Supplemental Materials

Quantifying the impact of synoptic circulation on ozone variations in North China from April-October 2013-2017

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Text S1 Segmented synoptic-regression approach

In an attempt to objectively define and weight the meteorological variables, Eder et al. (1994) indicated that most influence the O_3 concentrations within each weather type, and they developed stepwise linear regression models of the following form:

$$O_3 = \beta_0 + \sum_{i=1}^{n} \beta_i x_i \qquad (1)$$

where O_3 represents the predicted MDA8 O_3 for each weather category, β_0 is a constant, β_i are the coefficients (determined by the least squares method) of the independent meteorological variables x_i, and n is the number of independent meteorological variables in the equation. A stepwise regression procedure was utilized because it sequentially identifies the ‘best subset’ of the independent meteorological variables.

This paper used multiple linear regression with a stepwise method for variable selection to reconstruct the time series for O_3 with F probability <0.05 to enter and F probability <0.10 to exit. After excluding the missing data and disordering the time sequences, 80% of these days were used to build the potential forecast equations, and the remaining 20% were used to validate the accuracy of the equations.

Tables

Table S1. Locations, period of available data, average MDA8 O_3 concentrations, and exceedance ratios of 58 cities. Abb, Lon, Lat and Alt are short for abbreviation, longitude, latitude and altitude, respectively.

Province	City name	Abb	Lon	Lat	Alt	Period	O_3 ($\mu g\ m^{-3}$)	Exceedance Ratio (%)
Hebei	Chengde	CD	117.91	40.95	379.20	2013-2017	118	18.93
Hebei	Zhangjiakou	ZJK	114.87	40.81	860.20	2013-2017	114	15.84
Shanxi	Datong	DT	113.31	40.10	1051.17	2015-2017	112	9.38
Beijing	Beijing	BJ	116.38	40.04	58.25	2013-2017	127	29.43
Hebei	Qinhuangdao	QHD	119.60	39.93	2.80	2013-2017	102	9.56
Hebei	Tangshan	TS	118.18	39.63	6.83	2013-2017	124	25.12
Hebei	Langfang	LF	116.71	39.54	19.50	2013-2017	120	22.87
Shanxi	Shuozhou	SZ	112.43	39.34	1094.60	2015-2017	133	23.13
Tianjin	Tianjin	TJ	117.35	39.09	6.27	2013-2017	113	17.24
Hebei	Baoding	BD	115.47	38.87	15.00	2013-2017	125	25.68
Shanxi	Xinzhou	XZ	112.72	38.45	778.00	2015-2017	110	13.13
Hebei	Cangzhou	CZ	116.86	38.30	14.33	2013-2017	127	25.59
Hebei	Shijiazhuang	SJZ	114.48	38.03	153.75	2013-2017	116	21.18
Shanxi	Yangquan	YQ	113.56	37.86	767.83	2015-2017	119	20.63
Shanxi	Taiyuan	TY	112.52	37.86	800.89	2013-2017	116	18.67
Hebei	Hengshui	HS	115.68	37.74	23.00	2015-2017	138	34.86
Shanxi	Jinzhong	JZ	112.73	37.70	796.00	2015-2017	110	16.25
Shanxi	Lvliang	LL	111.13	37.51	943.00	2015-2017	88	3.75
Shandong	Yantai	YT	121.37	37.50	9.17	2015-2017	118	12.50
Shandong	Weihai	WH	122.09	37.49	26.00	2015-2017	115	9.53
Shandong	Dezhou	DZ	116.30	37.46	22.67	2015-2017	146	40.78
Shandong	Dongying	DY	118.64	37.43	3.25	2015-2017	146	35.94
Shandong	Binzhou	BZ	118.00	37.38	16.67	2015-2017	116	17.19
Hebei	Xingtai	XT	114.49	37.06	71.75	2013-2017	115	19.96
Shandong	Zibo	ZB	118.01	36.73	81.67	2015-2017	139	32.03
Shandong	Weifang	WF	119.14	36.71	53.80	2015-2017	142	34.38
Shandong	Jinan	JN	116.98	36.65	55.25	2015-2017	130	45.31
Hebei	Handan	HD	114.51	36.60	64.50	2013-2017	116	31.25
Shandong	Liaocheng	LC	115.99	36.45	44.67	2015-2017	133	29.06
Shandong	Laiwu	LW	117.69	36.21	207.67	2015-2017	123	21.56
Shandong	Tai’an	TA	117.11	36.19	170.00	2015-2017	126	22.81
Shanxi	Changzhi	CZH	113.11	36.19	924.40	2015-2017	141	36.72
Shandong	Qingdao	QD	120.39	36.15	23.78	2015-2017	105	12.66
Henan	Anyang	AY	114.37	36.09	84.20	2015-2017	119	22.03
Shanxi	Linfen	LFE	111.51	36.08	466.33	2015-2017	115	19.84
Henan	Hebi	HB	114.25	35.79	115.67	2015-2017	123	19.38
Henan	Puyang	PY	115.04	35.77	56.00	2015-2017	124	22.19
Shanxi	Jincheng	JC	112.85	35.50	743.17	2015-2017	103	15.94
Shandong	Jining	JN	116.59	35.42	34.00	2015-2017	135	31.09
Shandong	Rizhao	RZ	119.51	35.41	31.00	2015-2017	122	16.09
Henan	Xinxiang	XX	113.88	35.29	75.50	2015-2017	125	27.81
Shandong	Heze	HZ	115.45	35.25	47.00	2015-2017	131	25.00

