Supporting Information for

Multi-year emission of carbonaceous aerosols from cooking, fireworks burning, sacrificial incenses, joss paper burning, and barbecue and the key driving forces in China

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Contents of this file

Text S1 to **S4**

Figures S1 to **S14**

Tables S1 to **S4**

Text S1: POI data came from the Open Platform of Amap (https://lbs.amap.com/). Amap is a leading provider of digital mapping, navigation, and location service in China. We have extracted the POI data by the keywords of fireworks, barbecue, restaurants, and temples, and eliminated the points with irrelevant keywords (Wu et al., 2021). The extraction was performed on Python 3.8 platform with the Requests library and Pandas library. We got 430,343 barbecue restaurants, 1,986,674 common restaurants, 70,766 temples, and 73,523 fireworks shops. The POI data were divided among 366 cities in China. Each point of POI contains latitude, longitude, name, category, and address. Unfortunately, they do not contain more detailed information on sales volume, turnover, etc.

Text S2: To understand the consumption of sacrificial incenses, joss paper, and fireworks, we have organized household investigations in China. This survey covered 27 provinces in China. We have investigated the per capita consumption of sacrificial incense, joss paper, and fireworks, and the dates for burning them. And we asked each respondent for household population, address (in the urban or rural region), and the time when local fireworks were prohibited. After the manual screening, we eliminated invalid questionnaires. Finally, 2461 valid questionnaires were collected.

Text S3: The emissions were spatially allocated by using two datasets: population distribution data (www.worldpop.org) and land-use data (Gong et al., 2019, 2020). The urban region and rural region were distinguished by land-use data. According to the distribution of rural regions and urban regions, the population distribution data was divided into the rural population and the urban population. But the result was contradictory to the census. The rural population was about four times the level of the urban population. Thus, data from the statistical yearbook (366 cities) was used to correct this bias.

Text S4: Chinese New Year's Eve (CNE, the last day of one lunar year) and Chinese Spring Festival (CSF, the first day of the next lunar year) are the Chinese Lunar New Year, and they are also the most important traditional festivals in China. The Spring Lantern Festival (LF) falls on the 15^{th} day of the first lunar month in China. CNE, CSF, and LF are three traditional Chinese festivals in which fireworks were set off for celebration. The burning of fireworks has also led to the explosions in the concentration of pollutants (Yang et al., 2014; Zhao et al., 2017; Wu et al., 2018; Yao et al., 2019). Qingming Festival (QF) and Zhongyuan Festival (ZF) are traditional sacrificial festivals. In those days, people sweep tombs and worship their ancestors by burning joss paper and sacrificial incense. These festivals also prevail in the Sinosphere. The burning of joss paper and sacrificial incense has attracted the attention of the scientific community, and it's also the source of air pollutants in certain periods (Chiang & Liao, 2006; Wei et al., 2018; Chen et al., 2019; Zhang et al., 2019).

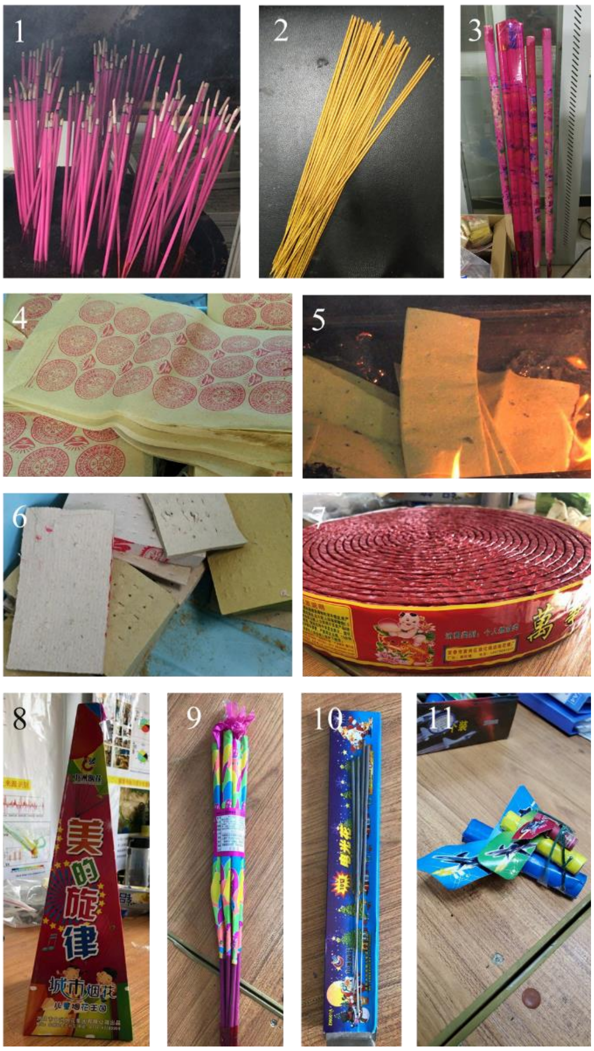

Figure S1 Pictures of materials used in this study (1: red incense (RI), 2: environmental incense (EI), 3: high incense (HI), 4: red print paper (RP), 5: large sacrificial paper (LP), 6: small sacrificial paper (SP), 7: firecrackers (FC), 8: fountain fireworks (FF), 9: handheld fireworks (HF), 10: handheld fountain (HT), 11: spin fireworks (SF). Pictures of meats used in barbecue and cooking experiments, including chicken (CK), beef (BF), lamb (LB), pork (PK), cooking of meat (MT1), cooking of meat and pepper (MT2), cooking of meat and garlic (MT3), cooking of meat, pepper, and garlic (MT4), were not present).

