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Supplement of

Impacts of condensable particulate matter on atmospheric organic aerosols and fine particulate matter ($PM_{2.5}$) in China

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Supporting Information

S1. Meteorological evaluation

Comparisons between simulated and observed hourly meteorological variables including T, RH, WS, and WD from October 14 to November 14, 2014, at the Beijing site are displayed in Fig. S1. Results show that the model reproduced the hourly variations of T and RH reasonably well, although the maximum and minimum T, and RH did not totally match the observed values. The simulated WS were overestimated, but the hourly changes were reproduced. The variations of WD were not well captured, but the magnitudes of simulated WD were consistent with the observations over the whole period. A more detailed model evaluation for meteorological variables during October 14 –November 14, 2014 and December 1–30, 2018 at 9 cities over China is given in Table S1. MB, GE, RMSE denote the bias, root mean square error, and fractional error, respectively, and R refers to the correlation coefficient between observed and simulated results. For the Beijing site in 2014, the MB of T was -0.3 ℃, indicating a small deviation of modeled temperature. Good correlations between simulation and observation were shown for T, RH, and WS with R values of 0.90, 0.75, and 0.62, respectively. For all these cities, T, RH, and WS had the R values of 0.83~0.94, 0.67~0.89, and 0.21~0.70 during the study period in 2014, respectively. The R values for T, RH, and WS in 2018 were 0.74~0.95, 0.52~0.85, and 0.33~0.75, respectively. The GE and RMSE of WS were lower than model performance criteria (2 m/s) (Emery et al., 2001) for most cities, displaying relatively good simulations of wind speed. In summary, the WRF model showed a relatively consistent simulation performances of meteorological variables.

