate matter from industrial sources and domestic sources reached 46,532 tons and 11,480 tons, respectively. Weihai had the smallest particulate matter emissions, with industrial and domestic sources emitting 5,082 tons and 4.034 tons, respectively. Fifteen cities were dominated by emissions from industrial sources, while only Qingdao was dominated by emissions from domestic sources. However, in 2020, the total emission of particulate matter in Jinan was the largest, among which the emissions of particulate matter from industrial sources and domestic sources reached 13,414 tons and 12,147 tons, respectively. Dongying had the smallest particulate matter emissions, with industrial and domestic sources emitting 3,470 tons and 822 tons, respectively. Thirteen cities, including Yantai, Linyi and Rizhao, were dominated by emissions from industrial sources, while three cities, Zibo, Jining and Weihai, were dominated by emissions from domestic sources.

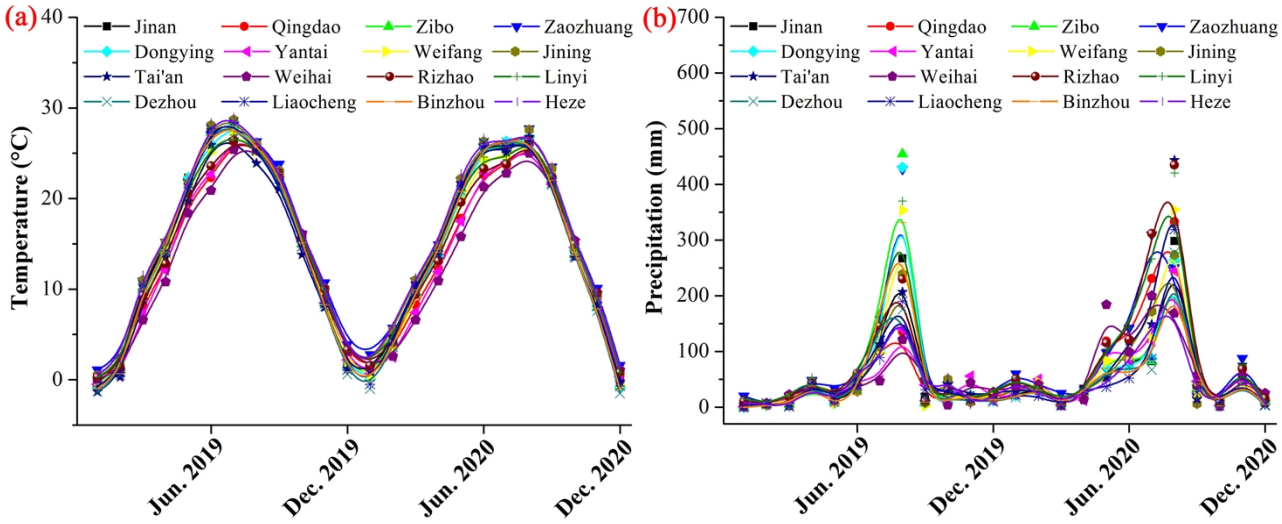

Fig. S2 Temperature (a) and precipitation (b) conditions in Shandong Province in 2019-2020