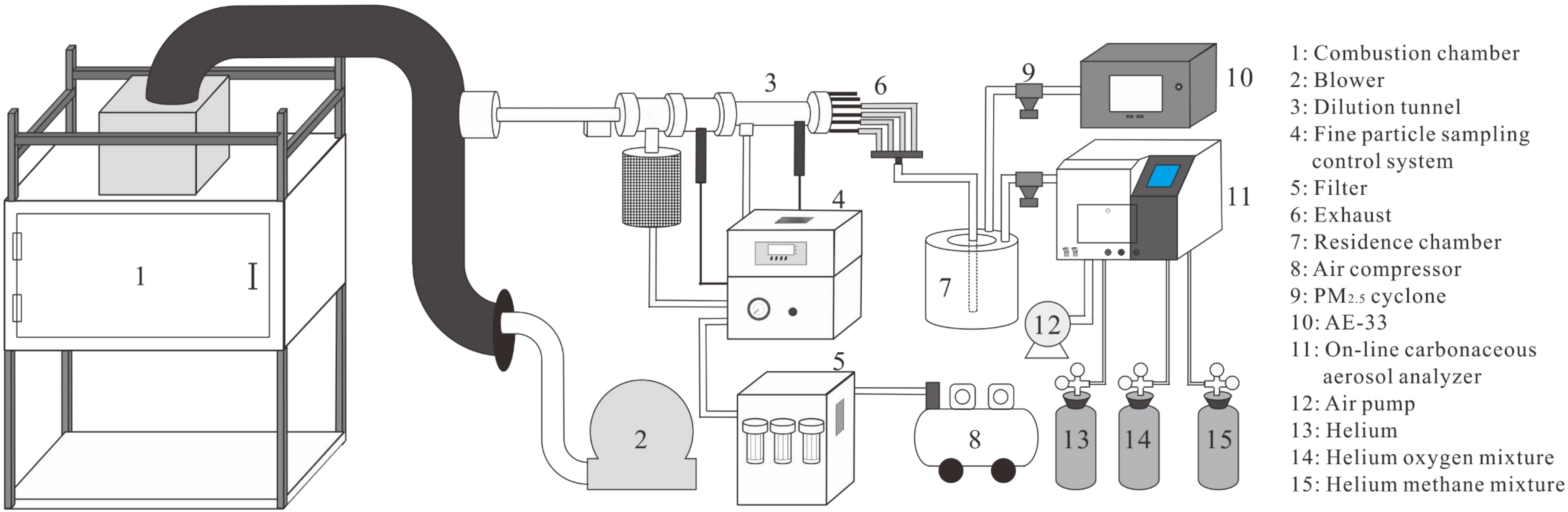

Figure S2 Structure of the combustion and dilution sampling system adopted in this study

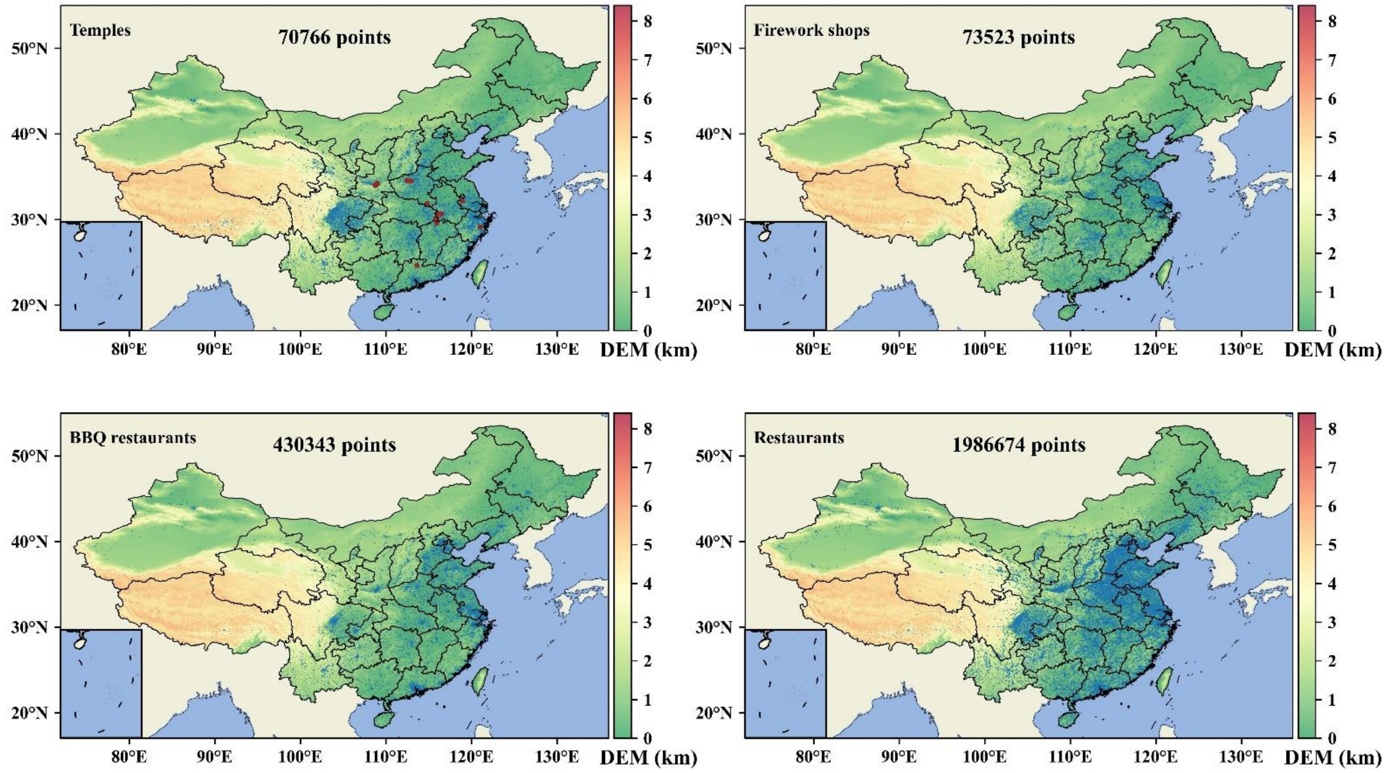

Figure S3 The distribution of temples, firework shops, barbecue restaurants, and common restaurants in China; The blue dots represent points of interest, and the red dots in the first picture are cradles of Chinese Buddhism.