Henan	Jiaozuo	JZ	113.23	35.22	93.00	2015-2017	122	23.91
Shanxi	Yuncheng	YC	111.02	35.05	380.20	2015-2017	117	19.06
Shandong	Linyi	LY	118.33	35.05	69.50	2015-2017	135	29.69
Shandong	Zaozhuang	ZZH	117.52	34.82	71.40	2015-2017	133	28.13
Henan	Kaifeng	KF	114.34	34.79	79.25	2015-2017	114	15.47
Henan	Sanmenxia	SMX	111.17	34.79	353.25	2015-2017	121	19.06
Henan	Zhengzhou	ZZ	113.65	34.78	111.44	2013-2017	101	17.34
Henan	Luoyang	LY	112.42	34.66	133.29	2015-2017	127	27.66
Henan	Shangqiu	SQ	115.66	34.42	33.25	2015-2017	124	18.44
Henan	Xuchang	XC	113.81	34.01	71.00	2015-2017	124	20.00
Henan	Pingdingshan	PDS	113.28	33.73	75.75	2015-2017	129	25.78
Henan	Zhoukou	ZK	114.66	33.61	45.75	2015-2017	116	13.28
Henan	Luohe	LH	114.03	33.57	65.75	2015-2017	127	22.81
Henan	Nanyang	NY	112.53	32.99	124.00	2015-2017	128	22.97
Henan	Zhumadian	ZMD	114.01	32.99	78.00	2015-2017	124	21.09
Henan	Xinyang	XY	114.06	32.12	89.50	2015-2017	110	10.31

Table S2 Days of occurrence and the proportion of the most-polluted synoptic categories (LP and C) in May and the second half of May in each weather category in different years.

	Year	N-E-S directions	S-W-N directions	LP	C	A	Proportion (%)
May	2013	5	14	4	4	4	25.8
	2014	7	16	3	4	1	22.6
	2015	7	10	4	4	6	25.8
	2016	8	12	2	2	7	12.9
	2017	5	13	3	8	2	35.5
	mean	6.4	13	3.2	4.4	4	24.5
The second half of May	2013	2	8	2	2	2	25.0
	2014	1	11	2	2	0	25.0
	2015	3	7	3	0	3	18.8
	2016	5	6	2	0	3	12.5
	2017	2	5	1	7	1	50.0
	mean	2.6	7.4	2	3.7	2.25	35.6

Table S3 Equations of the multiple stepwise regressions for each weather type in 14 cities, where O_3 indicates MDA8 O_3.

