Supporting information

1 Regional division

The analysis in this study was conducted for seven administrative regions: North China (i.e., Beijing, Tianjin, Hebei, Shanxi, and Inner Mongolia), North-east China (i.e., Liaoning, Jilin, and Heilongjiang), East China (i.e., Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, and Shandong), Central China (i.e., Henan, Hubei, and Hunan), South China (i.e., Guangdong, Guangxi, and Hainan), South-west China (i.e., Chongqing, Sichuan, Guizhou, Yunnan, and Xizang), and North-west China (i.e., Shaanxi, Gansu, Qinghai, Ningxia, and Xinjiang).

2 Validation of meteorological simulation

Meteorological parameters simulated by WRFv3.8 were compared with observation data downloaded from the National Climatic Data Center (NCDC). The variables included the temperature at 2 m, wind speed at 10 m, and humidity at 2 m. The statistical indices used include the mean observation (Mean OBS), mean simulation (Mean SIM), mean bias (MB), gross error (GE), root mean square error (RMSE), and index of agreement (IOA). The model shows good agreement with observations and captures the trend of meteorological parameters between the two years. The average temperature of observations in North, North-east, East, South, North-west, and South-west China showed an increase by 1.24℃, 0.81℃, 0.41℃, 0.65℃, 0.26℃, and 0.04℃, while the temperature in Central China showed a decrease by 0.29℃. The simulation showed temperature increases by 0.98℃, 0.90℃, 0.32℃, and 0.44℃ in North, North-east, East, and South China, and temperature decreases by 0.24℃, 0.13℃, and 0.09℃ in Central, North-west, and South-west China. The increments were slightly underestimated; the inconsistent results for North-west and South-west China were small and within the systematic bias.

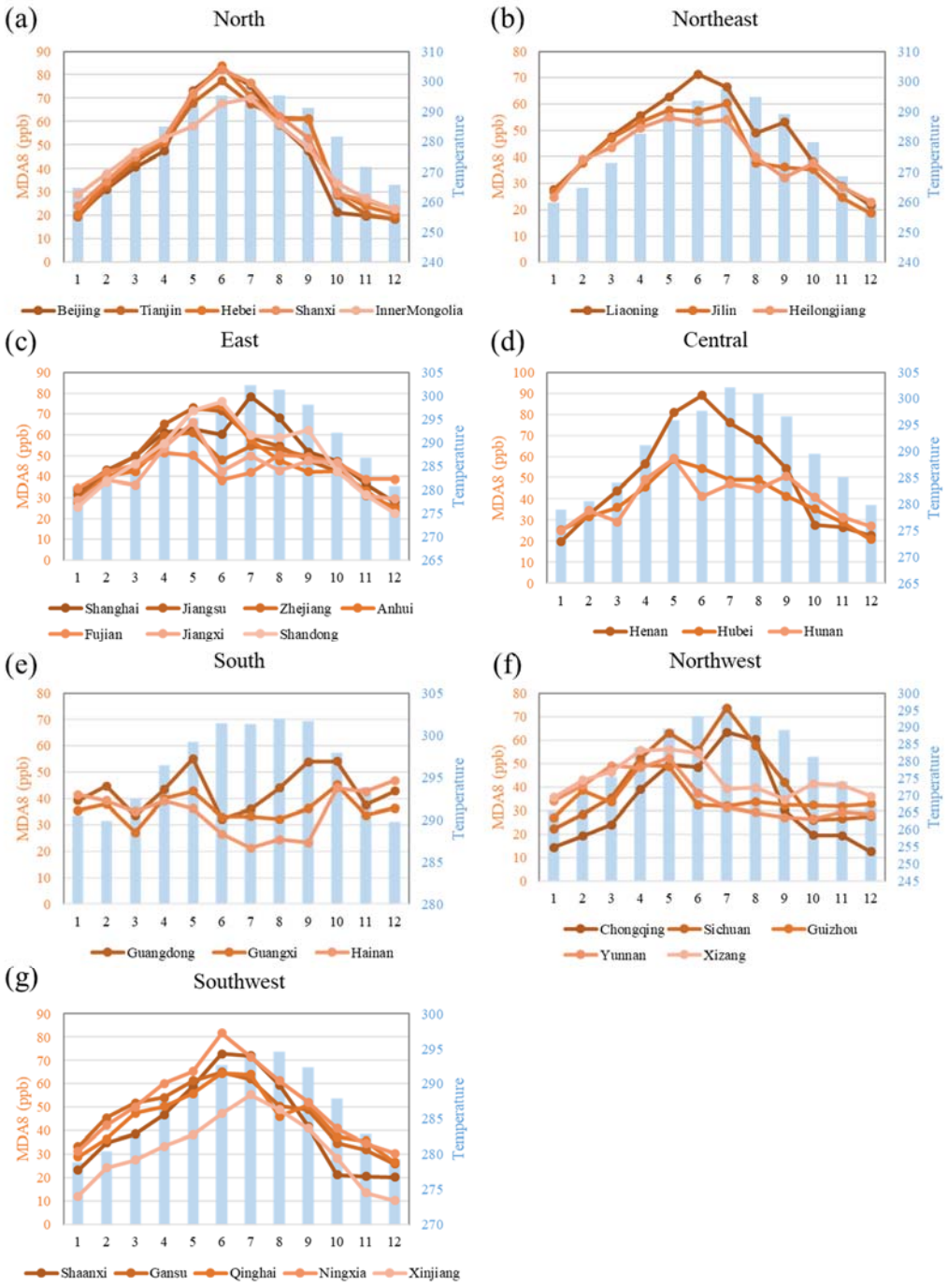

Fig. S1 Monthly variation of observed AvgMDA8 O_3 (ppb) and temperature (K) of each region in 2017: (a) North China; (b) Northeast China; (c) East China; (d) Central China; (e) South China; (f) Northwest China; (g) Southwest China

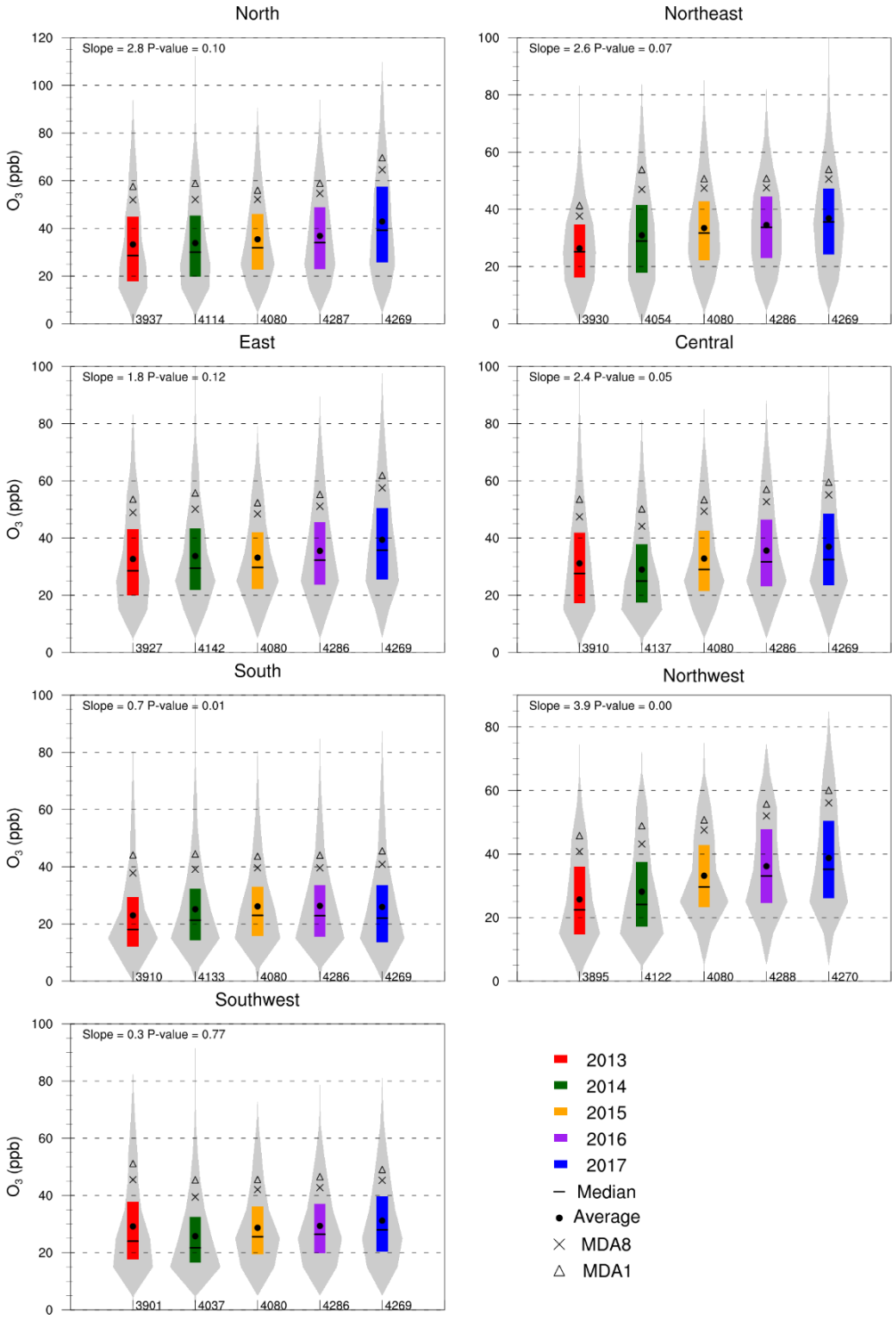

Fig. S2 Inter-annual changes of O_3 concentration in the warm season during 2013–2017

(Grey shading represents the concentration distribution of O_3 observation over all valid hourly data, values on the *x*-axis represent the numbers of valid hourly data, color boxes show the range of the 25th and 75th percentile values, the solid lines show the median value, the filled dots show the average value, the cross symbols show the AvgMDA8 O_3, and the hollow triangles show the AvgMDA1 O_3)