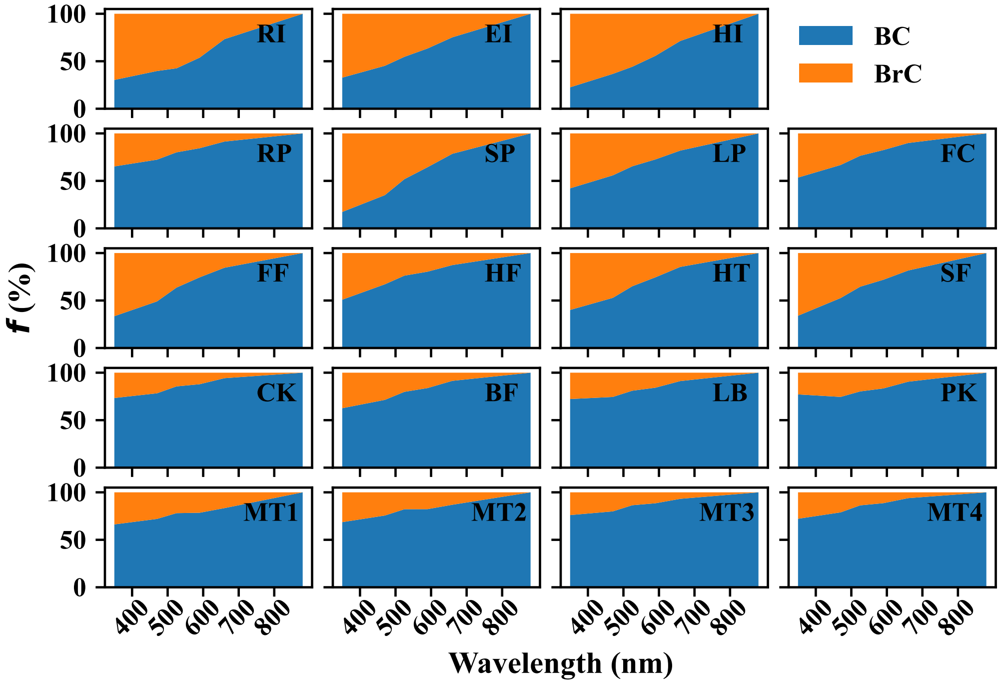

Figure S4 Contributions (%) of BC and BrC to the total light absorption in different wavelengths.

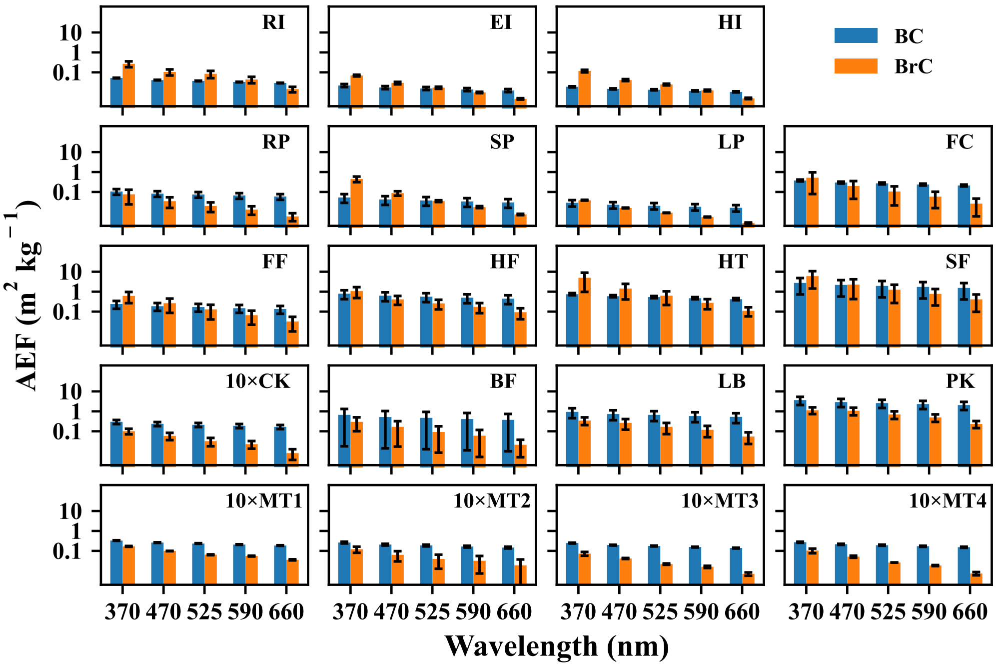

Figure S5 AEF_{BrC} and AEF_{BC} of FM in different wavelengths.

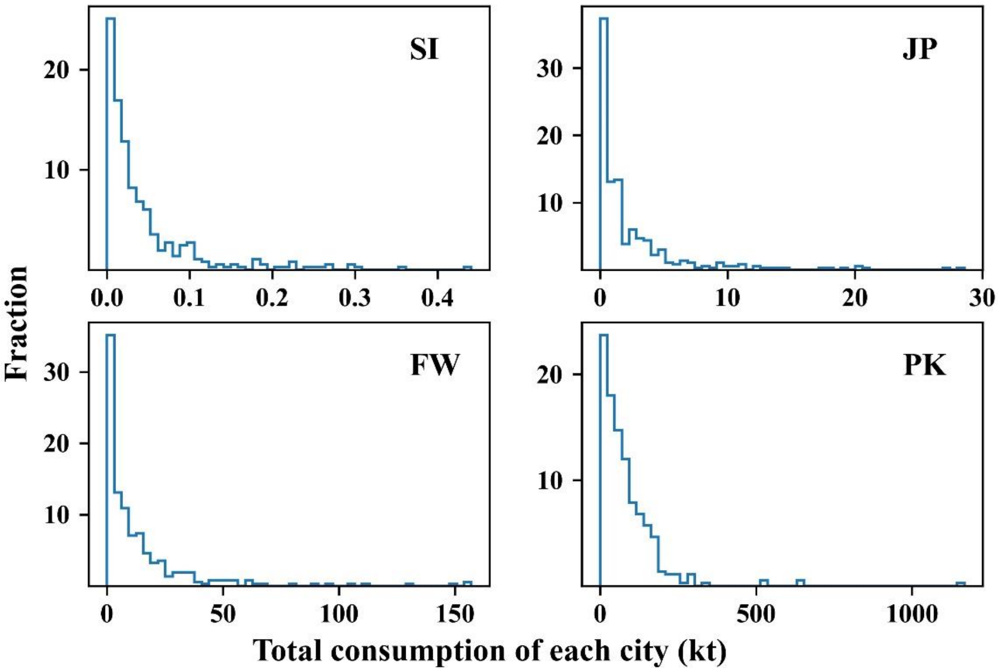

Figure S6 The distribution of total consumption of sacrificial incense, joss paper, fireworks, and pork in 366 cities in China