Categories	Cities	Regression equation
N-E-S direction	CD	O_3=4.78Tmax+10.62V+7.92ws-0.92RH_lag-1.20Tmax_lag+7.16V_lag+76.40
	ZJK	O_3=-0.32RH+2.21Tmax+7.16V+5.53ws-0.39RH_lag-4.59U_lag+80.72
	BJ	O_3=5.40Tmax+14.64V+13.25ws-0.29RH_lag-26.06
	QHD	O_3=2.41Tmax-4.96U+12.11V+35.23
	TS	O_3=-3.43TCC+5.29Tmax+12.03V-0.66RH_lag+39.62
	LF	O_3=5.41Tmax+6.42V-0.38RH_lag-7.26
	TJ	O_3=4.72Tmax+2.84V+-0.48RH_lag-1.62Tmax_lag+3.88V_lag-4.67ws_lag-1.46pre_lag+1534.81
	BD	O_3=2.49TCC+4.85Tmax+9.37V-0.53RH_lag-6.97U_lag+7.65V_lag+10.06
	CZ	O_3=-0.43RH+4.81Tmax+7.76V+21.69
	SJZ	O_3=4.00Tmax-0.60RH_lag+36.41
	TY	O_3=3.61Tmax+4.09ws+3.30TCC_lag-0.44RH_lag-9.86
	XT	O_3=4.59Tmax-13.32U+0.07wd-0.86RH_lag-3.02V_lag+28.31
	HD	O_3=6.08Tmax-0.53RH_lag-1.59Tmax_lag+22.32
	ZZ	O_3=4.64Tmax-0.06wd+0.84rain_lag-27.47
S-W-N direction	CD	O_3=4.29TCC+6.35Tmax+8.76ws-0.72RH_lag+5.23V_lag-18.27
	ZJK	O_3=4.33TCC+4.51Tmax+3.11V+3.72ws+4.37TCC_lag-0.64RH_lag+4.81V_lag-6.01
	BJ	O_3=7.54Tmax-5.27U+16.45V+4.27TCC_lag-0.60RH_lag+4.32V_lag-0.06wd_lag-56.35
	QHD	O_3=-0.52RH+3.88Tmax+17.84V+51.59
	TS	O_3=6.74Tmax+4.32U+8.64V-0.62RH_lag+6.93V_lag-10.58
	LF	O_3=3.06TCC+7.57Tmax+7.64V+1.51pre+3.76TCC_lag-0.60RH_lag-1607.79
	TJ	O_3=5.65Tmax+6.54V+3.68V_lag-43.17
	BD	O_3=6.86Tmax-13.59ws-0.72RH_lag+20.64
	CZ	O_3=-0.65RH+5.16Tmax+8.70V-8.22ws+7.02TCC_lag-0.58RH_lag+4.14V_lag-0.06wd_lag+35.19
	SJZ	O_3=6.30Tmax-13.69U-45.68
	TY	O_3=3.37TCC-0.85RH+3.13Tmax-1.28pre+4.86TCC_lag-1.17rain_lag-11.06U_lag+1310.49
	XT	O_3=5.59Tmax+5.43ws+4.94TCC_lag-0.52RH_lag-45.10
	HD	O_3=0.29RH+4.25Tmax-1.24rain+4.99ws_lag+20.15
	ZZ	O_3=2.55Tmax-2.36rain+4.46TCC_lag+1.40
LP	CD	O_3=4.66Tmax+16.13V-0.60RH_lag+43.36
	ZJK	O_3=3.98Tmax-12.35U+18.14
	BJ	O_3=7.41Tmax+18.41V-0.55RH_lag-35.05
	QHD	O_3=3.49Tmax+21.88V+17.42ws_lag-0.57
	TS	O_3=-5.34TCC-0.63RH+6.39Tmax+23.92V+10.46ws_lag+3.36
	LF	O_3=6.10TCC+8.69Tmax+2.37pre+6.50TCC_lag-1.06RH_lag-2514.48
	TJ	O_3=-0.69RH+5.79Tmax+6.45V-0.54
	BD	O_3=10.59Tmax+4.41pre-0.55RH_lag-4567.38
	CZ	O_3=-0.82RH+4.60Tmax-0.63rain-7.54U+63.69
	SJZ	O_3=6.44Tmax-15.83U+8.82V-56.75
	TY	O_3=7.50Tmax+6.39TCC_lag-1.01RH_lag-16.70U_lag-13.85ws_lag-59.26
	XT	O_3=9.50Tmax+2.83pre-2986.28
	HD	O_3=5.46Tmax-1.79rain+2.33pre-2364.01
	ZZ	O_3=4.30Tmax-24.63ws+22.57
C	CD	O_3=3.71TCC+6.30Tmax+6.29V-1.16RH_lag-7.77U_lag-7.94ws_lag+1.17pre_lag-1161.59
	ZJK	O_3=3.43Tmax+5.85V+35.00
	BJ	O_3=7.50TCC+8.28Tmax+15.51V-0.77RH_lag-97.08

	QHD	O_3=-0.80RH+3.38Tmax-1.89pre-3.57TCC_lag+2014.76
	TS	O_3=-1.07RH+6.36Tmax+7.73U+10.29V+31.38
	LF	O_3=8.71Tmax+10.40V+8.00TCC_lag-1.01RH_lag-106.54
	TJ	O_3=-5.45TCC+5.89Tmax+6.23V-19.91
	BD	O_3=6.49Tmax+6.72V+5.91TCC_lag-1.01RH_lag-13.63
	CZ	O_3=-1.30RH+4.70Tmax+88.72
	SJZ	O_3=-9.24TCC+5.38Tmax-12.90U+32.83
	TY	O_3=7.33TCC+7.73Tmax-150.86
	XT	O_3=5.74Tmax+0.11wd+2.07Tmax_lag-113.54
	HD	O_3=-1.18RH+3.57Tmax-6.63U+103.09
	ZZ	O_3=6.51Tmax+4.75TCC_lag-105.13
A	CD	O_3=5.24TCC-0.98RH+5.13Tmax+0.05wd+5.56V_lag+17.98
	ZJK	O_3=2.39TCC+3.43Tmax+5.27ws-6.10U_lag+5.81ws_lag+0.81
	BJ	O_3=4.63TCC+6.86Tmax-3.8rain-0.38RH_lag-54.49
	QHD	O_3=3.31Tmax+14.30V+7.38V_lag+18.83
	TS	O_3=6.24Tmax+8.14ws-0.62RH_lag+6.64V_lag-5.01
	LF	O_3=4.38TCC+5.75Tmax-0.54RH_lag-6.36ws_lag-12.04
	TJ	O_3=5.38Tmax-2.11rain-0.31RH_lag-7.28
	BD	O_3=6.59Tmax-44.28
	CZ	O_3=-0.40RH+3.98Tmax+6.54V+6.19V_lag+39.87
	SJZ	O_3=-0.39RH+6.29Tmax-6.37U-22.34
	TY	O_3=4.17TCC-0.43RH+4.99Tmax+4.15ws_lag-29.53
	XT	O_3=-0.45RH+5.75Tmax+3.46ws_lag-11.86
	HD	O_3=-0.61RH+6.14Tmax-9.17
	ZZ	O_3=5.05Tmax+3.33TCC_lag-1.16pre_lag+1124.41