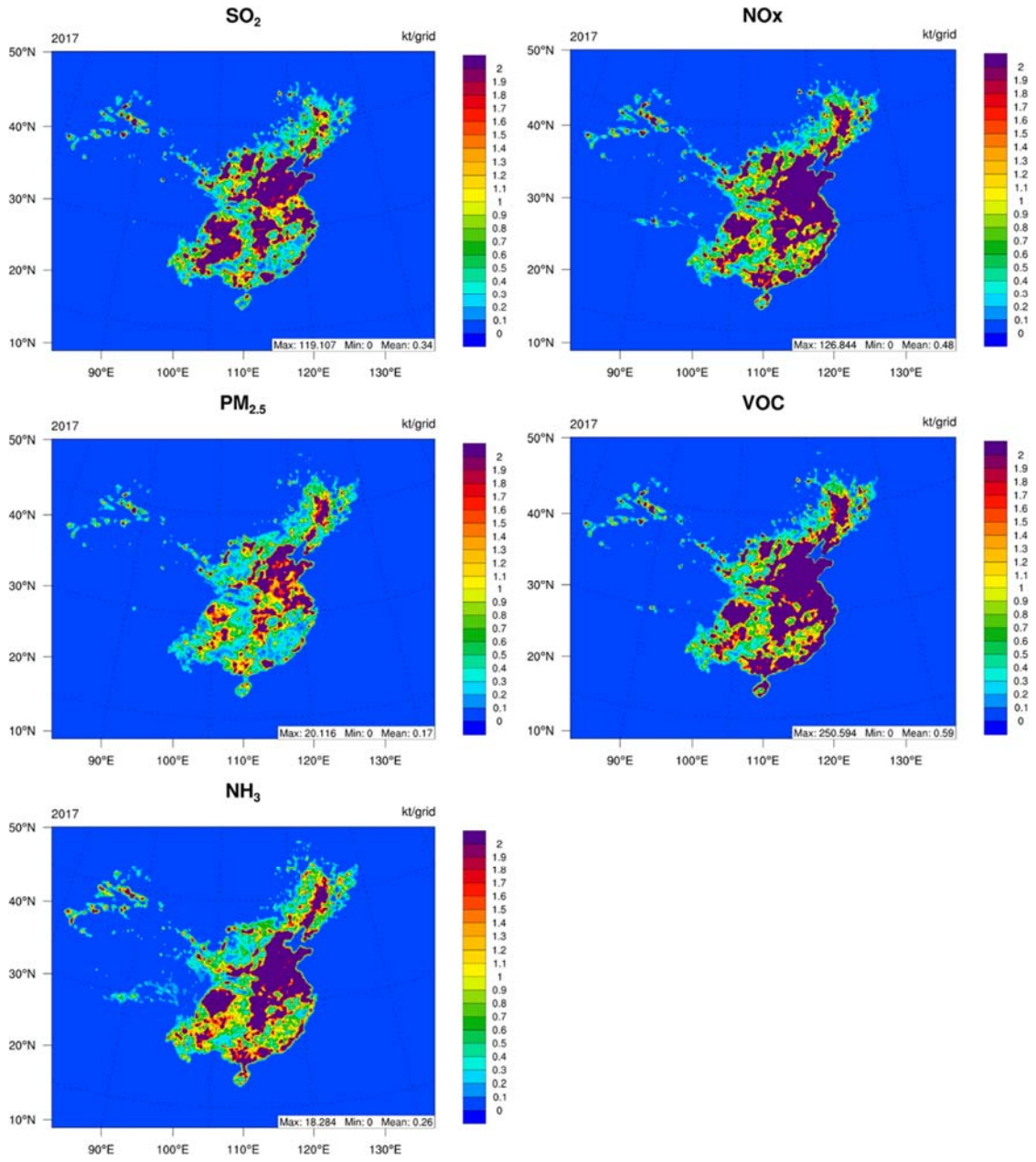

Fig. S3 Spatial distribution of the annual anthropogenic emissions in 2017

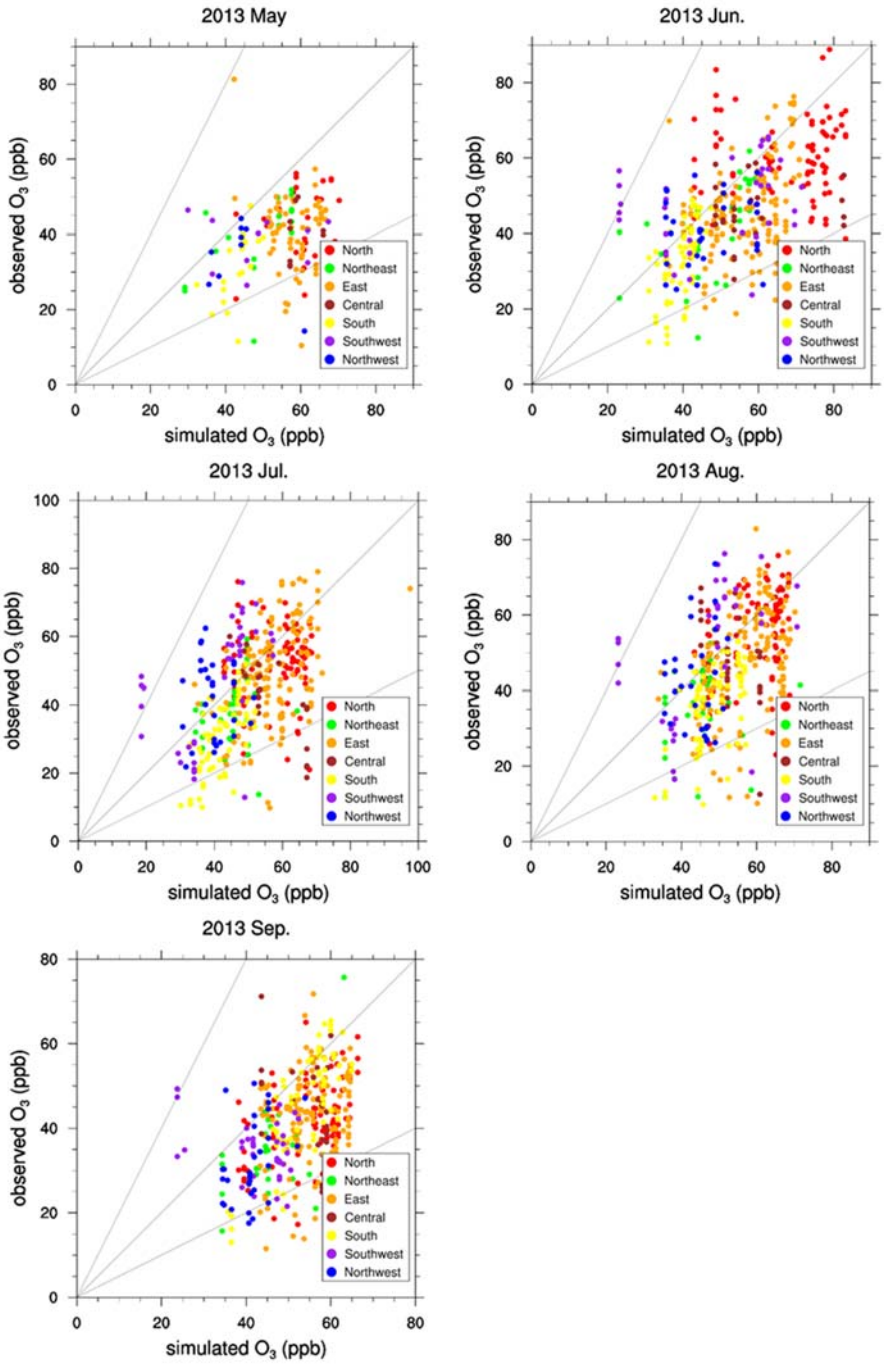

Fig. S4 The CMAQ performance in simulating AvgMDA8 O_3 in 2013. The 1:1, 2:1, and 1:2 lines are shown for reference

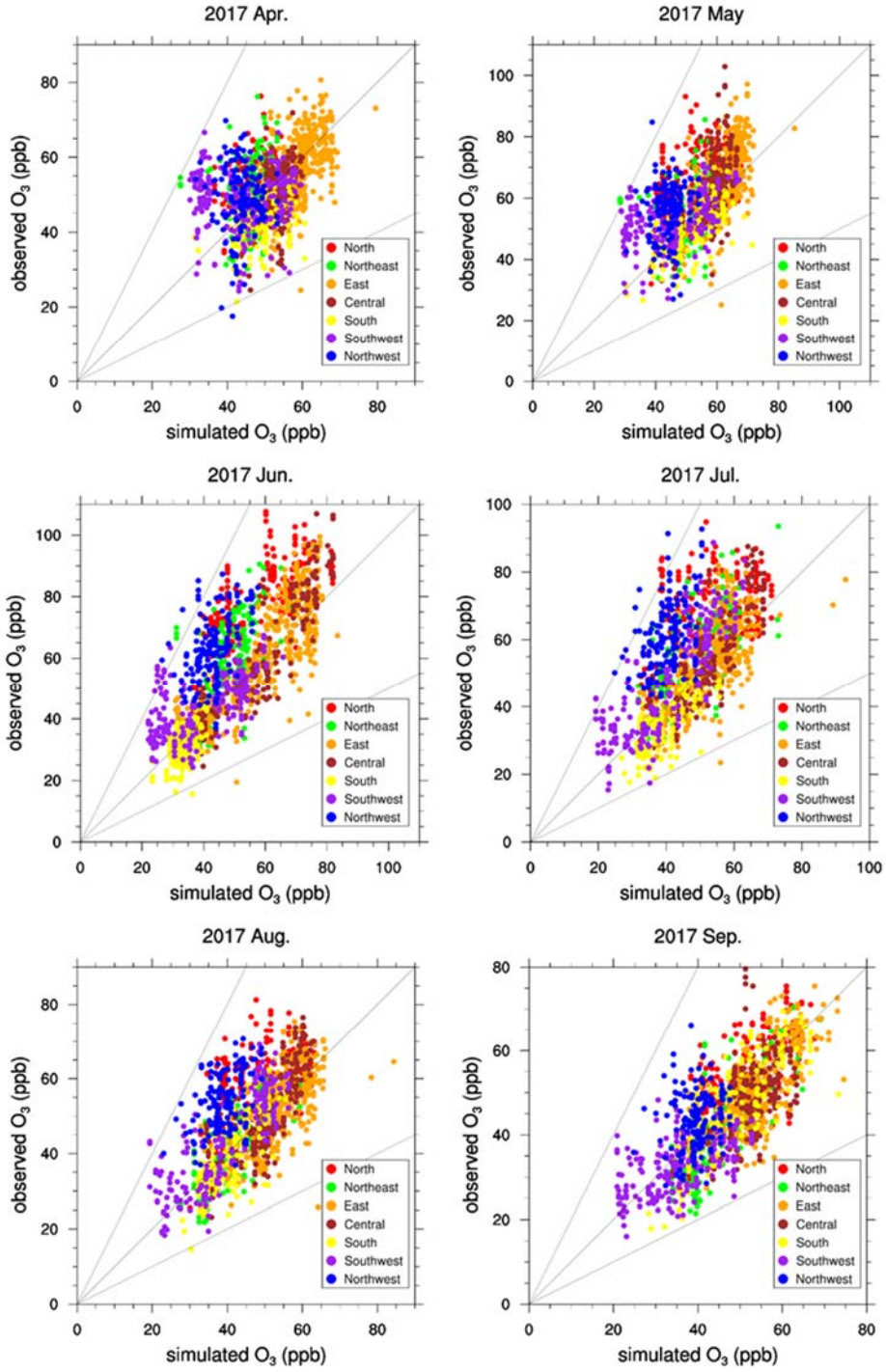

Fig. S5 The CMAQ performance in simulating AvgMDA8 O_3 in 2017. The 1:1, 2:1, and 1:2 lines are shown for reference