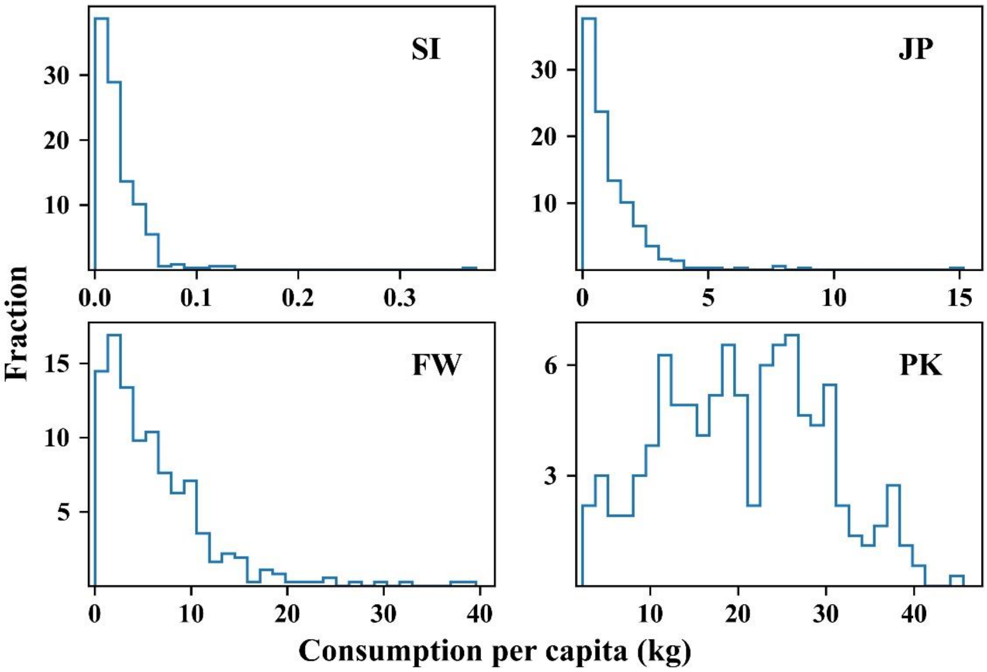

Figure S7 The distribution of per capita consumption of sacrificial incense, joss paper, fireworks, and pork in 366 cities in China

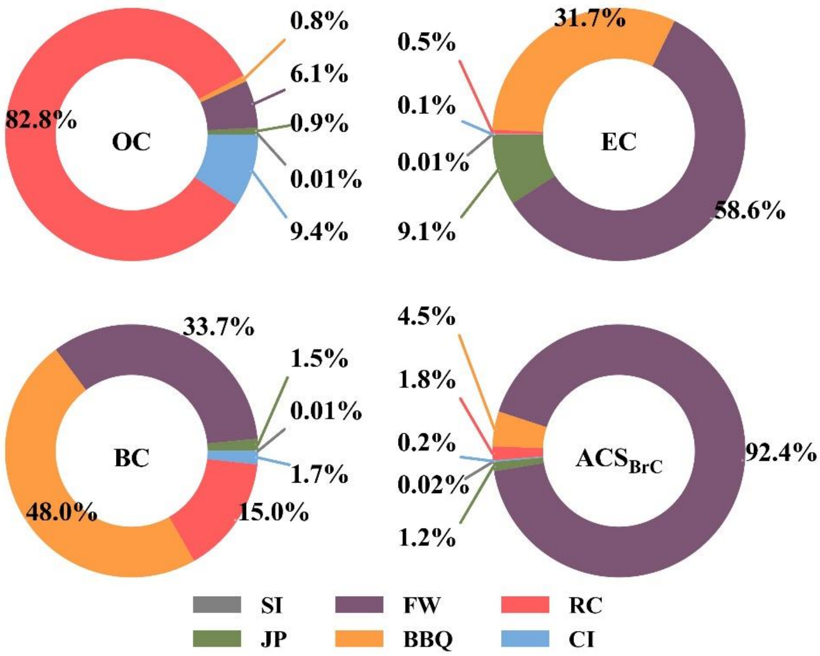

Figure S8 Contribution of different sources to the total CA emissions from FMS of China in 2018 (SI: sacrificial incense; JP: joss paper; FW: fireworks; BBQ: barbecue; RC: residential cooking; CI: catering industry).