Table S4. Three statistic factors (R^2, rmse, and CV) for the building and validation datasets for 5 weather categories and composite model for 14 cities. Com: composite model (integration of each category's modelling results). R^2 (%): variance in the individual model's coefficients of determination, rmse (μg m^{-3}): root mean square error, and CV (%): coefficient of variation defined as rmse/mean MDA8 O_3.

		Building						Validation					
Cities	Parameter	com	HP	UP	LP	C	A	com	HP	UP	LP	C	A
CD	R^2	0.63	0.56	0.59	0.51	0.62	0.64	0.66	0.84	0.61	0.52	0.42	0.69
	rmse	29.62	29.1	33.81	34.06	24.38	28.17	28.75	22.4	31.84	29.18	29.54	30.96
	CV	0.25	0.29	0.26	0.25	0.19	0.28	0.25	0.24	0.24	0.23	0.22	0.32
ZJK	R^2	0.54	0.43	0.59	0.38	0.26	0.56	0.51	0.67	0.45	0.49	0.36	0.67
	rmse	29.3	26.27	31.39	35.28	31.32	25.81	32.82	32.45	37.83	35.27	31.64	23.38
	CV	0.26	0.28	0.25	0.28	0.25	0.26	0.28	0.32	0.3	0.28	0.25	0.21
BJ	R^2	0.66	0.57	0.7	0.56	0.56	0.66	0.69	0.39	0.61	0.77	0.62	0.96
	rmse	35.41	34.76	34.67	42.85	37.44	32.62	38.77	39.19	37.26	40.4	35.79	42.08
	CV	0.28	0.34	0.25	0.29	0.25	0.3	0.3	0.38	0.25	0.26	0.26	0.41
QHD	R^2	0.36	0.24	0.32	0.32	0.24	0.44	0.33	0.27	0.35	0.28	0.25	0.43
	rmse	33.82	30.68	35.37	39.53	38.38	28.52	37.23	32.88	35.71	43.57	42.23	35.03
	CV	0.33	0.35	0.32	0.34	0.34	0.31	0.38	0.42	0.34	0.37	0.38	0.4
TS	R^2	0.63	0.57	0.6	0.66	0.58	0.58	0.75	0.59	0.59	0.87	0.78	0.73
	rmse	34.65	33.46	35.97	37.24	35.6	34.83	38.48	36.18	38.08	36.92	45.67	35.23
	CV	0.28	0.34	0.26	0.27	0.26	0.32	0.32	0.36	0.28	0.25	0.36	0.33