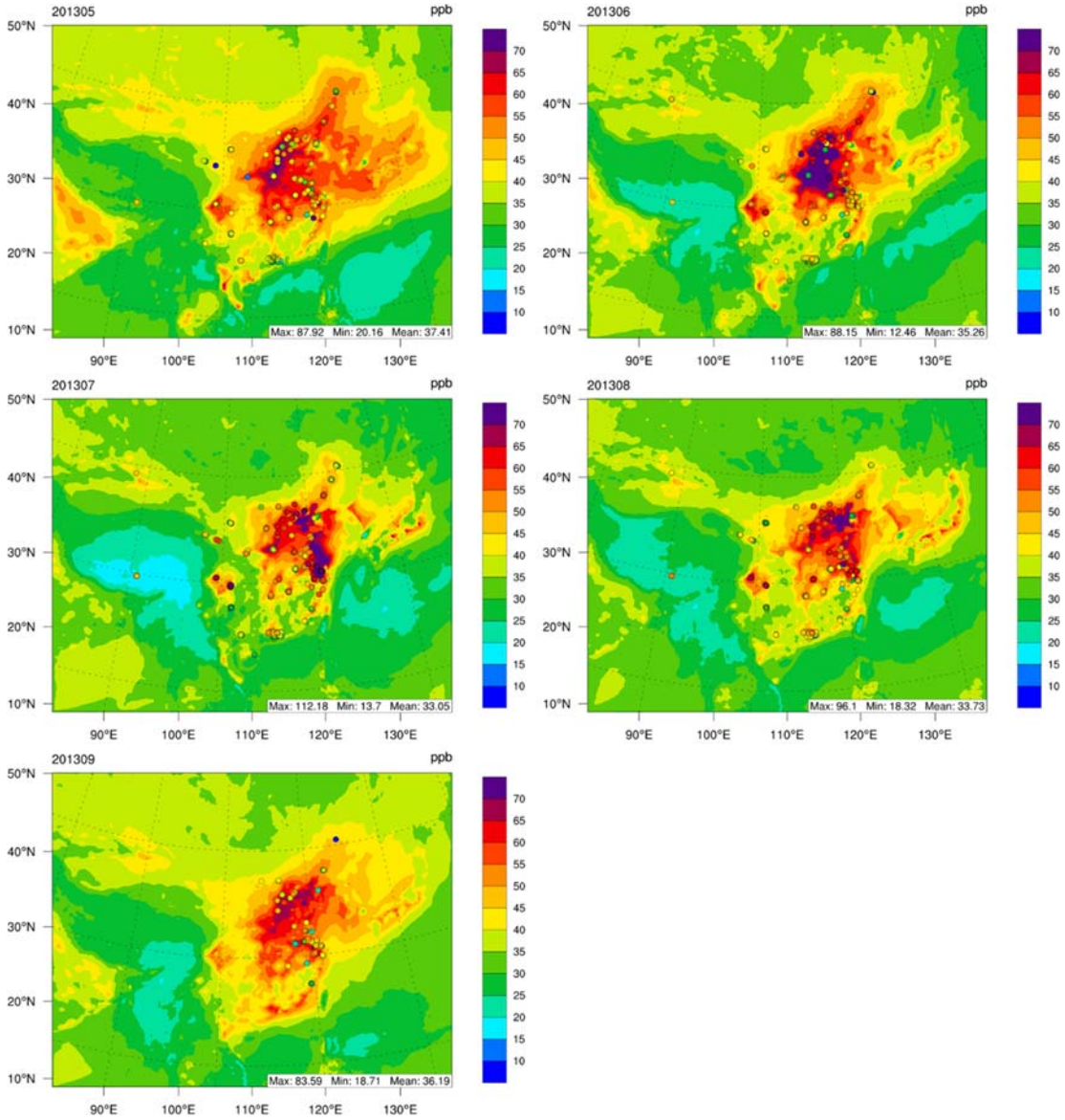

Fig. S6 Spatial distribution of the simulated AvgMDA8 O_3 in 2013 (the background colors represent the simulation and the filled dots represent the observations)

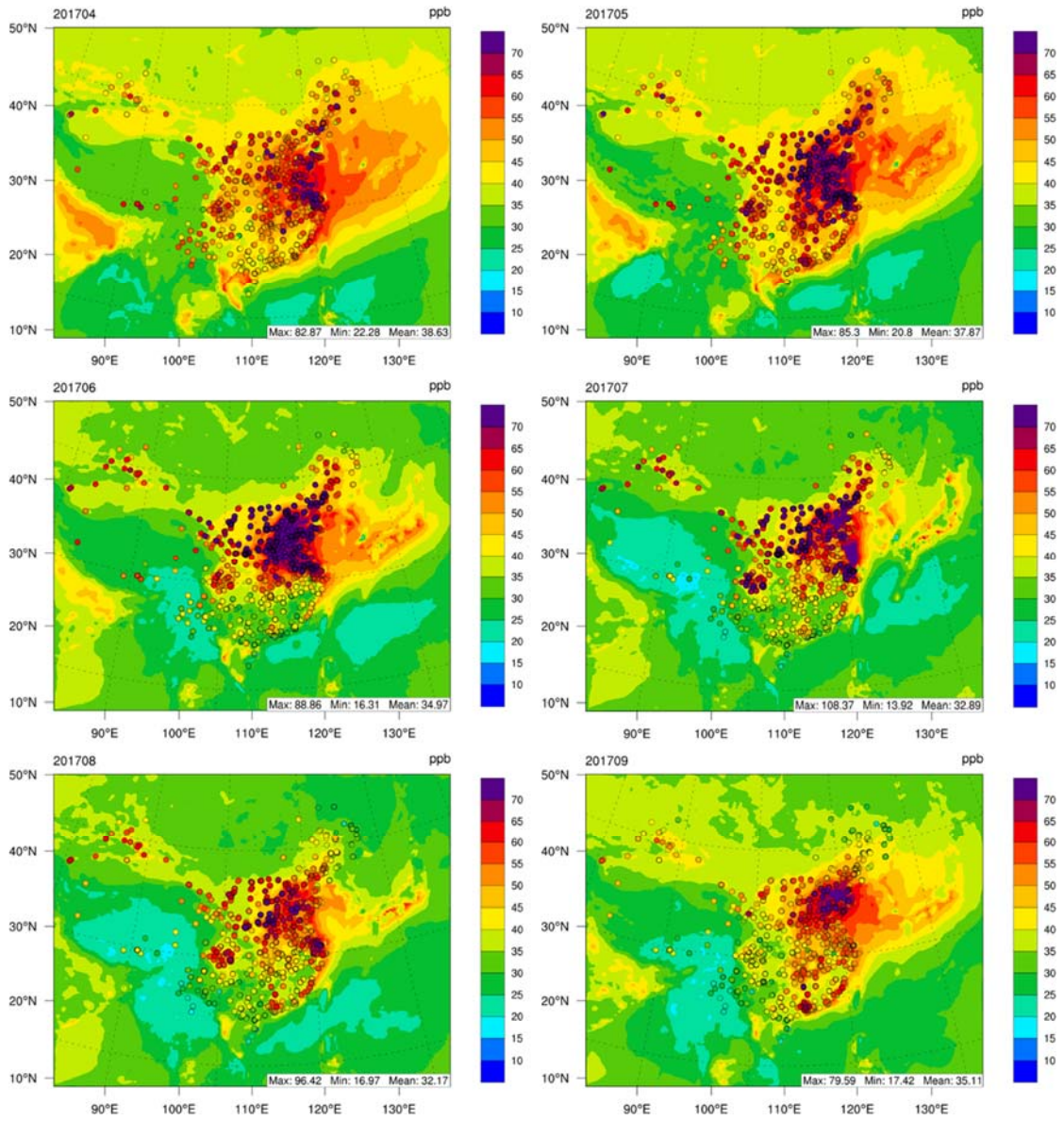

Fig. S7 Spatial distribution of the simulated AvgMDA8 O_3 in 2017 (the background colors represent the simulation and filled dots represent the observations)