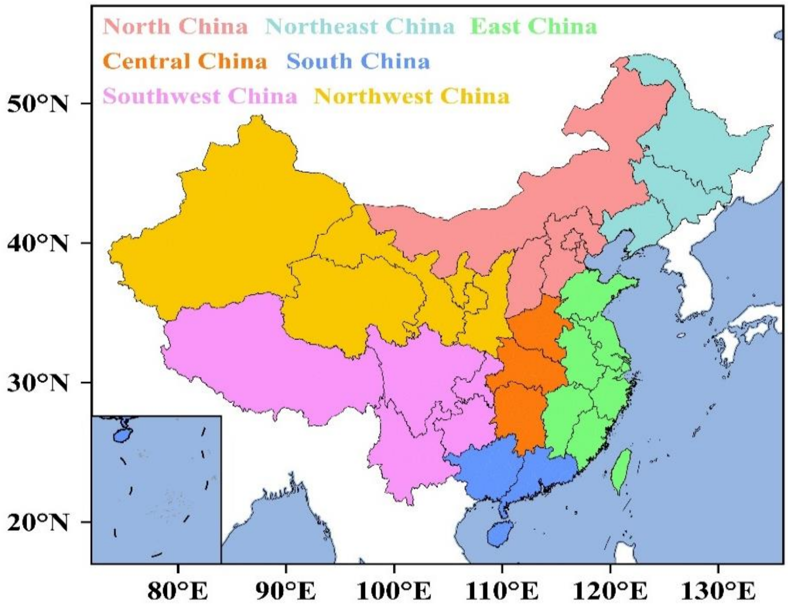

Figure S9 The seven geographical regions in China

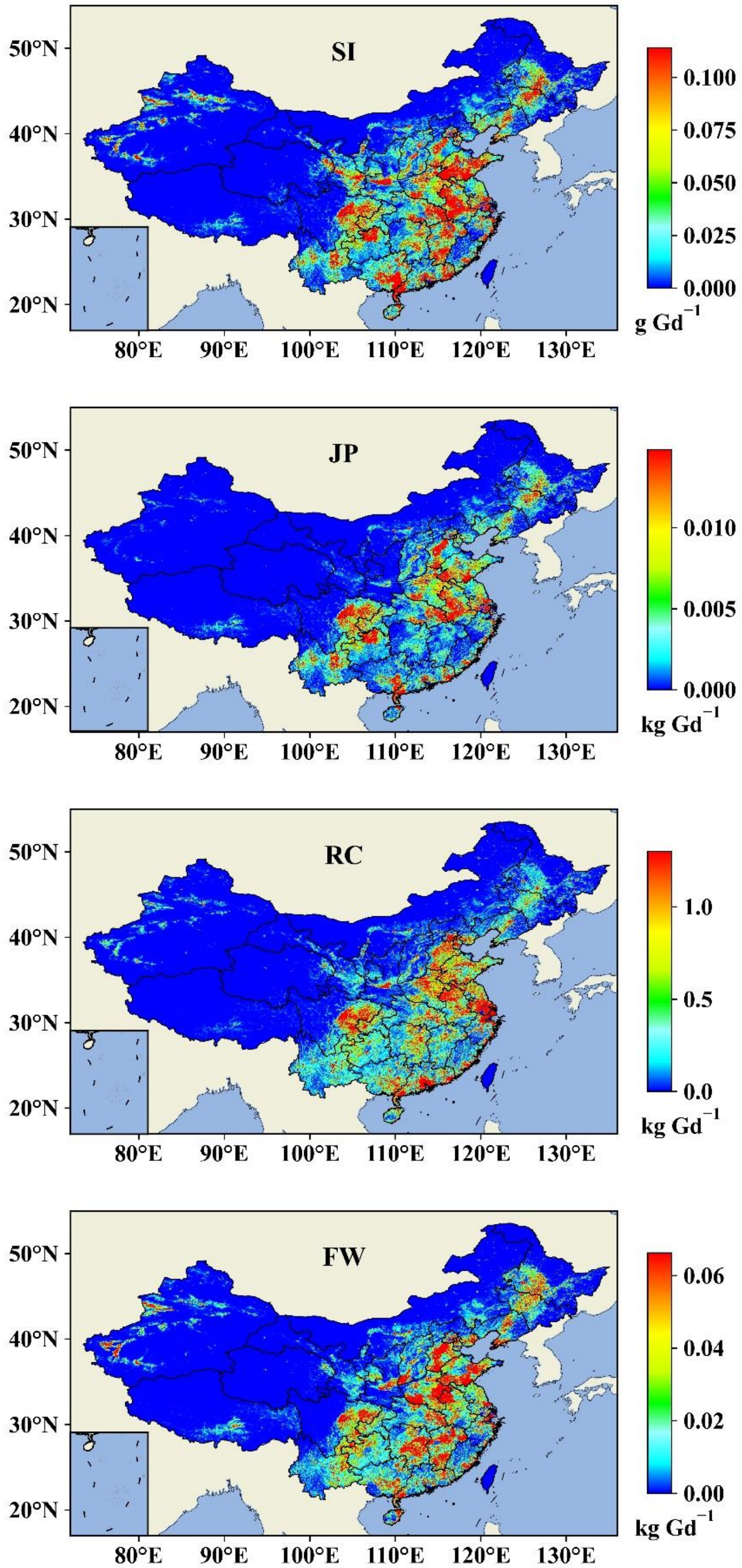

Figure S10 Distribution of OC emission from different sources in 2018. Colorbar shows the emissions in each grid.