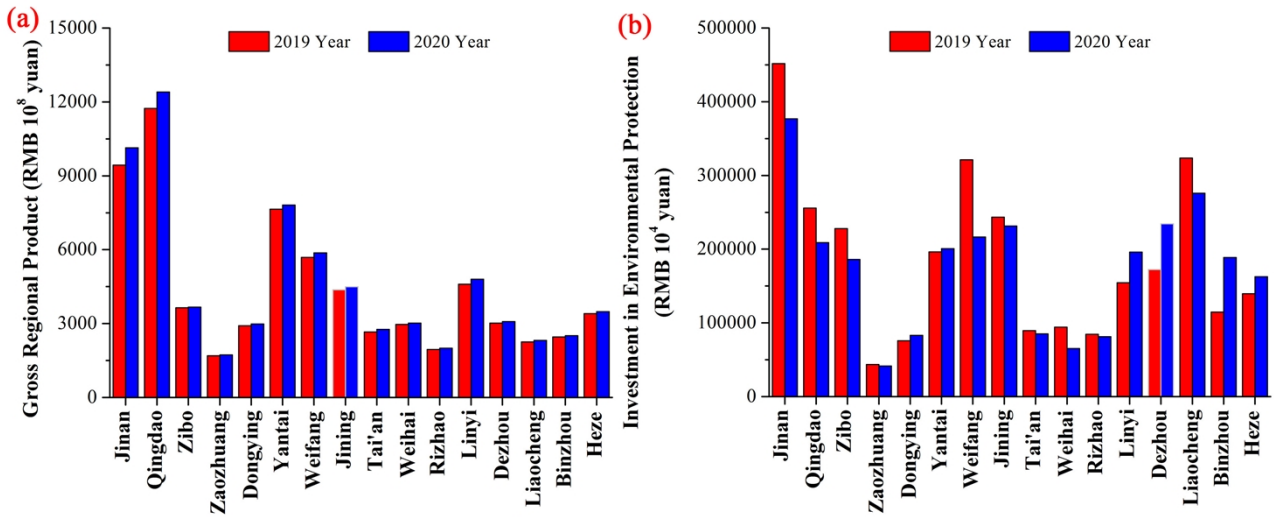

Fig. S3 Economic status of Shandong Province from 2019-2020: GRP (a) and investment in environmental protection (b)

Fig. S3 shows the GRP and investment in environmental protection of 16 cities in Shandong Province in 2019-2020. In 2019 and 2020, Shandong's economic development was stable and improving, with the GRP of the region reaching 7.05 trillion yuan and 7.31 trillion yuan, respectively. There are large differences among cities in Shandong Province: Qingdao, Jinan and Yantai are at the forefront of the whole province. In 2019 and 2020, the regional GRP of Qingdao reached 1,174.131 billion yuan and 1,240.056 billion yuan, respectively, accounting for 17% of the whole province. The economic strength of Zaozhuang, Rizhao and Liaocheng is weak. In 2019 and 2020, the regional GRP of Zaozhuang was only 169.391 billion yuan and 173.325 billion yuan, respectively, accounting for approximately 2% of the province. In Shandong Province, investment in environmental governance varies greatly among cities. In 2019 and 2020, Jinan had the largest investment in environmental governance, reaching 4517.32 million yuan and 3768.07 million yuan, respectively, while Zaozhuang had the least investment, reaching 435.08 million yuan and 416.25 million yuan, respectively.