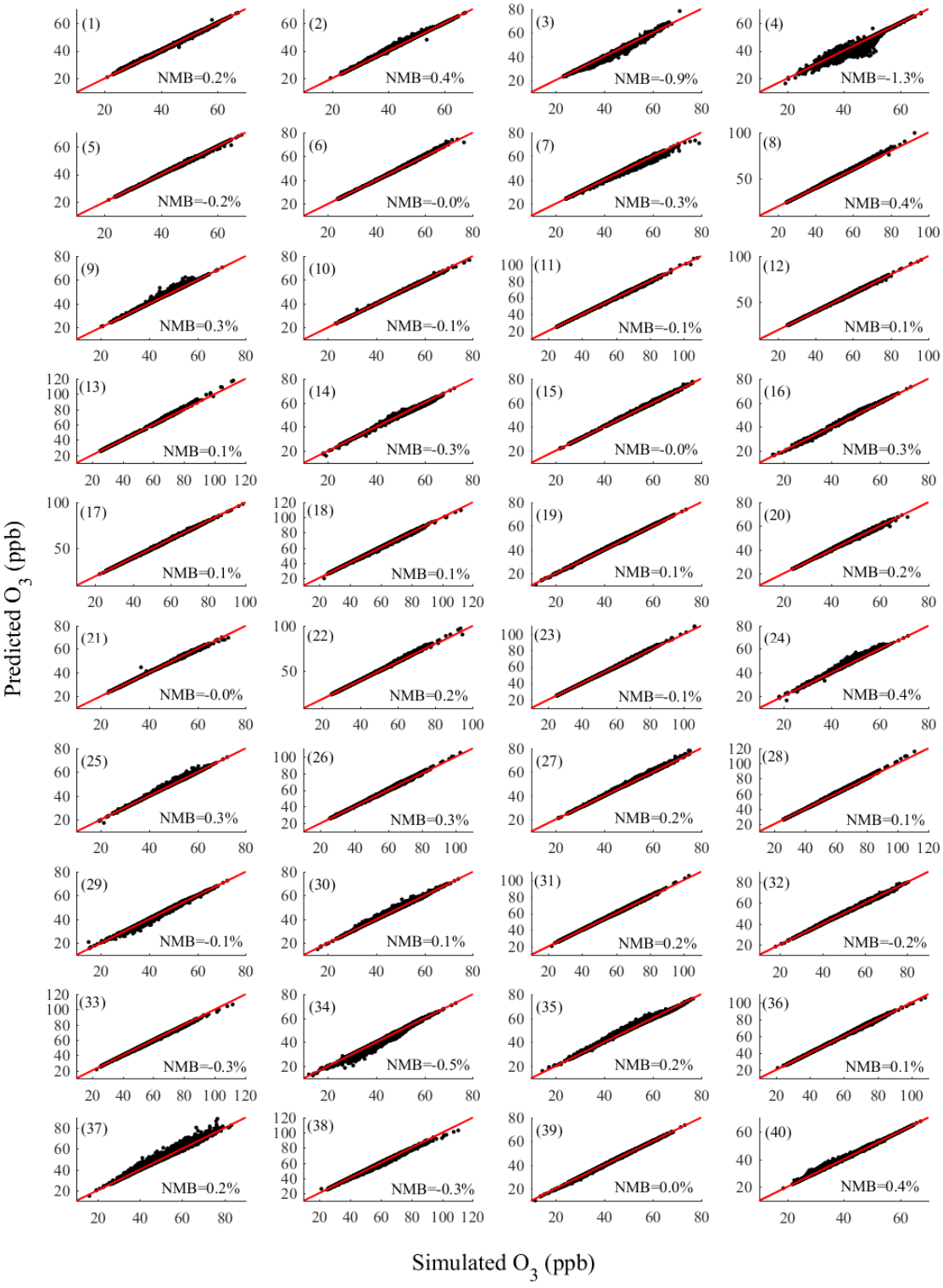

Fig. S8 Leave-one-out comparison of O_3 between pf-RSM prediction and CMAQ simulations in April 2017 (The red line is the one-to-one line that would indicate perfect agreement)

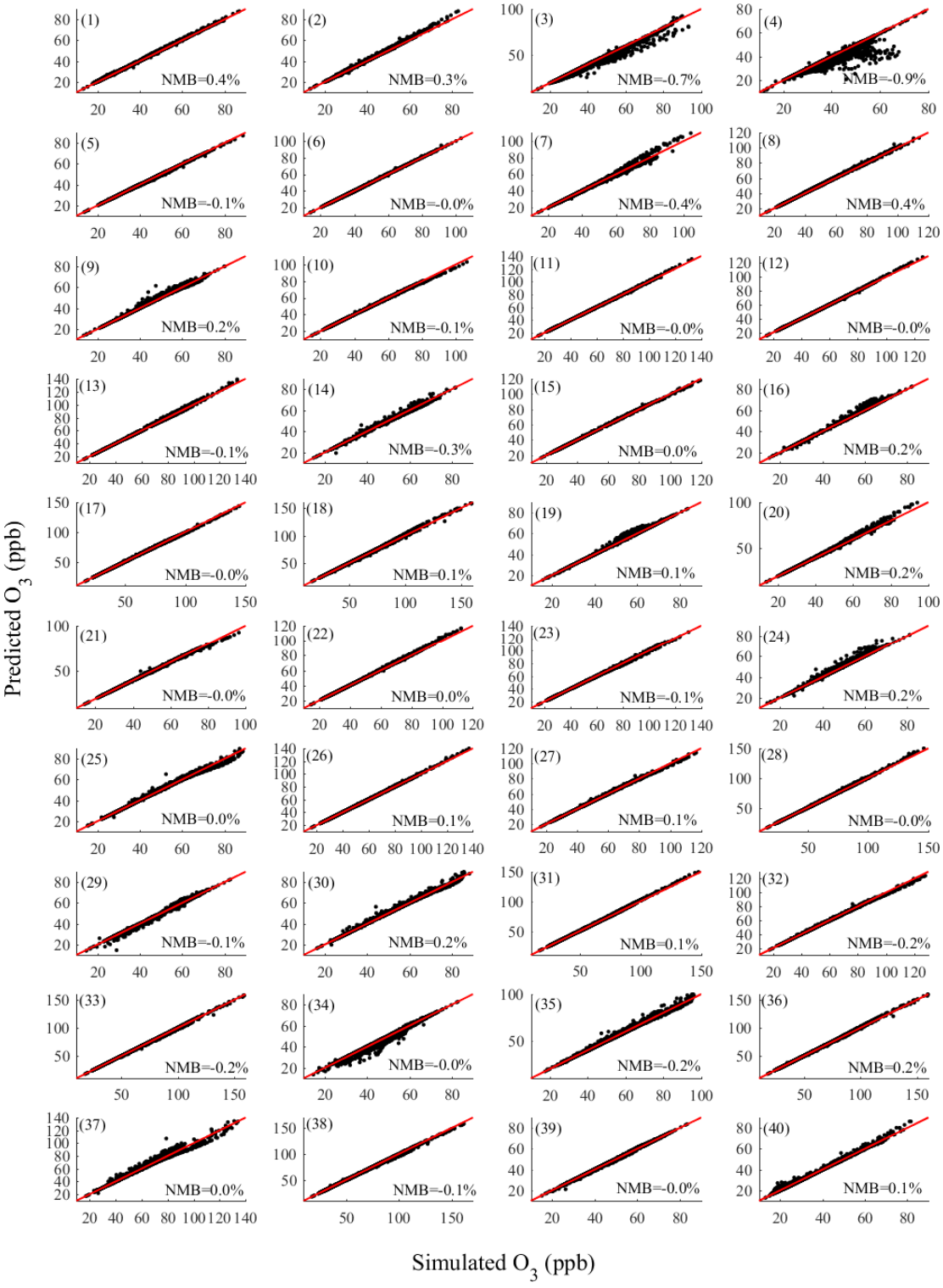

Fig. S9 Leave-one-out comparison of O_3 between pf-RSM prediction and CMAQ simulations in July 2017 (The red line is the one-to-one line that would indicate perfect agreement)

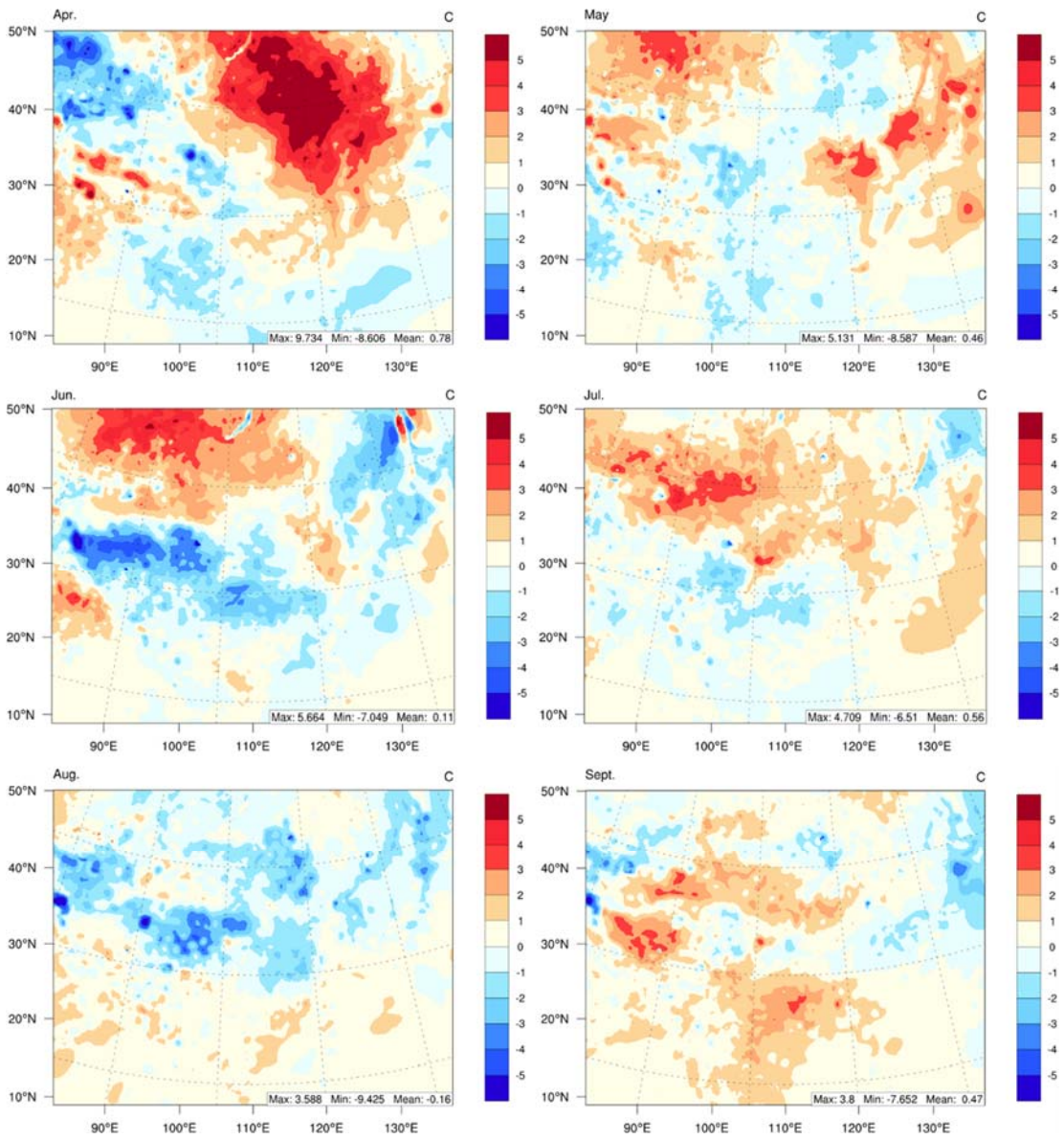

Fig. S10 The difference in temperature (℃) between 2013 and 2017 (= 2017–2013) during April to September