S2. Supplementary figures and tables

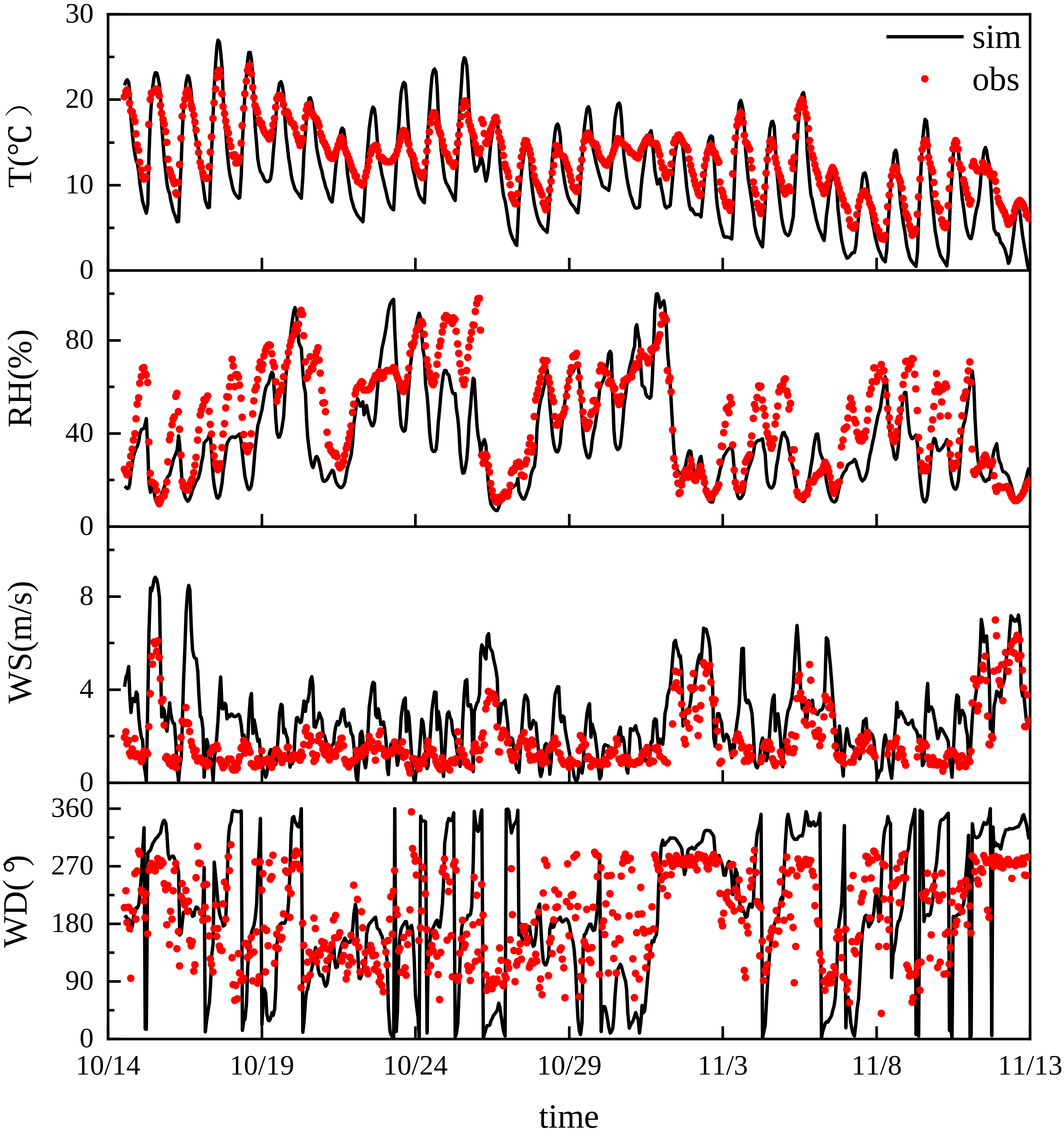

Figure S1. The observed and simulated hourly meteorological variations of temperature (T), relative humidity (RH), wind speed (WS), and wind direction (WD) during the episode from October 14 to November 14, 2014 at the Beijing site.