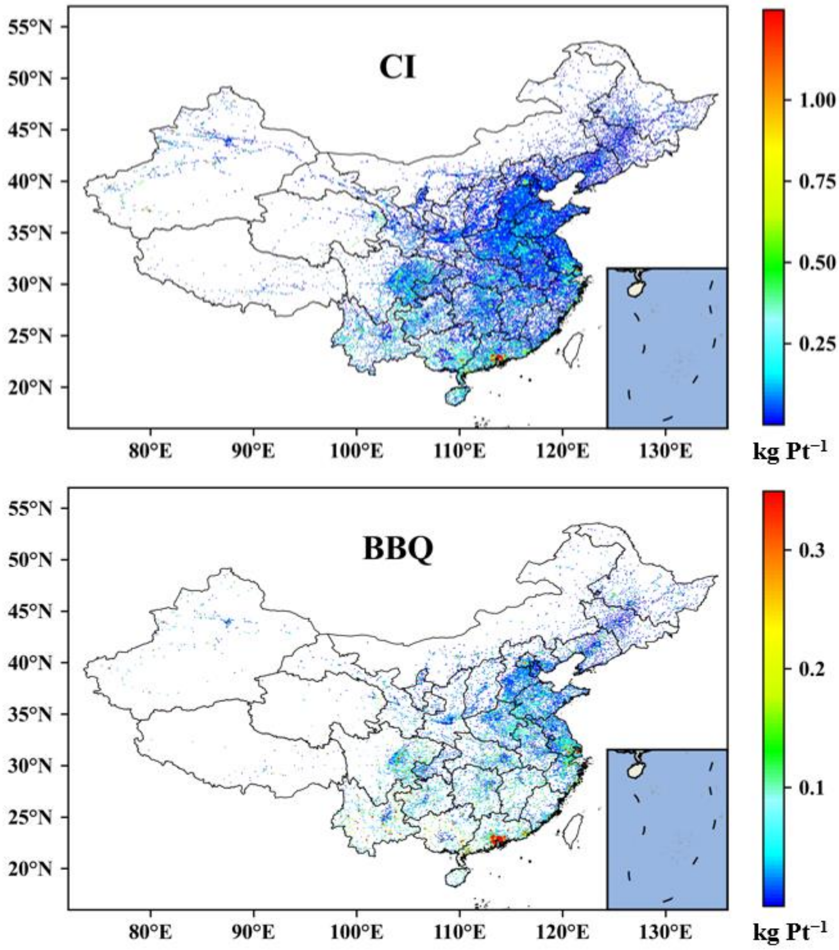

Figure S11 Distribution of OC emission from different sources in 2018. Each point represents a restaurant that deals in barbecue or cooking. Colorbar shows the emission from each point.

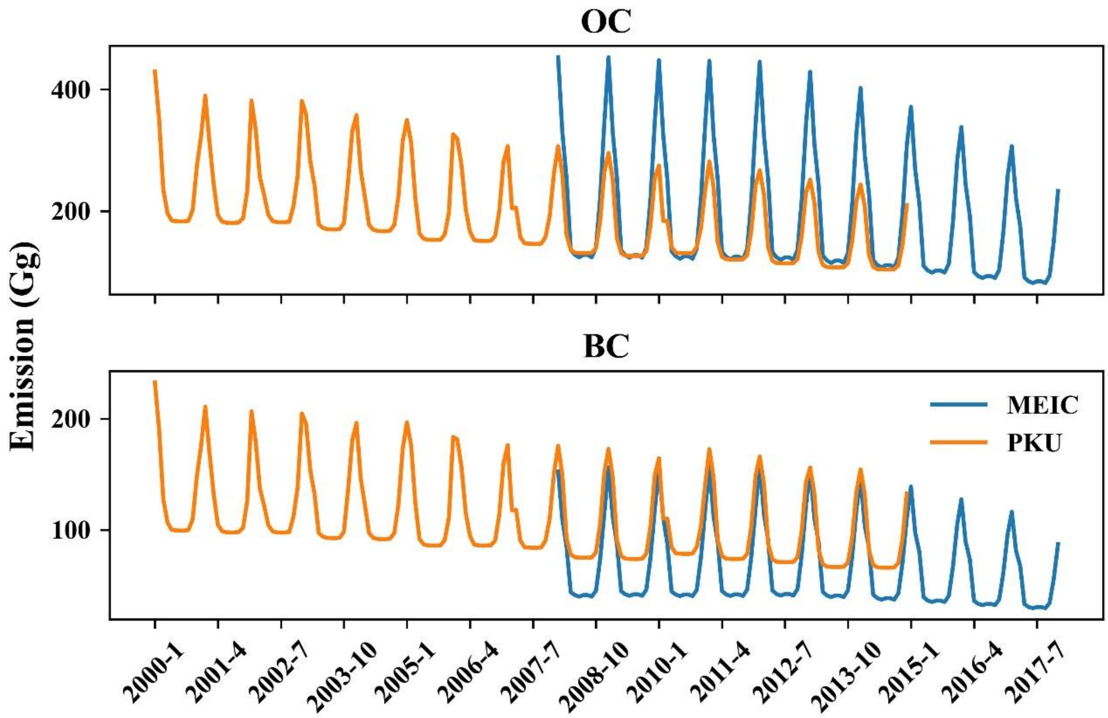

Figure S12 Monthly OC and EC emission from residential sources (residential & commercial sources) in MEIC inventory (Li et al., 2017) and PKU inventory (Wang et al., 2014; Huang et al., 2015).

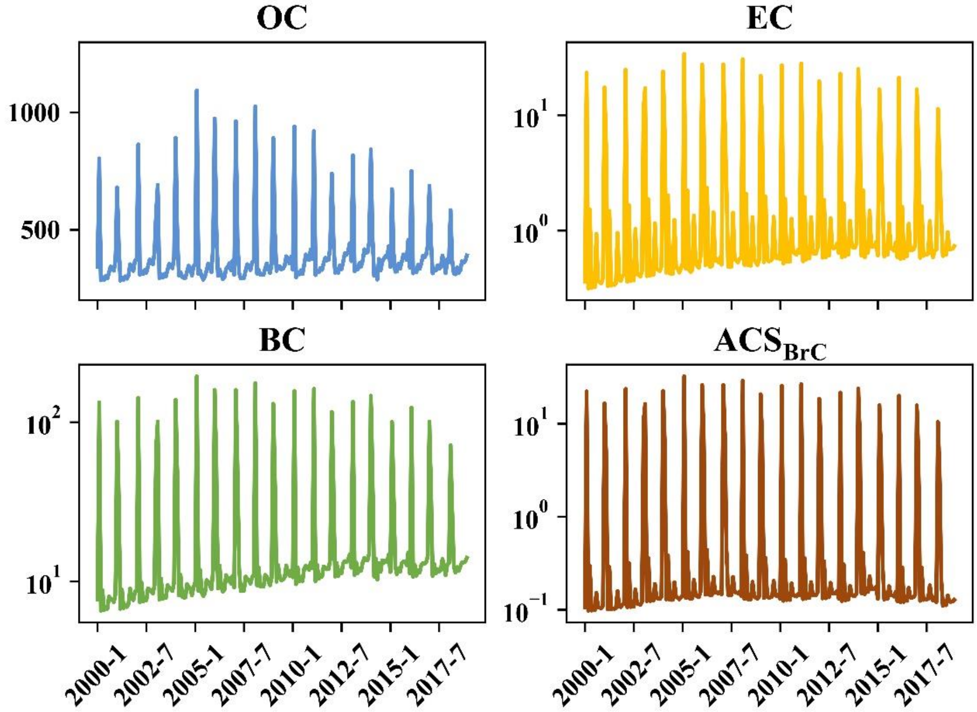

Figure S13 Monthly variation of CA emission from FMS from 2000 to 2018 in this study (OC, EC, BC: t, ACS_{BrC}: Gm^2).