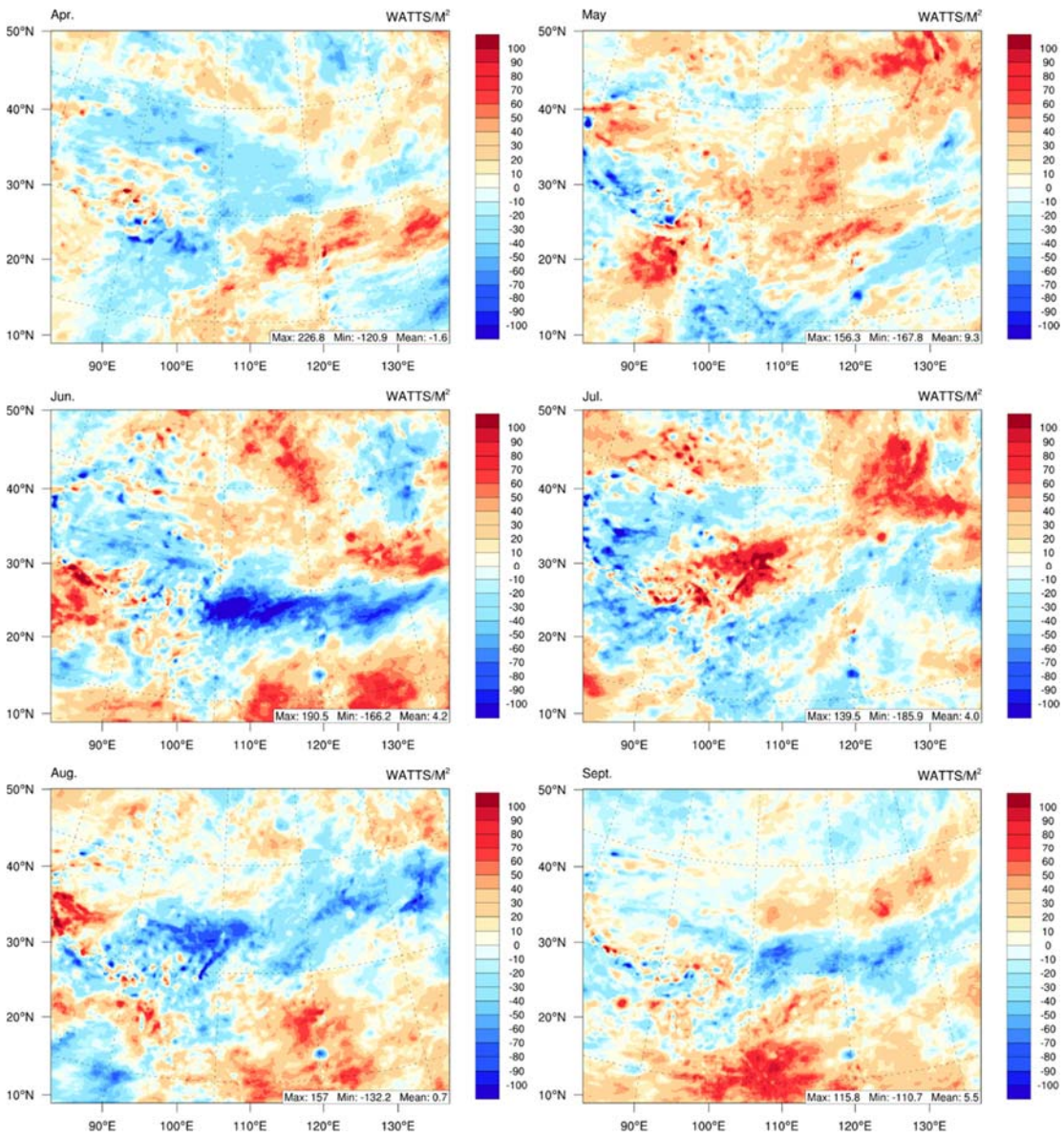

Fig. S11 The difference in RGRND (w/m^2) between 2013 and 2017 (= 2017–2013) during April to September

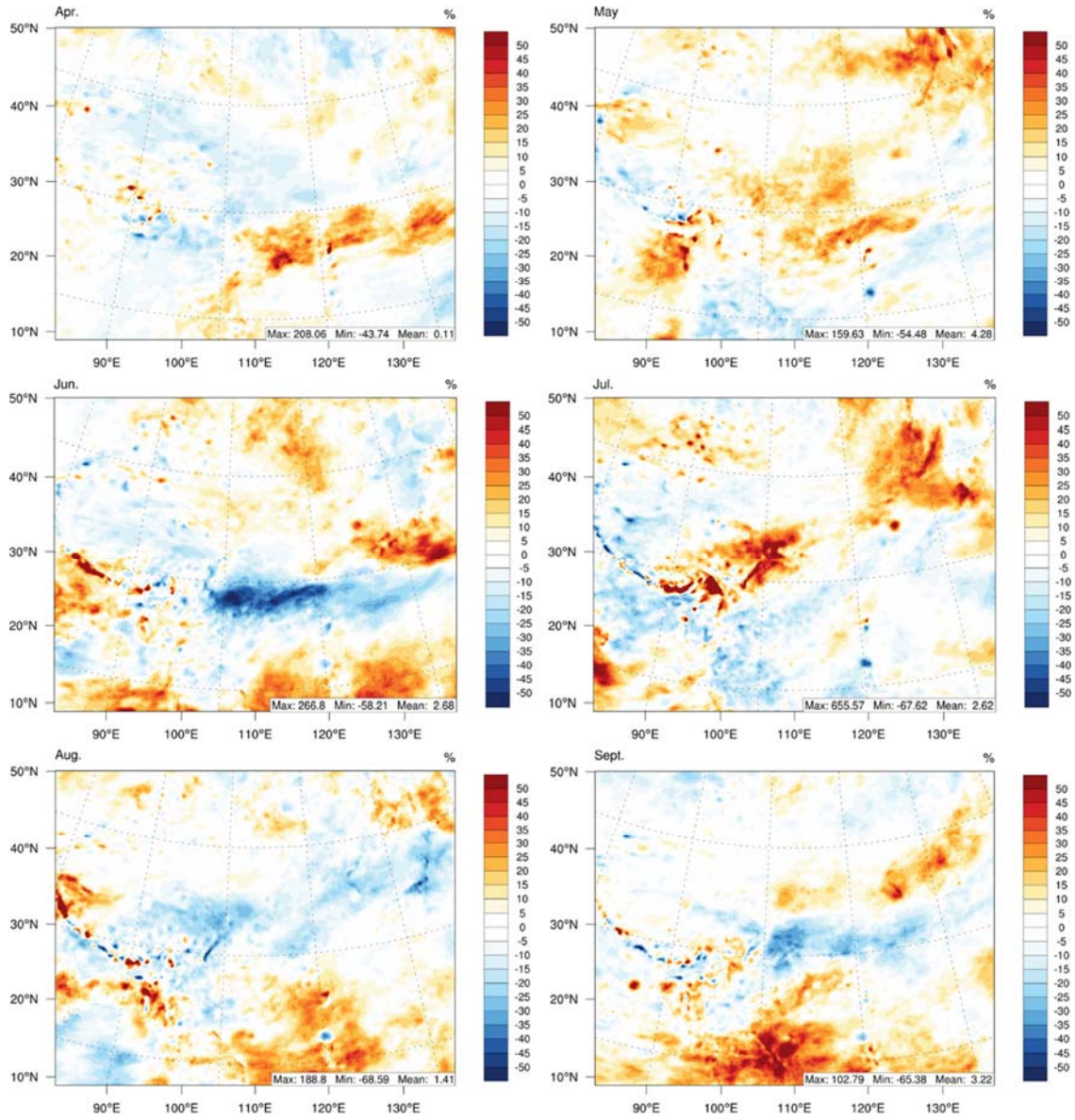

Fig. S12 The relative change (%) in RGRND between 2013 and 2017 (= 2017–2013) during April to September