LF	R^2	0.65	0.64	0.61	0.58	0.61	0.67	0.66	0.73	0.6	0.31	0.72	0.64
	rmse	31.34	29.03	31.93	36.81	34.75	28.67	31.53	27.52	31.98	36.89	34.08	29.45
	CV	0.26	0.29	0.25	0.27	0.26	0.27	0.27	0.27	0.26	0.28	0.25	0.29
TJ	R^2	0.60	0.61	0.53	0.56	0.47	0.64	0.57	0.53	0.65	0.52	0.63	0.6
	rmse	30.15	26.7	32.92	31.38	35.36	26.11	31.76	29.9	32.35	35.37	31.99	30.55
	CV	0.27	0.29	0.27	0.24	0.28	0.27	0.28	0.3	0.27	0.25	0.24	0.32
BD	R^2	0.56	0.56	0.51	0.51	0.5	0.56	0.60	0.77	0.46	0.39	0.41	0.71
	rmse	35.76	33.24	37.42	41.58	37.12	33.51	34.12	23.78	36.39	40.3	45.01	24.06
	CV	0.29	0.31	0.29	0.3	0.26	0.31	0.27	0.27	0.26	0.26	0.29	0.22
CZ	R^2	0.56	0.57	0.51	0.47	0.45	0.5	0.64	0.54	0.59	0.43	0.71	0.59
	rmse	31.88	29.95	33.24	32.59	34.89	31.75	31.41	28.11	32.54	42.94	28.73	26.92
	CV	0.25	0.27	0.24	0.23	0.24	0.29	0.25	0.26	0.24	0.31	0.22	0.24
SJZ	R^2	0.53	0.4	0.46	0.42	0.46	0.61	0.46	0.57	0.42	0.45	0.33	0.52
	rmse	35.98	35.38	37.68	39.16	39.28	30.07	42.05	34.2	44.21	47.1	46.36	40.63
	CV	0.31	0.37	0.3	0.29	0.29	0.31	0.36	0.43	0.35	0.31	0.34	0.39
TY	R^2	0.52	0.41	0.45	0.5	0.35	0.54	0.56	0.47	0.31	0.64	0.46	0.64
	rmse	32.78	26.44	33.97	38.08	40.18	29.86	34.86	25.38	36.7	40.42	42.06	31.22
	CV	0.37	0.38	0.38	0.36	0.35	0.41	0.41	0.38	0.41	0.42	0.39	0.46
XT	R^2	0.54	0.5	0.45	0.37	0.4	0.63	0.55	0.42	0.47	0.67	0.41	0.85
	rmse	35.78	32.06	35.57	45.71	42.72	26.66	40.41	44.56	36.45	40.7	49.68	26.33
	CV	0.32	0.35	0.31	0.34	0.3	0.29	0.33	0.39	0.29	0.28	0.37	0.24
HD	R^2	0.47	0.42	0.39	0.25	0.37	0.59	0.46	0.34	0.23	0.33	0.5	0.48
	rmse	34.88	33.56	32.14	44.1	40.15	29.32	39.17	30.36	46.31	41.13	43.42	32.6
	CV	0.3	0.34	0.26	0.32	0.31	0.31	0.34	0.34	0.35	0.34	0.31	0.32
ZZ	R^2	0.29	0.31	0.12	0.15	0.19	0.45	0.27	0.19	0.19	0.27	0.2	0.43
	rmse	46.39	39.04	49.17	57.84	55.37	33.55	51.17	42.61	50.83	56.1	66.58	39.52
	CV	0.47	0.45	0.53	0.5	0.43	0.41	0.5	0.43	0.46	0.53	0.57	0.52

Figures

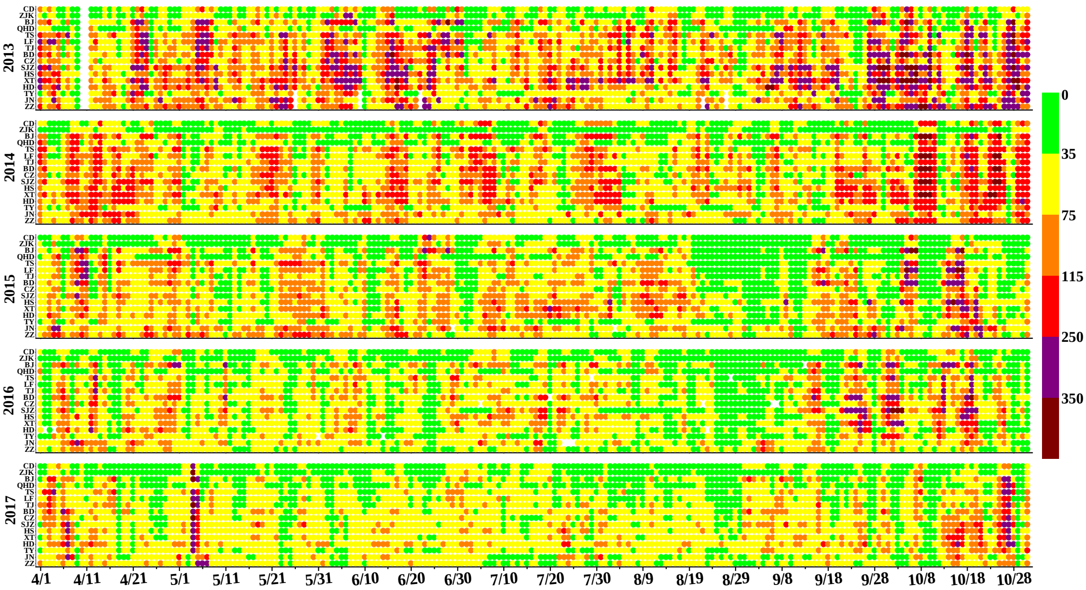

Fig. S1. Time series of daily averaged $PM_{2.5}$ concentrations in 14 cities (north to south) during April to October from 2013 to 2017. Six ranks are separated, representing different air-quality levels, including excellent (green spots), good (yellow), lightly polluted (orange), moderately polluted (red), heavily polluted days (purple) and severe polluted (maroon) with cut off concentrations as 35, 75, 115, 150 and 250 μg m^{-3}.