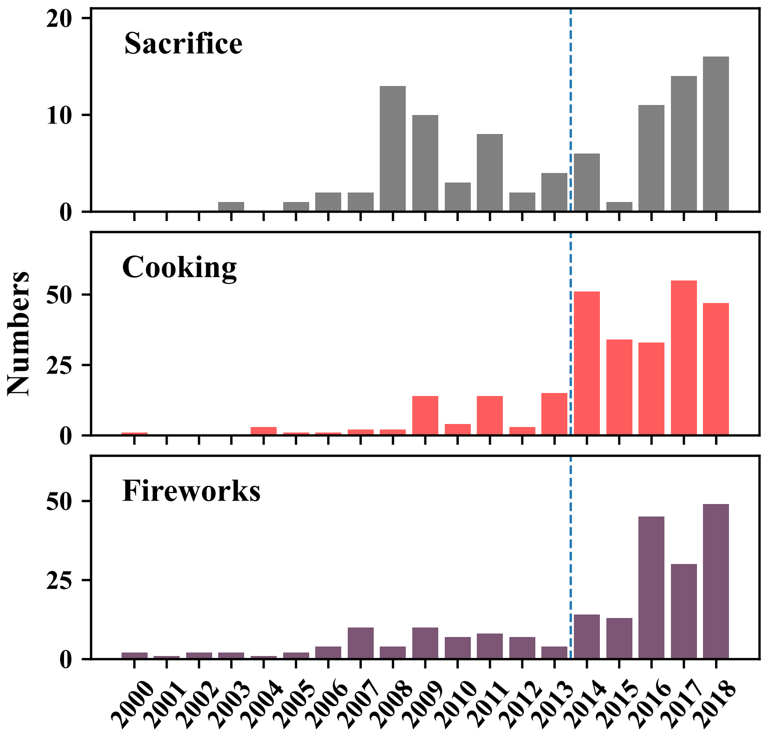

Figure S14 Number of cities that implemented emission control policies of FMS in 2000–2018. The blue dash line represents the time of the pronouncement of the Air Pollution Prevention and Control Action Plan on September 10, 2013.

Table S1 The coefficients of activity data for FMS.

Sources	CV	References
Sacrificial incense	−50–50%	Subject judgment
Joss paper	−50–50%	Subject judgment
Barbecue	−20–20%	(Wu et al., 2021)
Cooking	−20–20%	(Wu et al., 2021)
Fireworks	−50–50%	Subject judgment

Table S2 Uncertainties of CA emission inventories of FMS.

	OC	EC	BC	ACS_{BrC}
2000	−16.7–17.2%	−109–112%	−40.4–42.4%	−110–117%
2001	−16.4–16.8%	−110–112%	−40.0–43.1%	−112–113%
2002	−16.6–17.0%	−110–108%	−40.3–41.7%	−113–112%
2003	−16.0–16.8%	−110–109%	−42.3–43.9%	−114–116%
2004	−16.1–17.1%	−109–112%	−42.9–44.4%	−113–116%
2005	−16.0–16.9%	−108–111%	−42.9–43.1%	−113–115%
2006	−16.2–17.2%	−109–112%	−42.7–44.3%	−113–114%
2007	−16.2–16.5%	−108–114%	−42.9–44.6%	−111–116%
2008	−16.3–17.0%	−109–111%	−41.1–42.0%	−111–116%
2009	−16.5–17.3%	−103–108%	−39.9–40.8%	−110–115%
2010	−16.1–17.2%	−103–108%	−39.6–40.4%	−112–111%
2011	−16.4–17.0%	−102–106%	−38.5–40.7%	−110–114%
2012	−16.7–17.1%	−100–104%	−39.2–39.1%	−109–115%
2013	−16.6–17.4%	−99.6–102%	−37.9–39.8%	−109–112%
2014	−16.2–16.9%	−105–107%	−39.1–42.2%	−110–117%
2015	−16.7–17.4%	−96.6–101%	−37.0–37.9%	−111–112%
2016	−16.8–17.5%	−95.7–101%	−37.0–38.0%	−109–112%
2017	−17.0–17.7%	−97.8–99.3%	−36.5–37.9%	−109–115%
2018	−17.6–17.8%	−85.9–91.4%	−35.7–35.1%	−105–107%

Tabel S3 Emission factors of FMS in the literature.

Source	Pollutant	Emission factors	Experiments	References
Sacrificial incenses	$PM_{2.5}$	2.5–3 g kg^{-1}	Samplings at a chamber using US EPA method 1.	Jilla & Kura. (2017)
	CO	110–120 g kg^{-1}		
	$PM_{2.5}$	7.7–205.4 g kg^{-1}	Chamber experiments with 10 incenses.	Lee & Wang. (2004)
	$PM_{2.5}$	11.09–23.38 g kg^{-1}	Chamber experiments with 4 incenses.	Kuo et al. (2016)
	$PM_{2.5}$	5.0–55.7 g kg^{-1}	23 tests were conducted in a specifically designed chamber, particles were collected on filters.	Jetter et al. (2002)
	PM_{10}	5.4–49.4 g kg^{-1}		
	$PM_{2.5}$	0.4–44.5 g kg^{-1}	6 brands of Singaporean incenses were burned. Filter samples were collected in a combustion chamber.	See & Balasubramanian. (2011)
	OC	0.01–1.79 g kg^{-1}		
	EC	0.26–29.5 g kg^{-1}		
	mercury	9.78–13.82 ng g^{-1}	Samplings at a traditional temple in China.	Shen et al. (2017)
	PAHs	8.81–9.14 mg kg^{-1}	Considering the impact of additions on PAHs emissions from incenses.	Yang et al. (2013)
	OC	21.4–49.2 mg kg^{-1}	-	This study
	BC	1.07–3.09 mg kg^{-1}		
Joss paper	PAHs	67.3–74.6 mg kg^{-1}	Samplings at two paper furnaces at temples.	Yang et al. (2005)
	mercury	4.67–13.16 ng g^{-1}	Samplings at a traditional temple in China.	Shen et al. (2017)
	$PM_{2.5}$	4.23±0.71 g kg^{-1}	Four types of sacrificial offerings were burned in an incinerator. Particles were sampled using a dilution tunnel.	Zhang et al. (2019)
	OC	1.26±0.42 g kg^{-1}		
	EC	0.63±0.28 g kg^{-1}		