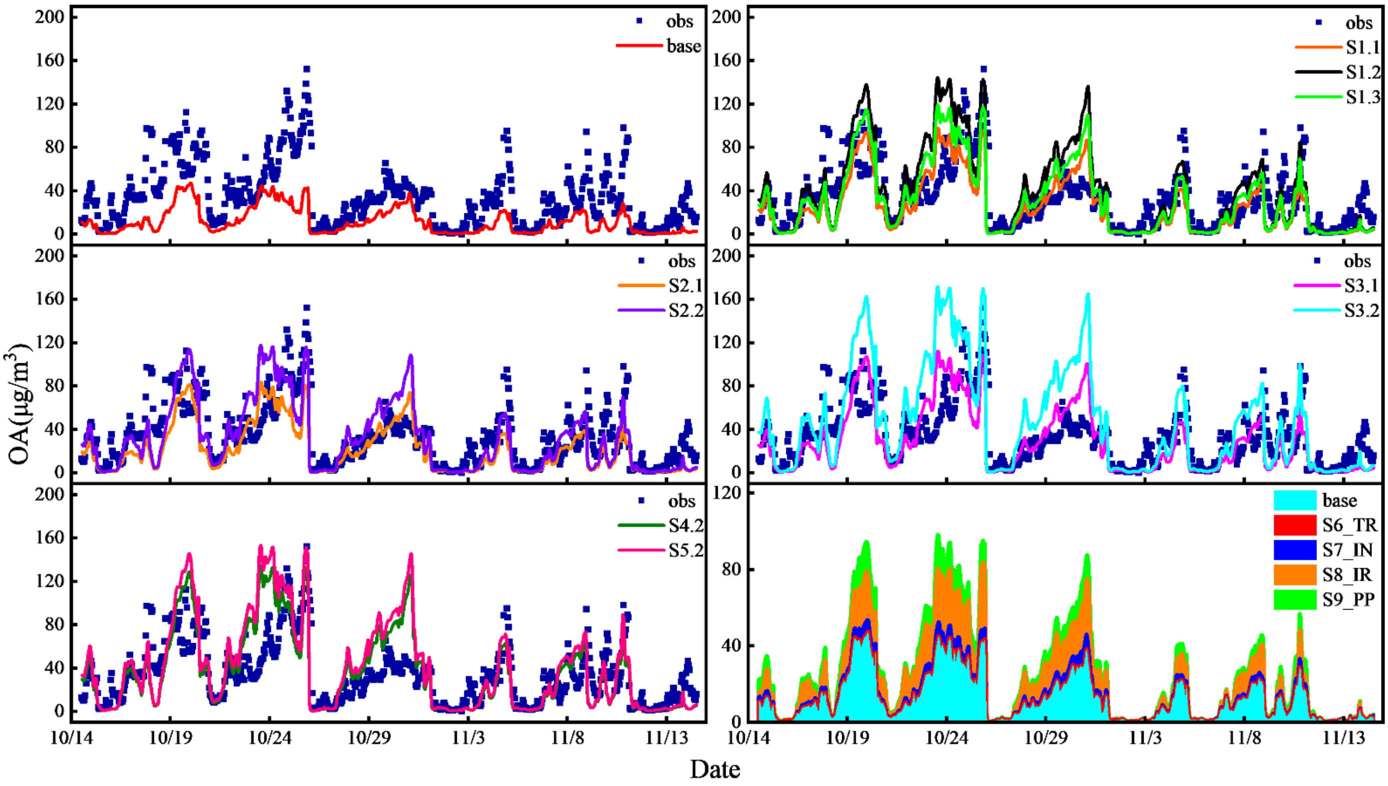

Figure S2. The observed and simulated hourly OA concentrations during the episode from October 14 to November 14 in 2014 at the Beijing site in the sensitivity cases as summarized in Table 3.

Table S1 Model evaluation statistics for meteorological variables including T, RH and WS.

		2014 (October 14 to November 14)						2018 (December 1 to 30)					
Variables		OBS	SIM	MB	GE	RMSE	R	OBS	SIM	MB	GE	RMSE	R
T (□)	Beijing	11.91	11.61	-0.30	2.01	2.52	0.90	-2.15	-3.29	-1.14	2.07	2.63	0.90
	Baoding	11.93	12.83	0.90	2.10	2.65	0.91	-2.35	-1.53	0.82	2.21	2.79	0.90
	Xingtai	13.52	13.84	0.32	1.82	2.35	0.90	-0.06	-0.08	-0.02	1.80	2.22	0.91
	Jinan	14.17	13.04	-1.13	1.68	2.12	0.94	1.16	-0.21	-1.37	1.80	2.29	0.95
	Changsha	18.65	18.90	0.25	2.08	2.76	0.84	5.90	8.82	2.92	3.14	3.66	0.88
	Hangzhou	17.71	17.29	-0.42	1.74	2.12	0.90	7.57	9.01	1.44	1.88	2.52	0.91
	Guangzhou	22.13	24.04	1.91	2.17	2.89	0.86	16.01	17.60	1.59	2.51	3.33	0.85
	Guiyang	14.22	15.45	1.23	2.27	2.84	0.83	4.79	6.15	1.36	2.51	3.27	0.85
	Wulumuqi	6.93	7.54	0.61	1.78	2.27	0.93	-12.65	-10.79	1.86	2.96	3.92	0.74
RH (%)	Beijing	51.30	35.74	-15.56	17.84	23.19	0.75	29.55	35.00	5.45	9.03	11.67	0.85
	Baoding	57.15	37.51	-19.64	21.22	26.13	0.73	46.07	37.66	-8.41	13.03	17.80	0.74
	Xingtai	60.64	38.44	-22.20	23.29	28.42	0.68	45.83	32.91	-12.92	15.87	22.22	0.64
	Jinan	53.37	51.57	-1.80	8.35	11.21	0.89	47.49	49.77	2.28	11.66	15.30	0.82
	Changsha	64.42	58.96	-5.46	11.42	15.18	0.83	84.49	70.71	-13.78	16.72	23.23	0.80
	Hangzhou	70.37	69.19	-1.18	10.79	13.10	0.85	80.97	85.02	4.05	9.43	12.32	0.75
	Guangzhou	75.58	65.30	-9.28	11.94	15.93	0.80	78.90	66.98	-11.92	15.04	19.35	0.74
	Guiyang	85.30	78.05	-7.25	12.37	16.30	0.67	85.31	79.53	-5.78	11.12	16.79	0.72
	Wulumuqi	56.03	43.32	-12.71	14.87	17.62	0.84	73.54	72.89	-0.65	10.30	12.86	0.52
WS (m/s)	Beijing	2.03	2.97	0.94	1.34	1.67	0.62	2.38	3.41	1.03	1.47	1.90	0.56
	Baoding	2.11	2.84	0.73	1.26	1.64	0.57	1.71	2.50	0.79	1.21	1.57	0.53
	Xingtai	1.35	3.43	2.08	2.15	2.66	0.51	2.67	3.09	0.43	1.39	1.81	0.33
	Jinan	2.87	4.51	1.64	1.87	2.28	0.70	2.10	3.61	1.51	1.66	1.99	0.62
	Changsha	1.90	3.23	1.33	1.49	1.82	0.50	3.56	4.11	0.55	1.19	1.43	0.75
	Hangzhou	2.11	2.95	0.84	1.18	1.49	0.48	2.46	3.91	1.45	1.63	2.01	0.67
	Guangzhou	2.16	3.24	1.08	1.40	1.69	0.50	3.01	4.31	1.30	1.54	1.85	0.69
	Guiyang	2.41	3.68	1.27	1.49	1.85	0.43	2.69	4.00	1.31	1.56	1.95	0.34
	Wulumuqi	2.17	3.74	1.57	1.95	3.08	0.21	1.69	2.04	0.35	1.22	1.57	0.37