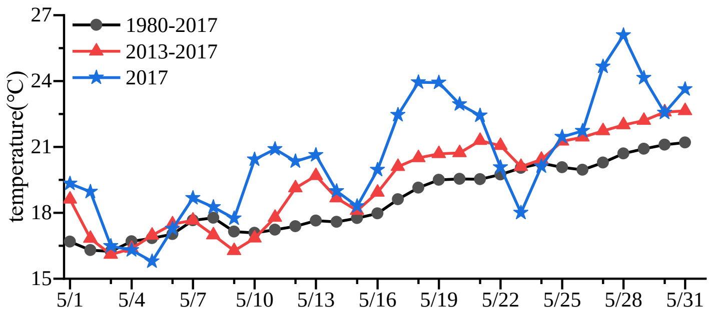

Fig. S2. Time series of the daily average temperature from 1980-2017, 2013-2017 and 2017.

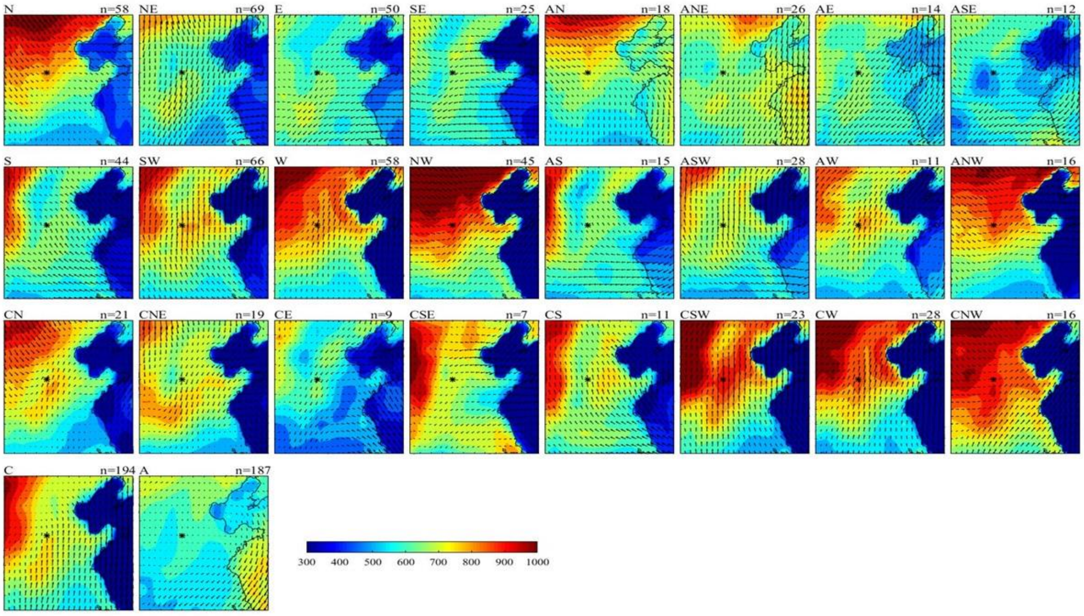

Fig. S3. Wind field and boundary layer height (based on ERA-interim data) and occurrence days under different weather conditions. The colour shading corresponds to the mean boundary layer height. The black '*' indicates the center of North China.