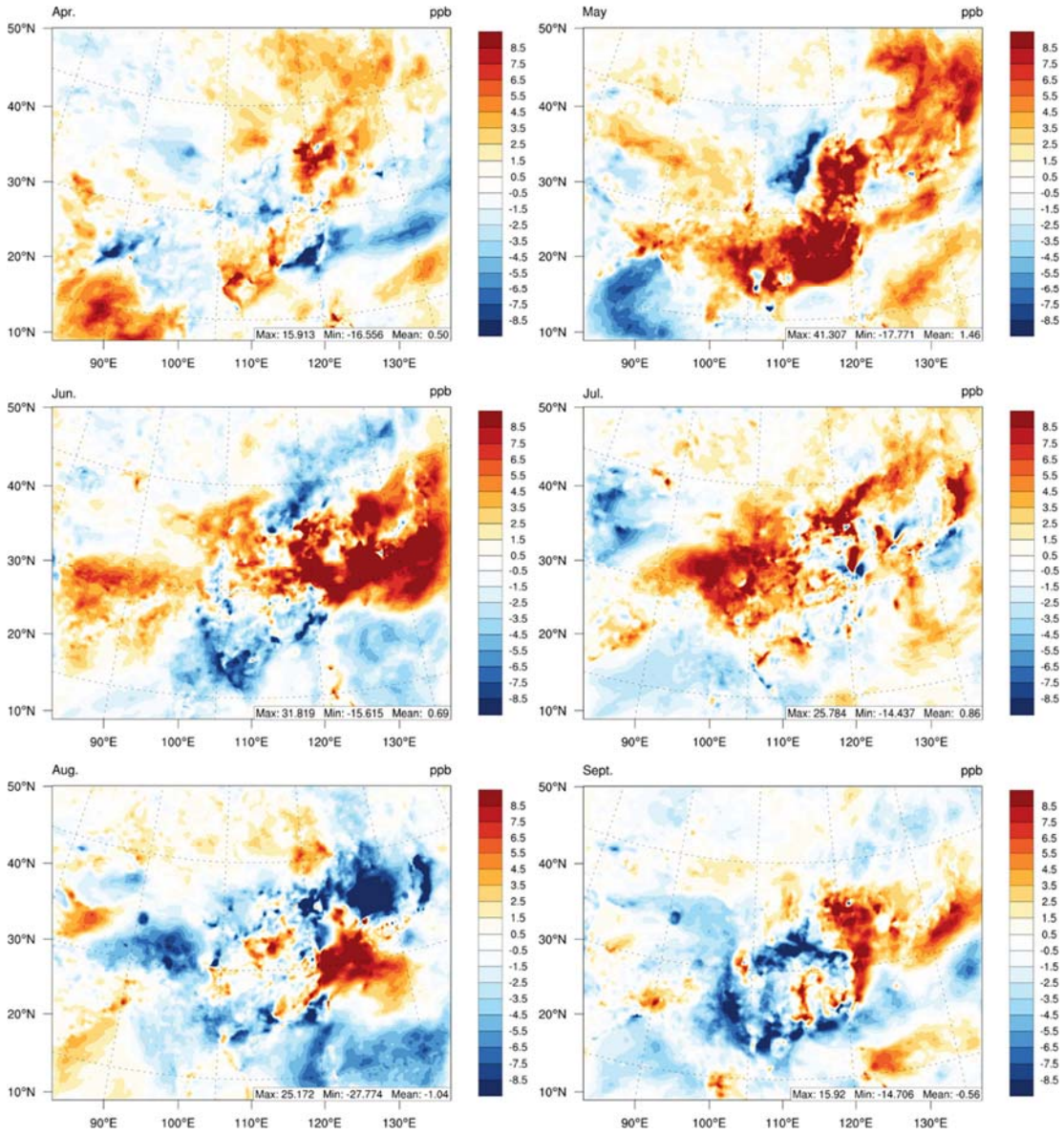

Fig. S13 The change of AvgMDA8 O_3 due to ΔMet-drive in April–September

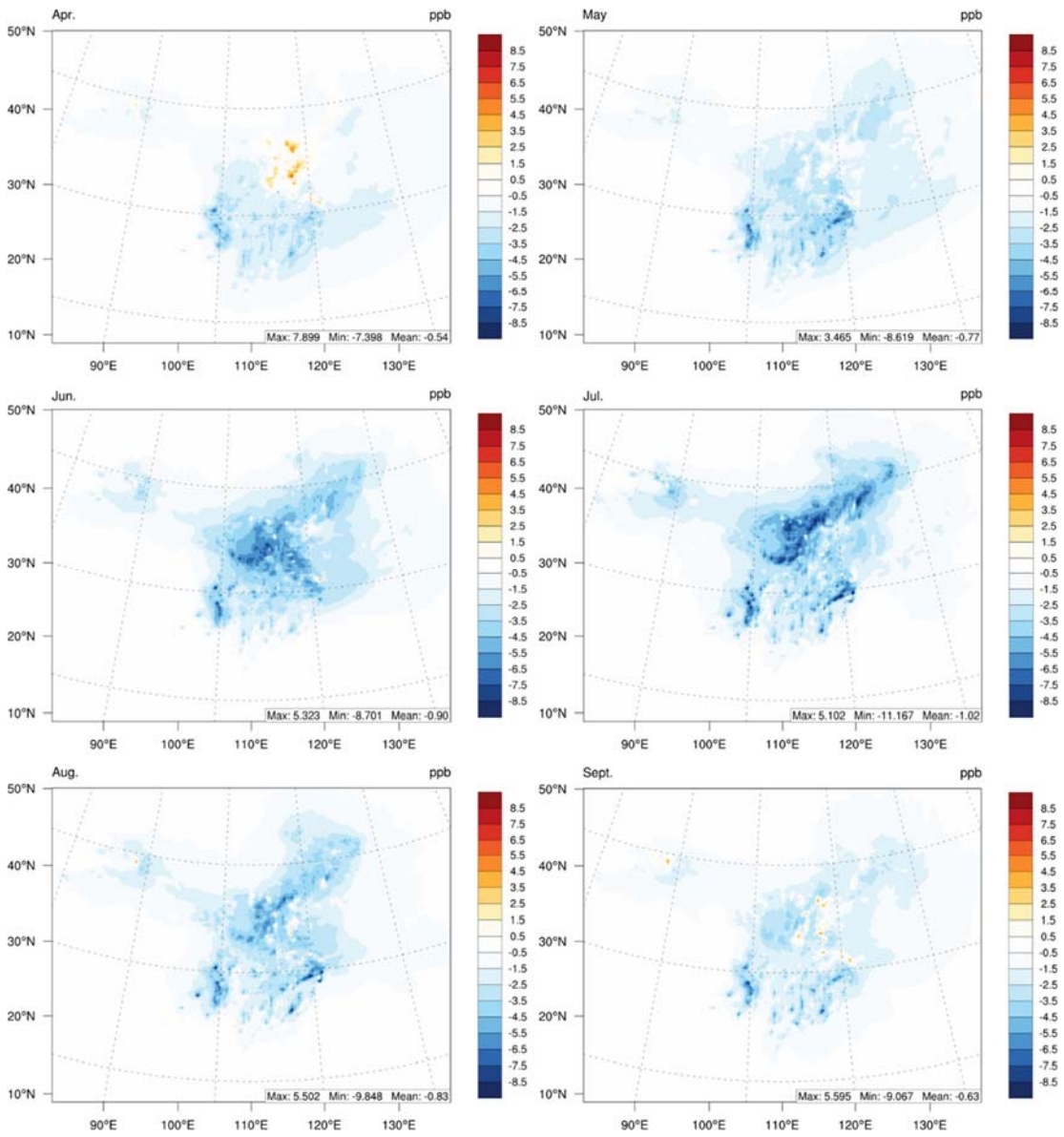

Fig. S14 The change of AvgMDA8 O_3 due to ΔEmis-drive in April–September

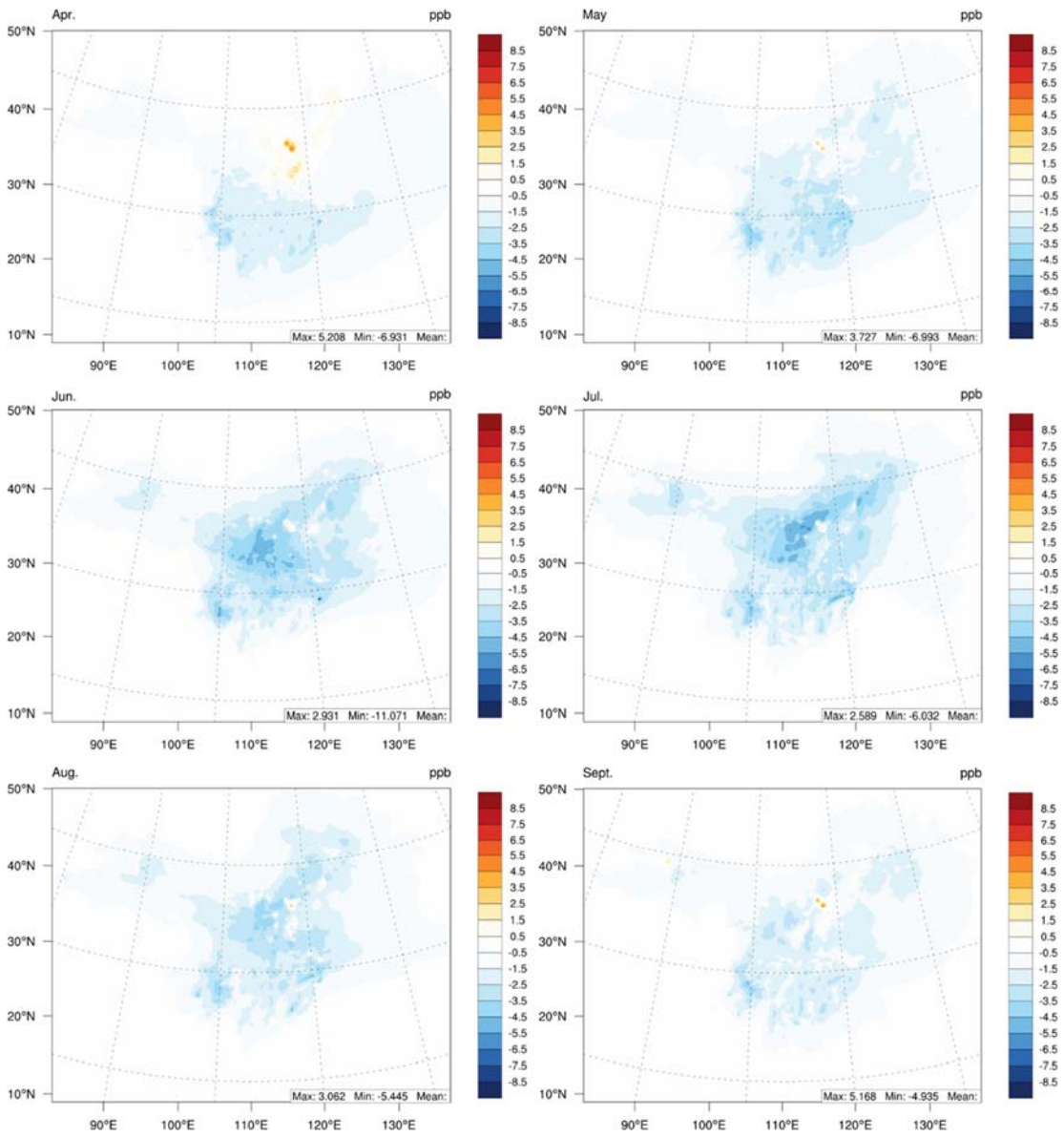

Fig. S15 The change of average O_3 due to ΔEmis-drive in April–September

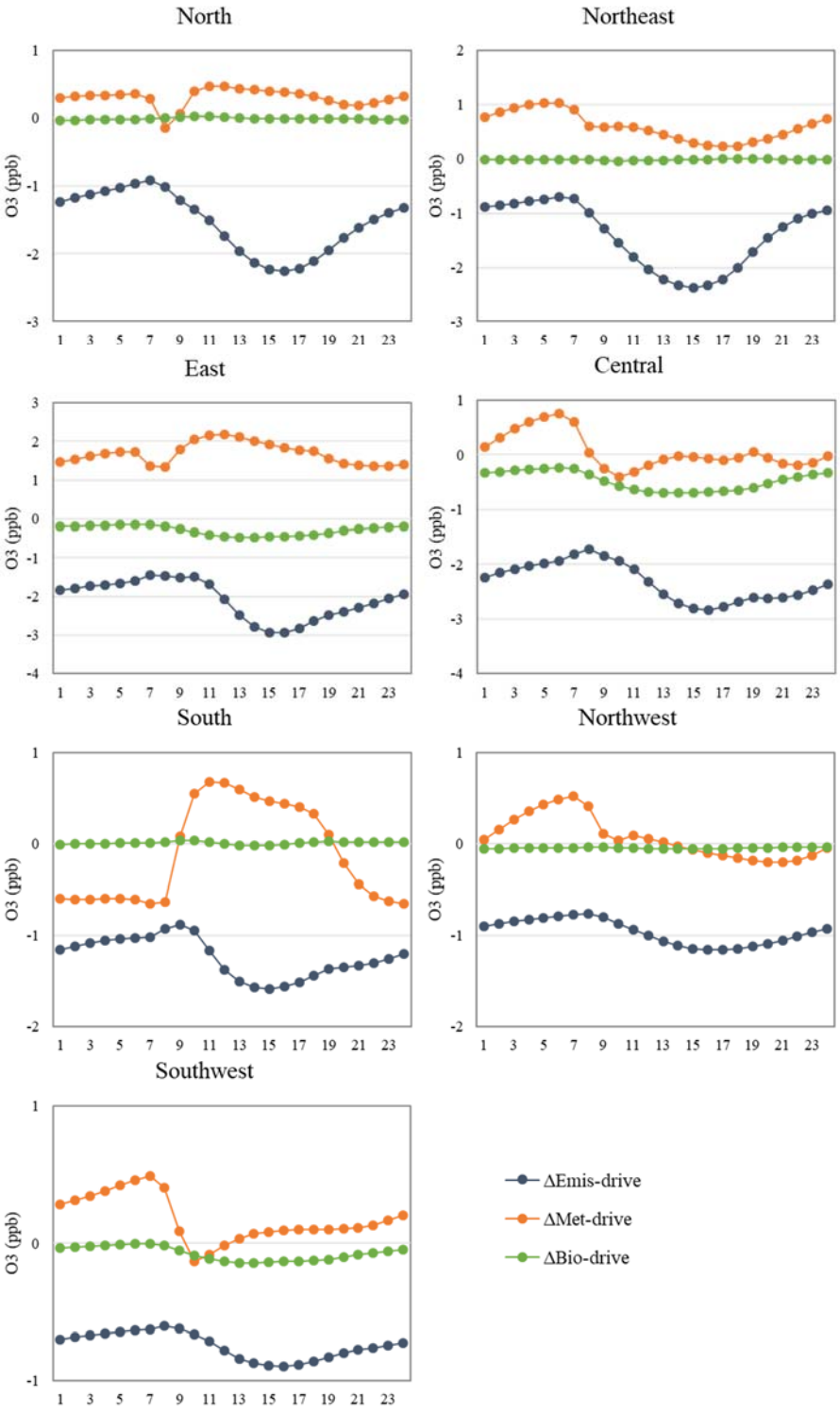

Fig. S16 The simulated diurnal variation of O_3 response (ppb) to the change in meteorology and emission in warm-seasons from 2013 to 2017