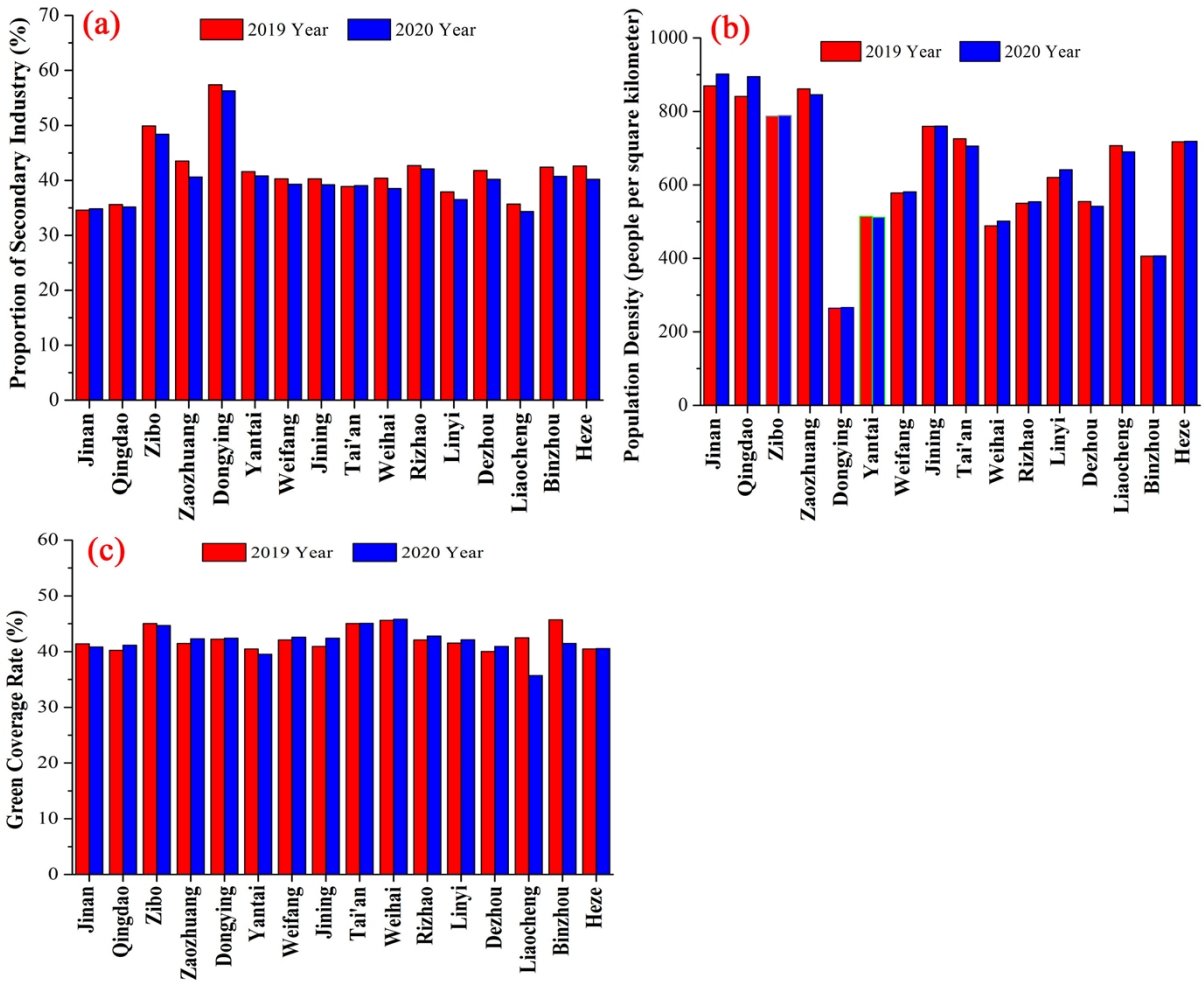

Fig. S4 The social situation of Shandong Province in 2019 and 2020: Proportion of secondary industry (a), population density (b) and green coverage rate (c)

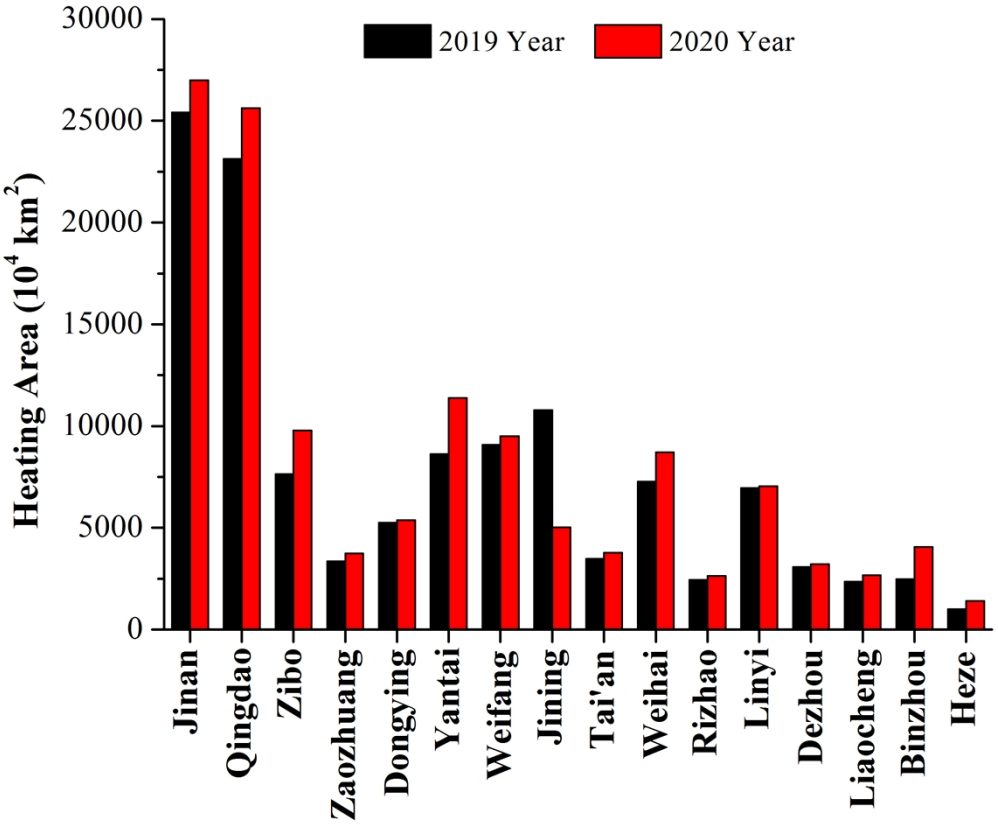

Fig. S5 The heating area of Shandong Province in 2019 and 2020

Table S1 The individual air quality index (IAQI) and limited value of related pollutant.