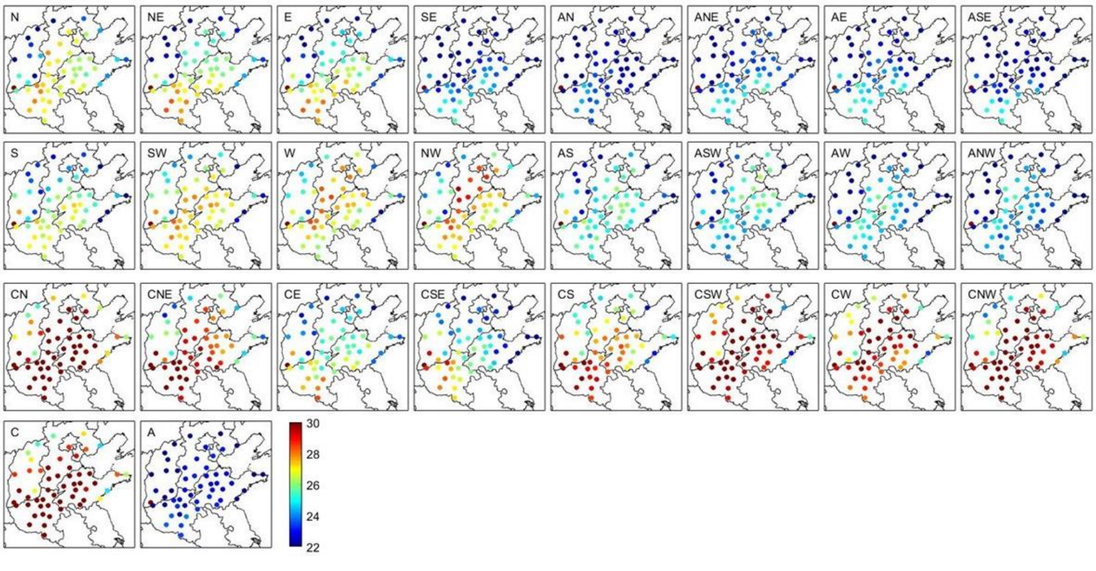

Fig. S4. Spatial distributions of average temperature for the 26 weather types. The first, second, and third rows correspond to the N-E-S direction, S-W-N direction, and LP, respectively; the fourth row from left to right is C and A, respectively.

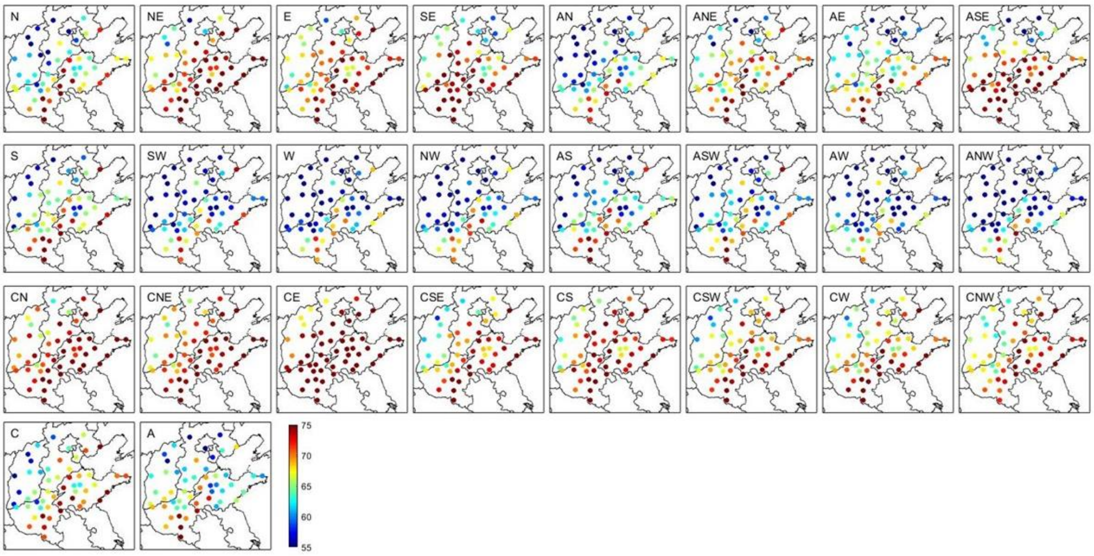

Fig. S5. Same as Fig. S4 but for RH (%).

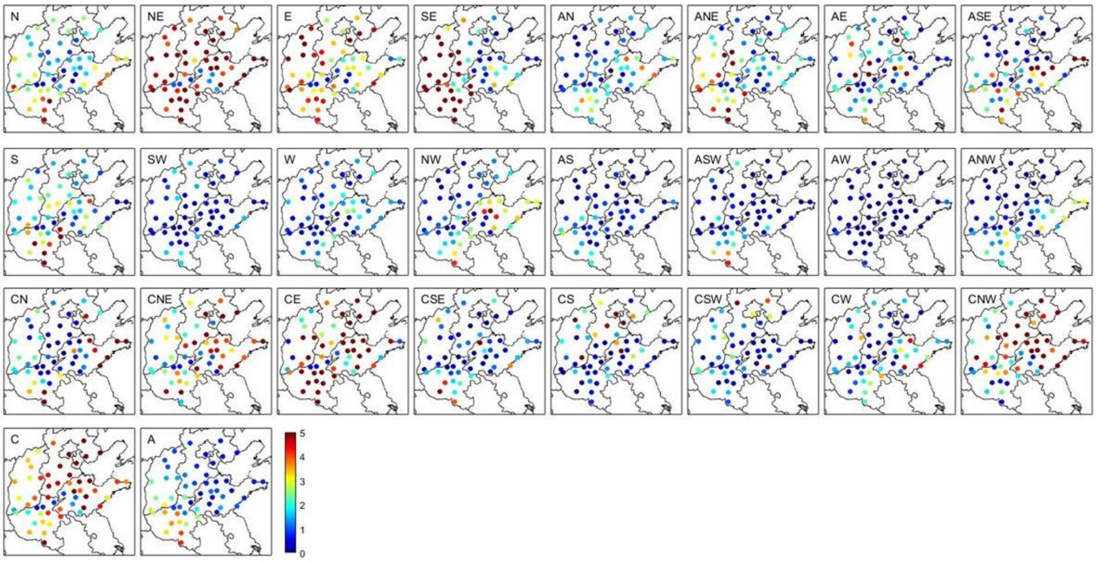

Fig. S6. Same as Fig. S4 but for rain (mm).