Note: OBS denotes the observation value; SIM denotes the simulation value; MB denotes mean bias; GE denotes gross error; RMSE denotes root mean square error; R denotes correlation coefficient.

Table S2 Model evaluation statistics for hourly PM$_{2.5}$ concentrations during October 14–November 14, 2014, and daily PM$_{2.5}$ concentrations during December 6–30, 2018, under different sensitivity simulation cases.

Period	City	Species	Cases	N	OBS	SIM	MB	NMB	NME	R
October 14–November 14, 2014	Beijing	PM$_{2.5}$	base	692	83.09	35.64	-47.45	-57.11%	57.32%	0.71
			S1.1		83.09	48.71	-34.38	-41.38%	44.54%	0.72
			S1.2		83.09	62.79	-20.30	-24.43%	41.82%	0.73
			S1.3		83.09	55.42	-27.67	-33.30%	42.13%	0.73
December 6–30, 2018	Handan	PM$_{2.5}$	base	18	89.60	58.14	-31.46	-35.11%	43.10%	0.60
			S1.1		89.60	76.95	-12.65	-14.12%	36.60%	0.59
			S1.3		89.60	91.43	1.83	2.04%	35.71%	0.58
	Shijiazhuang	PM$_{2.5}$	base	18	89.68	56.40	-33.28	-37.11%	37.11%	0.68
			S1.1		89.68	77.14	-12.54	-13.98%	26.93%	0.67
			S1.3		89.68	96.15	6.47	7.21%	33.33%	0.66
	Xingtai	PM$_{2.5}$	base	18	83.51	43.60	-39.91	-47.79%	49.75%	0.64
			S1.1		83.51	60.15	-23.36	-27.97%	37.40%	0.63
			S1.3		83.51	73.42	-10.09	-12.08%	32.58%	0.62

Note: OBS and SIM denote mean concentrations (μg m^{-3}) of observations and simulations, respectively; MB: mean bias; NMB: normalized mean bias; NME: normalized mean error; R: correlation coefficient.

Table S3 The collected CPM emission information from a review of references.