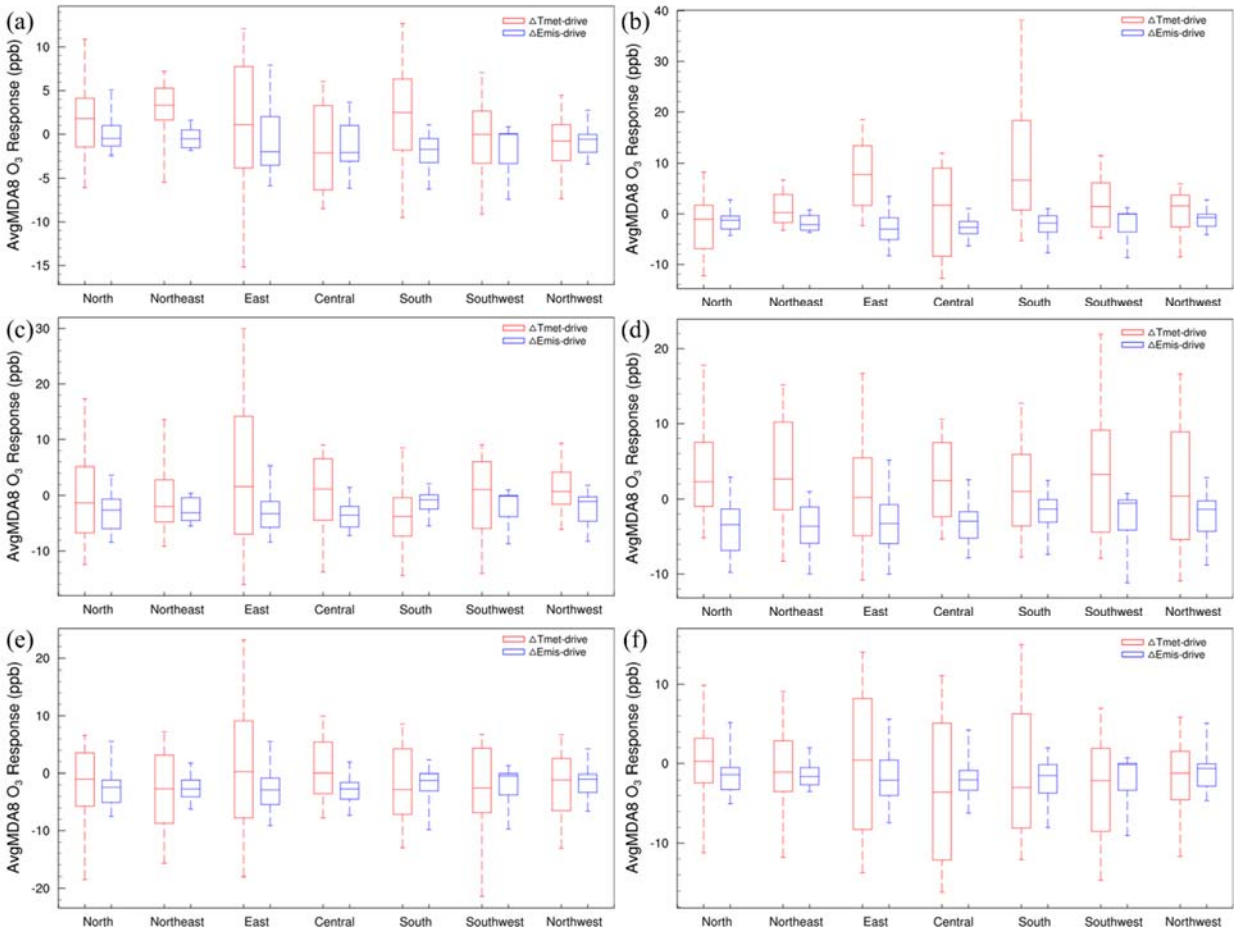

Fig. S17 The AvgMDA8 O_3 response to meteorology and emission in (a) April, (b) May, (c) June, (d) July, (e) August, and (f) September. Color boxes show the range of the 5th and 95th percentiles values and the median line shows the median value

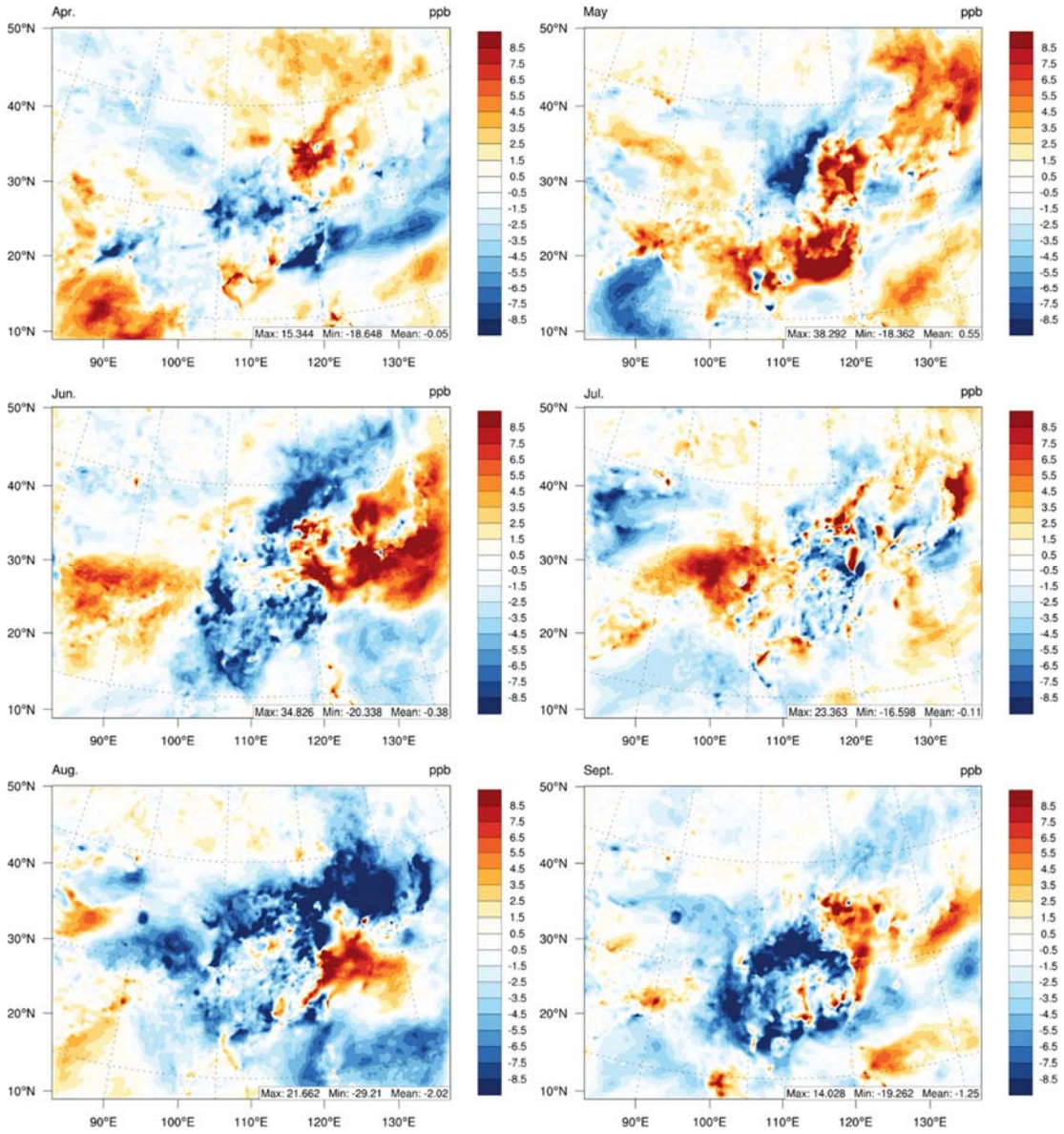

Fig. S18 The ΔTOT change of AvgMDA8 O_3 in April–September

Table S1 WRF performance at simulating meteorological variables in the warm season in 2013