	OC	14.6–75.5 mg kg^{-1}	-	This study
	BC	1.65–6.27 mg kg^{-1}		
Fireworks	TSP	67–140 g kg^{-1}	Fireworks were burned in a block room (41.2 m^3). Fireworks were put on preweighed aluminum foil and then ignited.	Croteau et al. (2010)
	K	23–45 g kg^{-1}		
	Mg	1.3–6.8 g kg^{-1}		
	PM_{10}	54–429 g kg^{-1}	Fireworks were burned in a sampling chamber with four ventilators.	Camilleri & Vella. (2016)
	$PM_{2.5}$	200–325 g kg^{-1}	7 types of fireworks were tested in a measurement chamber.	Keller & Schragen. (2021)
	PM_{10}	134–281 g kg^{-1}		
	OC	5.86–124 mg kg^{-1}	-	This study
	EC	2.89–37.3 mg kg^{-1}		
Cooking	$PM_{2.5}$	2.06±3.03 mg min^{-1}	15 Chinese dishes, and considering influences of oil temperature, meat type, cooking method, and so on.	Zhao et al. (2018)
	$PM_{2.5}$	4.88±3.43 g h^{-1}	Sampling particle and VOCs in 18 traditional cuisine restaurants in Beijing.	Lin et al. (2021)
	OC	0.42–7.28 g h^{-1}		
	Carbonyl compounds	0.70–1.53 μg kg^{-1}	Laboratory tests, and considering cooking styles.	Xiang et al. (2017)
	VOCs	12–38 mg kg^{-1}	Laboratory sampling with a dilution system.	Cheng et al. (2016)
	VOCs	11.15–189.8 g h^{-1}	Samplings at restaurants of seven cuisine types.	Wang et al. (2018a)
	Carbonyl compounds	90.4–274 μg kg^{-1}	Test by US EPA Test Method 5G.	Que et al. (2019)
	PM	16.8–22.3 mg min^{-1}	Chamber samplings of PM.	Wang et al. (2018b)
	PAHs	79.9–270.6 ng min^{-1}	Samplings at a residential kitchen in Beijing.	Zhao et al. (2019)

	$PM_{2.5}$	19–39 mg kg^{-1}	Laboratory tests, direct samplings of particles without cooling and dilution process.	Wang et al. (2015)
	$PM_{2.5}$	0.1–9.2 g kg^{-1}	Laboratory tests, and the sampling system were devised according to the restaurant facility.	Lin et al. (2019)
	OC	124–203 mg kg^{-1}	-	This study
	BC	1.34–1.79 mg kg^{-1}		
Barbecue	$PM_{2.5}$	15.48±7.22 g h^{-1}	Sampling particle and VOCs in 18 traditional cuisine restaurants in Beijing.	Lin et al. (2021)
	OC	4.31–32.1 g h^{-1}		
	Carbonyl compounds	1.60 μg kg^{-1}	Laboratory tests, and considering cooking styles.	Xiang et al., 2017)
	PM_1	8.5–270 mg min^{-1}	Laboratory tests, grilling meat 12 min on 550–600 °C. Considering the influences of the burner, pan, meat, and salt.	Amouei Torkmahalleh et al. (2018)
	Carbonyl compounds	191μg kg^{-1}	Test by US EPA Test Method 5G	Que et al. (2019)
	VOCs	41 mg kg^{-1}	Laboratory sampling with a dilution system.	Cheng et al. (2016)
	$PM_{2.5}$	21 mg kg^{-1}	Laboratory tests, direct samplings of particles without cooling, and diluted process.	Wang et al. (2015)
	OC	21.5–50.5 mg kg^{-1}	-	This study
	BC	1.66–191 mg kg^{-1}		

Table S4 Emission amounts of air pollutants from FMS or other sources.

Sources	Region	Pollutant	Time	Emission amount	References
Total	China	OC	2000–2014	2345–3587 Gg	Huang et al. (2015)
Residential & commercial				1675–2931 Gg	
Total	China	BC	2000–2014	1455–1624 Gg	Wang et al. (2014)
Residential & commercial				1061–1589 Gg	
Total	China	OC	2008–2017	2080–3190 Gg	Li et al. (2017)
		BC		1253–1728 Gg	
Residential		OC		1689–2512 Gg	
		BC		626–828 Gg	
Cooking in restaurants	China	VOCs	-	66245 t	Wang et al. (2018a)
Household cooking	Individual household	$PM_{2.5}$	-	12.4 kg	Wang et al. (2015)
Household cooking	Beijing	$PM_{2.5}$	2015	3.99 Gg	Cai et al. (2018)
		NMVOCs		4.02 Gg	
Catering industry	China	$PM_{2.5}$	2017	38.2 Gg	Jin et al. (2021)
		OC		26.8 Gg	
		BC		0.8 Gg	
Barbecue	Individual household	$PM_{2.5}$	-	3.8 kg	Wang et al. (2015)
Sacrificial incense	China	OC	2000–2018	0.54–1.43 t	This study
Joss paper				38.5–105 t	
Fireworks				267–674 t	
Barbecue				14.8–35.3 t	
Cooking				4418–7443 t	
Sacrificial incense		EC		0.03–0.08 t	
Joss paper				3.49–9.50 t	
Fireworks				76.3–193 t	
Barbecue				47.3–109 t	
Cooking				41.3–69.6 t	

Reference

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