Emission source		Fuel	APCD*	T(°C)	$FPM_{2.5}$ (mg/Nm^3)	CPM (mg/Nm^3)	CPM-organic (mg/Nm^3)	CPM-inorganic (mg/Nm^3)	Flue gas volume flow rate	Measurement methods	Location	References
coal-fired boiler	A	coal	FF + WFGD		12. 1 ±3. 6	17. 2 ± 1. 7	1%	67%		condensation	CFPP	(Pei, 2015)
	B		ESP + WFGD		33. 4 ±3. 7	23. 6 ± 2. 0						
	C		SCR+ESP+ WFGD		16. 2 ±2. 6	22. 8 ± 2. 3						
coal-fired boiler		coal	SCR+ESP+ BH+WFGD	88	1.04	12.94				condensation filter	CFPP	(Hu et al., 2016)
			integrated purification	40	27.41	22.6					heating plant	
			BH+WFGD	52	9.29	22.55					heating plant	
			integrated purification	43	46.58	35.81					industrial enterprise	
Iron and steel coking plant		coal	DFGD +FF +SCR	169.9	0.3 mg/m^3 0.4 mg/kg coal	1.2 mg/m^3 1.7 mg/kg coal	10.4%		231406 ±28521 m^3/h 168.6 t(coal)/h	indirect dilution GC-MS		(Zhang et al., 2020)
CFPP	#1	coal	SCR + ESP + WFGD + WESP	51		7.5 5.8 3.5				dry impinger indirect dilution direct dilution	coal-fired power plants	(Wang et al., 2020a)
	#2			48.8		3 2 2.5						
	#3			63.8		5.5 1.5 4						
	#4			50.6		2.5 1 2.5						
	#5			50.3		11 2.5 3						
	#6			52.1		10 1.5 1.3						
coking plant			DFGD +FF +SCR	169.9		24.5 1.2 0.5					iron and steel plant	
sintering plant			ESP+ absorption	129.2		10 5 1.5						

			tower									
WIPP	stack #1	household garbage kitchen waste	SNCR+SDFGD+ DFGD +activated carbon adsorption+ FF	146.5		19 0.5			300 tons/day		waste incineration power plants	
	stack #2			145.3		21 1.0						
WIPP	stack #1	household garbage kitchen waste	SNCR+ SDFGD+ bag filter	146.5	0.87± 0.1 mg/m^3 0.009± 0.001g/kg	19.04± 3.67 mg/m^3 0.201± 0.039g/kg	22.6%	77.1%	131784 m^3/h 300t(solid waste)/d	EPA 201A EPA 202 extraction gravimetric method/ GC-MS	Shandong	(Wang et al., 2018)
	#2			145.3	0.68 ±0.19 0.006± 0.002g/kg	21.09± 3.32 0.178± 0.028g/kg	5.3%	94.4%	105427 m^3/h 300t/d			
WIPP	#3	household garbage kitchen waste coal	ESP+ bag filter	120	3.3 ± 0.65				150 t/d	two–stage virtual impactor	Zhejiang	
circulating fluidized bed boiler		coal	SNCR&SCR +ESP+FGD+ WESP			3.75			220 t/h	parallel sampling system dilution	Ultralow Emission coal-fired Power Plant	(Zheng et al., 2018)
pulverized coal boiler		bituminous coal	SCR+ESP&FF+WFGD		9.8 ± 6.8 g/t(coal)	12 167.83 ± 33.92 g/t(coal)	5.8	6.2	200 t/h	EPA 202 extraction gravimetric method/	Coal-fired power plants (CFPPs) #1 #2 #3 #4	(Wu et al., 2020)
pulverized coal boiler			SCR+FF+WFGD		15.67± 4.12 g/t(coal)	15 138.45 ± 21.89	10.5	4.5	410 t/h			