IAQI	SO_2[a]	SO_2[b]	NO_2[a]	NO_2[b]	PM10[a]	CO[a]	CO[b]	O3[b]	O3[c]	PM2.5[a]
	μg/m^3	μg/m^3	μg/m^3	μg/m^3	μg/m^3	mg/m^3	mg/m^3	μg/m^3	μg/m^3	μg/m^3
0	0	0	0	0	0	0	0	0	0	0
50	50	150	40	100	50	2	5	160	100	35
100	150	500	80	200	150	4	10	200	160	75
150	475	650	180	700	250	14	35	300	215	115
200	800	800	280	1200	350	24	60	400	265	150
300	1600	1600	565	2340	420	36	90	800	800	250
400	2100	2100	750	3090	500	48	120	1000	1000	350
500	2620	2620	940	3840	600	60	150	1200	1200	500

a: Mean concentration for 24 h.

b: Mean concentration for 1 h.

c: Mean concentration for 8 h.

Table S2 The classification and level of AQI

AQI	Level	Classification	Color
0-50	Level 1	Excellent	Green
51-100	Level 2	Good	Yellow
101-150	Level 3	Mild Contamination	Orange
151-200	Level 4	Middle Level Pollution	Red
201-300	Level 5	Serious Contamination	Purple
> 300	Level 6	Severe Contamination	Maroon

Table S3 Pollutant concentration during January to March (lockdown period in 2020) of 2017-2023

Pollutional Index	2017	2018	2019	2020	2021	2022	2023
Concentration of SO_2 ($\mu g/m^3$)	38	23	20	13	15	12	13
Concentration of NO_2 ($\mu g/m^3$)	44	40	44	31	36	31	34
Concentration of PM10 ($\mu g/m^3$)	135	121	136	93	104	81	104
Concentration of PM2.5 ($\mu g/m^3$)	82	69	80	62	58	51	59
Concentration of $O_{3\text{-}8h}$ ($\mu g/m^3$)	102	114	105	104	102	104	115
Concentration of CO-95per (mg/m^3)	2.2	1.8	1.7	1.4	1.3	1.1	1.2

Table S4 AQI of 16 cities in Shandong Province in 2019-2020

City	2019							2020						
	SO_2	NO_2	PM10	PM2.5	O_3	CO	AQI	SO_2	NO_2	PM10	PM2.5	O_3	CO	AQI
Jinan	15	52	77	73	140	40	140	12	44	68	65	122	38	122
Qingdao	8	40	55	53	90	38	90	7	39	56	45	88	30	88
Zibo	20	53	77	77	141	48	141	17	48	70	72	126	45	126
Zaozhaung	17	43	82	62	128	35	128	16	38	72	74	115	35	115
Dongying	15	45	70	67	137	38	137	15	39	65	63	116	35	116
Yantai	8	34	60	50	99	33	99	8	32	54	43	94	28	94
Weifang	13	47	77	74	119	43	119	11	40	68	65	108	40	108
Jining	17	45	69	74	127	38	127	14	42	65	70	121	40	121
Tai’an	15	43	74	73	132	38	132	14	37	66	64	120	38	120
Weihai	6	25	53	42	100	28	100	5	19	44	35	85	23	85
Rizhao	9	44	68	63	105	40	105	8	39	56	50	99	33	99
Linyi	15	48	78	78	125	40	125	12	43	68	68	117	38	117
Dezhou	15	43	77	73	138	40	138	13	37	71	72	120	40	120
Liaocheng	14	48	81	79	141	43	141	12	42	72	73	113	40	113
Binzhou	19	49	71	73	141	43	141	16	47	66	68	130	40	130
Heze	14	42	80	78	125	35	125	11	38	75	73	110	35	110

Table S5 Correlation analysis between the pollutant index and emission load of particulate matter index in 2020

Pollutional Index	Total particulate matter emissions		Particulate matter emissions from industrial sources		Particulate matter emissions from domestic sources	
	Correlation	P value	Correlation	P value	Correlation	P value
Annual mean concentration of SO_2	0.036	0.896	-0.158	0.558	-0.028	0.918
Annual mean concentration of NO_2	0.401	0.124	0.037	0.892	0.341	0.196
Annual mean concentration of PM10	-0.049	0.858	0.038	0.888	-0.161	0.553
Annual mean concentration of PM2.5	-0.058	0.832	-0.091	0.736	-0.093	0.732
Annual mean concentration of $O_{3\text{-}8h}$	0.338	0.2	0.071	0.795	0.232	0.387
Annual mean concentration of CO-95per	0.303	0.253	-0.027	0.921	0.306	0.248
PDHP	-0.033	0.904	-0.049	0.857	-0.137	0.614
PDWP	-0.362	0.168	-0.106	0.695	-0.301	0.257