Meteorological variable	Statistic	Unit	North	North-east	East	Central	South	North-west	South-west
Wind Speed	MeanOBS	(m/s)	2.99	2.91	3.06	2.34	2.65	2.67	2.12
	MeanPRD	(m/s)	3.10	3.06	2.86	2.39	2.61	3.08	2.54
	Bias	(m/s)	0.11	0.16	–0.20	0.04	–0.05	0.42	0.42
	GrossError	(m/s)	1.19	1.05	1.13	0.97	1.00	1.50	1.24
	RMSE	(m/s)	1.58	1.33	1.61	1.34	1.32	2.03	1.64
	SysRMSE	(m/s)	0.93	0.89	1.17	1.00	0.90	1.32	1.04
	UnsysRMSE	(m/s)	1.26	0.98	1.10	0.87	0.95	1.53	1.26
	IOA		0.78	0.78	0.78	0.69	0.78	0.67	0.66
Temperature	MeanOBS	(K)	291.60	290.35	297.25	297.71	299.72	290.68	292.00
	MeanPRD	(K)	291.15	289.25	296.56	296.73	299.33	290.67	290.06
	Bias	(K)	–0.45	–1.10	–0.69	–0.97	–0.39	–0.01	–1.95
	GrossError	(K)	1.63	1.82	1.73	1.81	1.30	2.17	2.76
	RMSE	(K)	2.06	2.29	2.31	2.34	1.64	2.83	3.73
	SysRMSE	(K)	0.57	1.22	0.91	1.08	0.62	0.43	1.97
	UnsysRMSE	(K)	1.97	1.91	2.10	2.05	1.50	2.79	3.16
	IOA		0.97	0.93	0.91	0.91	0.91	0.97	0.94
Humidity	MeanOBS	(g/kg)	8.01	9.67	15.03	14.18	18.49	6.92	11.85
	MeanPRD	(g/kg)	7.99	9.06	14.95	14.20	18.12	6.59	10.77
	Bias	(g/kg)	–0.02	–0.61	–0.08	0.02	–0.37	–0.33	–1.08
	GrossError	(g/kg)	1.28	1.19	1.59	1.58	1.57	1.57	2.49
	RMSE	(g/kg)	1.77	1.51	2.14	2.08	2.04	2.16	3.86
	SysRMSE	(g/kg)	0.67	0.85	1.04	1.13	1.19	0.66	2.80
	UnsysRMSE	(g/kg)	1.61	1.22	1.83	1.70	1.62	2.03	2.60
	IOA		0.87	0.77	0.81	0.74	0.67	0.85	0.79

Table S2 WRF performance at simulating meteorological variables in the warm season in 2017

Meteorological variable	Statistic	Unit	North	North-east	East	Central	South	North-west	South-west
Wind Speed	MeanOBS	(m/s)	3.00	3.00	2.81	2.38	2.46	2.68	2.07
	MeanPRD	(m/s)	3.02	3.12	2.64	2.25	2.40	3.06	2.48
	Bias	(m/s)	0.01	0.12	–0.18	–0.14	–0.06	0.38	0.41
	GrossError	(m/s)	1.21	1.06	1.08	0.96	0.99	1.47	1.21
	RMSE	(m/s)	1.61	1.36	1.53	1.34	1.32	1.96	1.59
	SysRMSE	(m/s)	0.99	0.87	1.10	1.03	0.90	1.26	0.99
	UnsysRMSE	(m/s)	1.25	1.03	1.07	0.84	0.95	1.49	1.24
	IOA		0.78	0.79	0.78	0.71	0.76	0.71	0.66
Temperature	MeanOBS	(K)	292.84	291.16	297.66	297.42	300.37	290.95	292.04
	MeanPRD	(K)	292.13	290.14	296.88	296.49	299.78	290.55	289.96
	Bias	(K)	–0.71	–1.02	–0.77	–0.93	–0.60	–0.40	–2.08
	GrossError	(K)	1.76	1.79	1.74	1.73	1.39	2.30	2.83
	RMSE	(K)	2.22	2.26	2.31	2.27	1.73	2.98	3.80
	SysRMSE	(K)	0.77	1.12	0.97	0.99	0.68	0.64	2.10
	UnsysRMSE	(K)	2.06	1.92	2.08	2.02	1.57	2.89	3.16
	IOA		0.97	0.95	0.91	0.91	0.90	0.97	0.93
Humidity	MeanOBS	(g/kg)	8.22	9.23	15.52	15.13	19.34	7.16	12.96
	MeanPRD	(g/kg)	8.36	8.85	14.87	14.24	18.33	6.95	11.66
	Bias	(g/kg)	0.14	–0.38	–0.66	–0.89	–1.01	–0.20	–1.30
	GrossError	(g/kg)	1.39	1.18	1.65	1.65	1.75	1.63	2.51
	RMSE	(g/kg)	1.93	1.52	2.18	2.08	2.18	2.25	3.84
	SysRMSE	(g/kg)	0.87	0.70	1.23	1.30	1.38	0.59	2.73
	UnsysRMSE	(g/kg)	1.70	1.32	1.77	1.57	1.67	2.15	2.67
	IOA		0.87	0.80	0.79	0.76	0.63	0.83	0.81

Table S3 Precursor emission rates of 40 scenarios used to establish the response surface

Case	NO_x	SO_2	NH_3	VOC
#1	0.020	0.500	1.111	1.280
#2	0.045	1.500	0.099	0.720
#3	0.080	0.125	1.580	1.680
#4	0.125	0.875	1.605	0.013
#5	0.180	1.125	0.395	0.461
#6	0.245	1.875	0.420	1.549
#7	0.320	0.031	1.901	0.963
#8	0.405	0.469	0.011	1.795
#9	0.500	0.781	1.097	0.051
#10	0.605	1.719	1.298	0.627
#11	0.720	0.281	0.176	1.843
#12	0.845	1.219	1.855	1.181
#13	0.980	1.531	1.726	1.885
#14	1.125	1.969	0.538	0.115
#15	1.280	0.008	0.672	0.819
#16	1.445	0.242	1.956	0.157
#17	1.620	0.633	0.044	1.373
#18	1.805	1.617	1.328	1.949
#19	2.000	0.195	1.462	0.205
#20	0.195	1.055	0.274	1.037
#21	0.380	1.320	0.145	0.451
#22	0.555	1.930	1.824	1.539
#23	0.720	0.070	0.702	1.987
#24	0.875	0.680	0.903	0.001
#25	1.020	0.945	1.989	0.346
#26	1.155	1.805	0.001	1.332
#27	1.280	0.383	0.956	0.771
#28	1.395	1.367	1.176	1.705
#29	1.500	1.758	0.122	0.018
#30	1.595	1.992	1.669	0.492
#31	1.680	0.002	1.648	1.606
#32	1.755	0.123	0.440	1.009
#33	1.820	0.564	0.506	1.815
#34	1.875	1.561	1.922	0.062
#35	1.920	0.158	0.020	0.664
#36	1.955	0.967	1.172	1.905
#37	1.980	1.221	1.355	1.221
#38	1.995	1.904	0.206	1.900
#39	2.000	0.049	1.951	0.131
#40	0.000	0.576	1.761	0.861

Table S4 The average variation of AvgMDA8 O_3 for regions due to ΔMet-drive in April–September

Region	AvgMDA8 O_3 variation (Mean ± Std. Dev. ppb)					
	April	May	June	July	August	September
North	1.6 ± 1.8	–1.6 ± 2.8	–0.7 ± 4.0	2.3 ± 2.7	–0.6 ± 2.8	0.3 ± 1.9
North-east	3.3 ± 1.2	0.5 ± 1.7	–1.6 ± 2.5	2.8 ± 3.6	–2.5 ± 3.4	–0.7 ± 2.1
East	1.4 ± 3.4	7.8 ± 3.5	3.5 ± 6.8	0.4 ± 3.0	0.6 ± 4.7	0.6 ± 4.6
Central	–1.9 ± 2.7	1.6 ± 5.5	2.3 ± 3.0	3.1 ± 2.8	1.0 ± 3.0	–2.9 ± 4.9
South	2.7 ± 2.6	8.5 ± 5.3	–3.5 ± 2.3	0.9 ± 2.8	–3.0 ± 3.1	–2.9 ± 4.0
South-west	0.0 ± 1.7	1.7 ± 2.7	1.2 ± 3.3	2.9 ± 4.1	–2.1 ± 3.4	–2.6 ± 3.2
North-west	–0.8 ± 1.3	1.3 ± 2.0	1.0 ± 1.8	0.9 ± 4.2	–1.2 ± 2.7	–1.3 ± 2.1

Table S5 The average variation of AvgMDA8 O_3 for regions due to ΔEmis-drive in April–September

Region	AvgMDA8 O_3 variation (Mean ± Std. Dev. ppb)					
	April	May	June	July	August	September
North	–0.4 ± 0.8	–1.4 ± 0.8	–2.9 ± 1.6	–3.7 ± 1.8	–2.6 ± 1.3	–1.5 ± 1.0
North-east	–0.5 ± 0.6	–2.0 ± 0.8	–2.8 ± 1.3	–3.5 ± 1.5	–2.6 ± 1.0	–1.6 ± 0.7
East	–1.4 ± 1.8	–2.9 ± 1.3	–3.3 ± 1.5	–3.2 ± 1.6	–2.9 ± 1.5	–2.0 ± 1.4
Central	–1.8 ± 1.2	–2.7 ± 0.8	–3.6 ± 1.2	–3.1 ± 1.2	–2.8 ± 0.9	–2.0 ± 0.9
South	–1.8 ± 0.8	–1.9 ± 1.0	–0.9 ± 0.9	–1.4 ± 1.0	–1.4 ± 1.1	–1.6 ± 1.2
South-west	–0.7 ± 1.2	–0.8 ± 1.3	–0.9 ± 1.4	–1.2 ± 1.4	–1.0 ± 1.3	–0.8 ± 1.2
North-west	–0.7 ± 0.6	–0.9 ± 0.7	–1.5 ± 1.3	–1.7 ± 1.3	–1.3 ± 1.0	–0.9 ± 0.9