						g/ t(coal)						
circulating fluidized bed			SNCR+FF+WFGD&WESP		21.76 ± 5.91 g/t(coal)	9.5 109.89 ± 35.76 g/t(coal)	6.5	3	260 t/h			
pulverized coal boiler			SCR+ESP+WFGD&WESP		4.70 ± 1.19 g/t(coal)	10 74.33 ± 13.68 g/t(coal)	3.3	6.7	2209 t/h			
coal-fired boiler		coal	SCR+ ESP+ GGH+WFGD +WESP	80	1.1	7.9	4.3	3.6		ISO 23210-2009 EPA 202 extraction gravimetric method/ GC-MS	LH CFPP #1unit	(Li et al., 2017a)
coal-fired boiler	stage1	coal	SCR+ LLT-ESP+ MGGH + WFGD+ WESP	130	0.46	18.6	62%		2×10^6 Nm^3/h		YQ CFPP #1unit	(Li et al., 2017b)
	stage2				0.4	11.9	81%					
	stage3					27.1	87%					
coal-fired boiler	E1	coal		100	3.8	36.3	21.6	14.7			Zhejiang	(Qi et al., 2017)
	E2			97	3.8	31.8	10.3	21.5				
	E3			93	10.1	40.8	21.7	19.1				
coal-fired boiler	stage1	coal		86	3.5	48.7	44.3	4.4	10 L/min		JX CFPP #7unit	(Li et al., 2019)
	Stage2			95	7.8	35.2	28.8	6.4				
coal-fired boiler		coal			1.81	10.66	5.59	5.07	3688100 Nm^3/h 360.88 t(coal)/h		Ultralow-Emission JX CFPP #8unit	(Song et al., 2020)
coal-fired boiler		coal			1.4	32	29.9	2.1			FT #1unit	(Li, 2018)
					2.2	18.3	13.7	4.6			YQ #2unit	
coal-		coal	SCR+ESP+ WFGD		2.54	24.8	23.1	1.69			ZJK #8unit	(Zhou, 2019)
					6.14	16.24	11.4	4.85			WT #2unit	

fired boiler	stage1		SCR+LLT-ESP+WFGD +WESP		1.4	6.66	4.44	2.22			JX #7unit	
	stage2				0.83	6.69	5.51	1.45				
	stage3				1.14	8.93	6.68	2.25				
	stage4				1.77	6.66	4.05	2.61				
					1.81	10.66	5.59	5.07			JX #8unit	
coal-fired power plant		coal	SCR + BH + SWFGD	105	0.45 5.25 g/t(coal)	12.7 ± 1.44 142 g/t(coal)	90 ±3.7%		2300000 Nm^3/h 275 t(coal)/h	EPA 201A EPA 202/ extraction gravimetric method/ GC-MS		(Lu et al., 2019)
coal-fired boiler			SCR + ESP + WFGD	59	1.9 20.1 g/t(coal)	28.0 ± 6.32 307 g/t(coal)		93 ± 2.4%	80000 Nm^3/h 8 t(coal)/h		food processing plant	
Power plant		coal oil	ESP+FGD		0.75	2.15		89%		EPA 201A EPA 202 extraction gravimetric method	Taiwan, China	(Yang et al., 2014)
industry boiler		coal	Cyclone+ BH		16.9	29.3		69.4%				
brick manufacturing plant					8.67	83.5		72.3%				
incinerator			BH		0.15	0.17		89.8%				
arc furnace			BH		2.12	2.53		72.8%				
sintering		coke	ESP denitrification de-dioxin	161	1.01	65.3		95.4%	468 t flux/h	EPA 201A EPA 202 extraction gravimetric method	iron and steel plants	(Yang et al., 2015)
coke making		coke oven gas		178	0.37	89.7		52%	159 t coal/h			
blast furnace		mixed gas	BH	57.5	0.16	3.84		69.9%	166t steel/h			
Basic oxygen furnace		natural gas	BH	57.8	0.15	1.32		63.6%	15.7t waste steel/h			
electric arc furnace		natural gas	CO convertor + BH	70.5	0.28	2.02		58.4%	144t waste steel/h			
municipal solid waste incinerator		municipal solid	SNCR+ semidry lime	157	FCPM 10.2 ± 0.67 mg/Nm^3		OC+EC 33.1%		4210 Nm^3/h	dilution sampling/	central Taiwan,	(Yang et al., 2016)