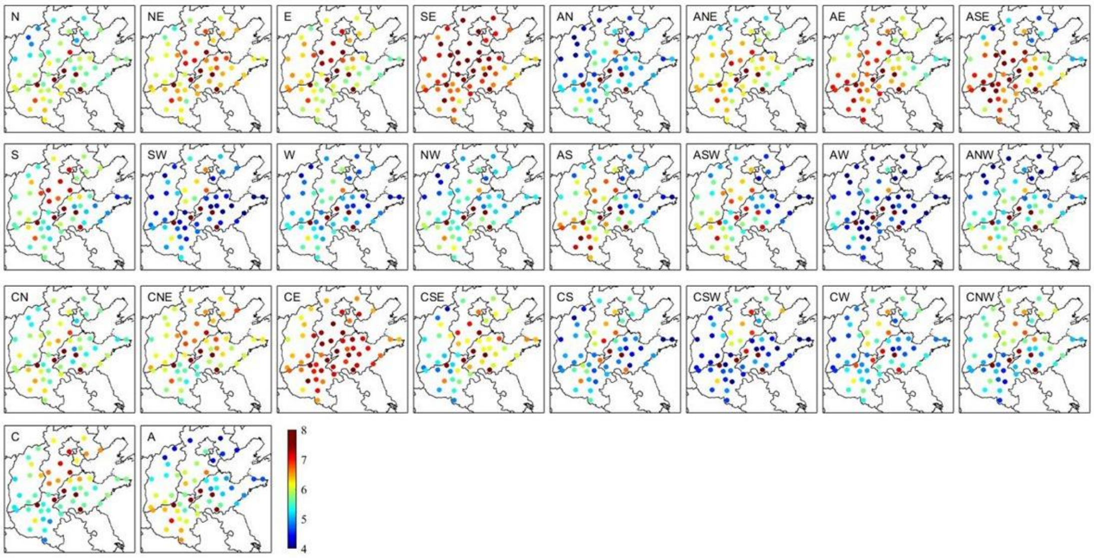

Fig. S7. Same as Fig. S4 but for TCC.

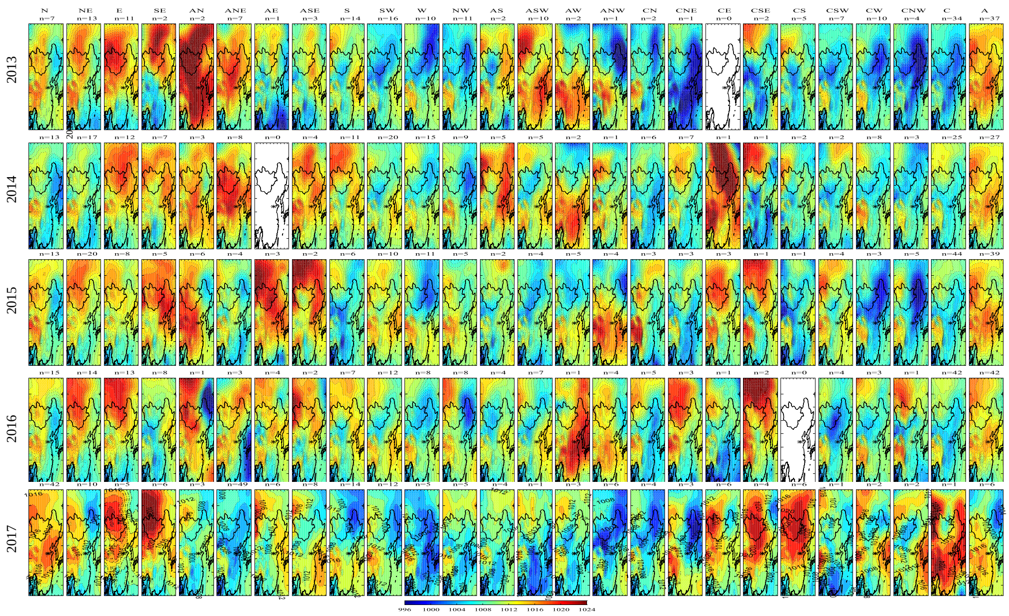

Fig. S8. Pressure field characteristics and occurrence days (n) of each weather type in 2013-2017.

Reference

Eder, B. K., Davis, J. M., and Bloomfield, P.: An Automated Classification Scheme Designed to Better Elucidate the Dependence of Ozone on Meteorology, J.appl.meteor, 33, 1182-1199, 1994.