Table S6 Correlation analysis between the pollutant index and emission load of particulate matter index in heating period in 2019-2020

Pollutional Index	Total particulate matter emissions		Particulate matter emissions from industrial sources		Particulate matter emissions from domestic sources	
	Correlation	P value	Correlation	P value	Correlation	P value
Mean concentration of SO_2	0.085	0.648	0.106	0.569	-0.086	0.647
Mean concentration of NO_2	0.369	0.041**	0.369	0.041**	0.102	0.585
Mean concentration of PM10	0.158	0.397	0.306	0.094*	-0.137	0.462
Mean concentration of PM2.5	0.196	0.292	0.296	0.106	-0.078	0.675
Mean concentration of $O_{3\text{-}8h}$	0.1	0.593	0.186	0.316	-0.108	0.563
Mean concentration of CO-95per	0.269	0.143	0.222	0.230	0.118	0.528
PDHP	-0.244	0.186	-0.197	0.287	-0.103	0.582
PDWP	-0.327	0.073*	-0.347	0.056*	-0.088	0.638

* $P < 0.05$; ** $P < 0.01$

Table S7 Correlation analysis between the pollutant index and economic index in 2019-2020

Pollutional Index	GRP		Investment in environmental protection	
	Correlation	P value	Correlation	P value
Annual mean concentration of SO_2	-0.338	0.063*	-0.118	0.527
Annual mean concentration of NO_2	-0.092	0.623	0.248	0.178
Annual mean concentration of PM10	-0.271	0.140	0.081	0.666
Annual mean concentration of PM2.5	-0.268	0.145	0.132	0.480
Annual mean concentration of $O_{3\text{-}8h}$	-0.312	0.087*	0.051	0.787
Annual mean concentration of CO-95per	-0.064	0.732	0.438	0.014**
PDHP	-0.032	0.863	0.041	0.828
PDWP	-0.109	0.560	-0.045	0.812

* $P < 0.05$; ** $P < 0.01$

Based on the correlation analysis between pollutant indicators and economic indicators of 16 cities in Shandong Province, as shown in Table S7, there were significant negative correlation between SO_2 and GRP, $O_{3\text{-}8h}$ and GRP, respectively. Nevertheless, there was significant positive correlation between CO-95per and investment in environmental protection. The results indicated that the economic level was played key role in improvement of SO_2, O_3 and CO. In addition, Shandong's economic structure is dominated by the tertiary industry, whose production value in 2019 and 2020 accounted for 52.8% and 53.5%, respectively. Since 2018, Shandong has promoted the transformation of old and new driving forces, changing the industrial status quo of a high proportion of traditional industries, "heavy" economic structure and high consumption of energy and resources. With digital empowerment, innovation-driven and intelligent manufacturing as the core elements of Shandong's industrial transformation momentum and competitive strength, the transformation of industrial structure can make Shandong achieve a "win-win" situation in both economic development and environmental protection.

Table S8 Correlation analysis between the pollutant index and social situation in 2019 and 2020

Pollutional Index	Proportion of secondary industry in 2019		Proportion of secondary industry in 2020		Population density in 2019		Population density in 2020		Green coverage rate in 2019		Green coverage rate in 2020	
	Correlation	P value	Correlation	P value	Correlation	P value	Correlation	P value	Correlation	P value	Correlation	P value
Annual mean concentration of SO_2	0.309	0.244	0.378	0.149	0.346	0.19	0.438	0.09	0.202	0.454	0.138	0.609
Annual mean concentration of NO_2	-0.048	0.86	-0.065	0.811	0.072	0.79	0.135	0.619	0.376	0.151	-0.067	0.804
Annual mean concentration of PM10	0.069	0.801	-0.094	0.728	-0.108	0.692	-0.124	0.648	-0.049	0.858	-0.335	0.205
Annual mean concentration of PM2.5	0.036	0.896	-0.016	0.952	-0.117	0.666	-0.052	0.849	-0.019	0.946	-0.313	0.238
Annual mean concentration of $O_{3\text{-}8h}$	0.143	0.597	0.113	0.676	0.276	0.301	0.274	0.305	0.382	0.144	0.032	0.905
Annual mean concentration of CO-95per	-0.079	0.772	-0.017	0.952	0.003	0.991	0.048	0.86	0.314	0.236	-0.008	0.978
PDHP	0.24	0.37	0.008	0.976	-0.142	0.6	-0.08	0.768	0.138	0.609	-0.27	0.311
PDWP	-0.119	0.66	0.12	0.657	0.004	0.987	-0.037	0.892	0.116	0.669	0.325	0.325