		waste	scrubber+activated carbon injection+ BH		61.6 ± 4.52 g/ton waste		OC/EC 1.73			extraction gravimetric method	China	
					0.29 ±0.03	28.1 ±17				in-stack sampling		
coal-fired boilers	1(n=4)	raw coal	cyclone	65.3	18.6± 13.7	22.7 ± 5.61	22.9%	77.1%		EPA 201A EPA 202 extraction gravimetric method	industrial plants	(Yang et al., 2018b)
	2(n=5)		EP	44.6	3.83± 1.05	3.92 ± 1.08	45.6%	54.4%				
	3(n=3)		baghouse	83.3	3.51± 3.21	8.61 ± 4.03	41.1%	58.9%				
	4(n=3)		EP	101	0.84± 0.18	5.96 ± 2.21	13.6%	86.4%			power plants	
oil-fired boilers	1(n=8)	heavy oil	no	148	141 ± 76.1	242 ± 131	80.5%	19.5%				
	2(n=2)		cyclone	195	22.6± 5.28	84.2 ± 38.1	62.4%	37.6%				
	3(n=1)		BH	125	2.31	3.16	20.4%	79.6%				
CFBs (n=5)		coal	cyclone+ BH	76.6	19.3± 2.94	27.2 ± 3.49	2.765	6.77 ± 1.74			industrial boilers	(Yang et al., 2018a)
WFBs (n=5)		wood	wet scrubber	70.6	90.8± 40.6	31.4 ± 14.1	3.104	4.98 ± 2.23				
HOFBs (n=4)		heavy oil	no	159	28 ± 5.6	163 ± 62.8	69.686	27.1 ± 23.7				
DFBs (n=1)		diesel	no	162	0.273	7.67	4.324	2.65				
NGFBs (n=3)		natural gas	no	133	0.352 ± 0.157	7.02 ± 3.1	2.349	3.38 ± 1.51				
CFPP	C	coal	SCR+ESP+WFGD+ WESP	47	3.9	7.33	4.04	3.29	119 t(coal)/h	EPA 202 extraction gravimetric method	north China around Beijing	(Wang et al., 2020b)
	D		SCR+BF+WFGD+ WESP	46	0.55	6.15	3.51	2.64	150.2 t(coal)/h			
CFPP	A		SCR+ESP+WFGD+ WESP	50.1	2.35	15.92	9.59	6.33			Xi'an city, Shaanxi	(Yang et al., 2021)
	B		SCR+LLTe+ ESP+ WFGD	53.9	3.96	30.69	8.73	21.96			Urumqi City, Xinjiang	

Note: Air pollution control devices (APCDs) include selective catalytic reduction denitration device (SCR), selective noncatalytic reduction (SNCR), electrostatic precipitator (ESP), gas−gas heat exchanger (GGH), tube type gas−gas heat exchanger (MGGH), wet flue gas desulfurization (WFGD), wet electrostatic precipitator (WESP), low-low temperature electrostatic precipitator (LLT-ESP), fabric filters (FF), baghouse (BH), seawater flue gas desulfurization (SWFGD), and semi-dry flue gas desulphurization(SDFGD).

Table S4 The model species for POA, ASOA (SOA from anthropogenic VOCs), BSOA (SOA from biogenic VOCs), and SISOA (SOA from low volatile S/IVOCs).

	model species
POA	ALVPO1I ASVPO1I ASVPO2I APOCI APNCOMI ALVPO1J ASVPO1J ASVPO2J APOCJ ASVPO3J AIVPO1J APNCOMJ
ASOA	AAVB1J AAVB2J AAVB3J AAVB4J AOLGAJ
BSOA	AISO1J AISO2J AISO3J AMT1J AMT2J AMT3J AMT4J AMT5J AMT6J AMTNO3J AMTHYDJ AGLYJ ASQTJ AOLGBJ
SISOA	ALVOO1I ALVOO2I ASVOO1I ASVOO2I ALVOO1J ALVOO2J ASVOO1J ASVOO2J ASVOO3J APCSOJ
SOA	AAVB1J AAVB2J AAVB3J AAVB4J AOLGAJ AORGCJ AISO1J AISO2J AISO3J AMT1J AMT2J AMT3J AMT4J AMT5J AMT6J AMTNO3J AMTHYDJ AGLYJ ASQTJ AOLGBJ ALVOO1I ALVOO2I ASVOO1I ASVOO2I ALVOO1J ALVOO2J ASVOO1J ASVOO2J ASVOO3J APCSOJ

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