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Emission inventory of air pollutants and chemical speciation for specific anthropogenic sources based on local measurements in the Yangtze River Delta region, China

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Abstract: A high-resolution air pollutant emission inventory in the Yangtze River Delta (YRD) region was updated for the year 2017 using emission factors and chemical speciation mainly from local measurements in this study. The inventory includes 424 NMVOC species and 43 $PM_{2.5}$ species, which can be subdivided into 259 specific source categories. The total emissions of SO_2, NO_x, CO, NMVOCs, PM_{10}, $PM_{2.5}$, and NH_3 in the YRD region in 2017 are 1,552, 3,235, 38,507, 4,875, 3,770, 1,597, and 2,467 Gg, respectively. SO_2 and CO emissions are mainly from boilers, accounting for 49% and 73%, respectively. Mobile sources dominate the NO_x emissions and contribute 57% of the total. VOC emissions mainly come from industrial sources, occupying 61%. Dust sources take up to 55% and 28% of PM_{10} and $PM_{2.5}$ emissions, respectively. Agricultural sources account for 91% of NH_3 emissions. Major $PM_{2.5}$ species are OC, Ca, Si, PSO4 and EC, accounting for 9.0%, 7.0%, 6.4%, 4.6% and 4.3% of total $PM_{2.5}$

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emissions. The main species of VOCs are aromatics, accounting for 25.3%. OVOCs contribute 21.9% of total VOC emissions. Toluene has the highest comprehensive contribution to ozone and SOA formation potentials, and the others are 1,2,4-trimethylbenzene, m,p-xylene, propylene, ethene, o-xylene, ethylbenzene and so on. Industrial process and solvent use sources are the main sources of ozone and SOA formation potential, followed by motor vehicles. Among industrial sources, chemical manufacturing, rubber & plastic manufacturing, appliance manufacturing and textile have made relatively outstanding contributions. The inventory can provide scientific guidance for future joint control of air pollutants in the YRD region, China.

Key words: emission inventory; $PM_{2.5}$ species; VOC species; the Yangtze River Delta region; air pollutant emissions

1. Introduction

Air pollutant emissions from anthropogenic sources have attracted wide attentions due to their adverse impacts on air quality (Monks et al., 2009), human health (Guan et al., 2016; Requia et al., 2018), and climate change (Fiore et al., 2012). Air pollutants include gaseous compounds, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), carbon monoxide (CO), nonmethane volatile organic compounds (NMVOCs), ammonia (NH_3), etc., and particles with different sizes including PM_{10} and $PM_{2.5}$, whose aerodynamic diameter less than 10 and 2.5 μm. NMVOCs and $PM_{2.5}$ are aggregates of various chemical compositions. NMVOCs contains thousands of species such as alkanes, alkenes, aromatics and oxygenated organic compounds (OVOCs), and is the key precursor of ozone (O_3) and secondary organic aerosols (SOA). $PM_{2.5}$ is composed of a complex mixture, including sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+), organic carbon (OC), element carbon (EC), and various elements, which degrades visibility and threaten public health (Qiao et al., 2014; Liang et al., 2016).

Emission inventory (EI) is a key fundamental for air pollution source apportionment, air quality forecasting and decision-making of air pollutant control measures. In the last two decades, emission inventories have been improved both in

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global and regional scales. According to recently reported inventories, anthropogenic emissions still show growing trends in global scale (Janssens-Maenhout et al., 2015; Klimont et al., 2017; Crippa et al., 2018; Hoesly et al., 2018). China's air pollutant emission intensity is at a higher level in the world due to the increasing energy consumption, urbanization and motorization. However, China's emissions are undergoing dramatic changes especially in key regions, such as the Jing-Jin-Ji (JJJ), Yangtze River Delta (YRD), and Pearl River Delta (PRD) regions, with the efforts of air pollution prevention and control measures in these years (Cai et al., 2018; Zheng et al., 2018). Updating the EI has become very necessary.

The YRD region is located in East China and covers Jiangsu, Zhejiang, Anhui, and Shanghai, which has the most intensive economy, population and transportation and results in its highest emission level in China. According to the new released data by the Multi-resolution EI for China (MEIC, http://meicmodel.org/), the emission intensities per unit area of SO_2, NO_x, NMVOCs, $PM_{2.5}$, and NH_3 in the YRD region are 2.3, 4.5, 5.2, 3.4, and 3.0 times of the national average. We have established an EI for the core cities in the YRD region in 2007 (Huang et al., 2011). After that, Fu et al. (2013) updated the EI for Jiangsu, Zhejiang, and Shanghai in the YRD region in 2010. In the last five years, only individual provinces or part of sources were updated in the YRD region (Fan et al., 2016; Zhou et al., 2017; Huang et al., 2018a; Wang et al., 2018b; Chen et al., 2019; Yang and Zhao, 2019). Due to the implementation of air pollution prevention and control measures, $PM_{2.5}$ pollution in the YRD region has been significantly alleviated, and the regional energy, industry and vehicle fleet are undergoing great changes in recent years (Zheng et al., 2016; Wang et al., 2017a; Zhang et al., 2017a). Updating the activity levels for detailed sources in the YRD region can help to simulate air quality and guide emission reduction measures more accurately.

Besides of activity levels, speciation profiles of $PM_{2.5}$ and NMVOC emissions are also very important to improve the performance of chemical transport models (CTMs) in simulating O_3 mixing ratios and $PM_{2.5}$ concentrations. Source profiles from USEPA's

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SPECIATE database has been commonly used to conduct source apportionment and create speciated EI for air quality modeling since the 1990s (USEPA, 2009; Simon et al., 2010). However, emission characteristics of anthropogenic sources have considerable difference between different regions. Differences in fuel properties, operating conditions, raw materials, and after-treatment techniques can result in inconsistent speciation profiles for $PM_{2.5}$ and NMVOCs. A previous study indicates that using the speciation profiles from SPECIATE database leads to relatively poor model performance for trace elements at an urban site in Beijing, China (Ying et al., 2018). The emission estimates for individual NMVOC species differ between one and three orders of magnitude for some species when different sets of speciation profiles are used, which will lead to significant deviations in O_3 and SOA simulation (Li et al., 2014; Zhao et al., 2017; Stroud et al., 2018; Wang et al., 2018c). In view of its importance to model performance, detailed and observation-based emissions of individual speciated $PM_{2.5}$ and NMVOCs have become critical.

In this study, we updated an anthropogenic air pollutant EI in the YRD region for the year of 2017 using the emission factors (EFs) and $PM_{2.5}$ and NMVOCs speciation profiles mainly derived from local measurements. The pollutants include SO_2, NO_x, CO, NMVOCs, PM_{10}, $PM_{2.5}$, and NH_3. In addition, 424 individual NMVOC species including alkanes, alkenes, aromatics, haloalkanes, and OVOCs and 43 $PM_{2.5}$ species including OC, EC, ions, and elements were included in the inventory. To obtain detailed sources of emissions, the EI was refined to 259 specific source categories in 4 levels based on the fuel types, industrial sectors, equipment types, and emission level, etc. Finally, the EI was validated using Community Multiscale Air Quality (CMAQ) model and observations in the YRD region in 2017.

2. Materials and methods

2.1 Domain of this study

The YRD region in this study covers three provinces, including Jiangsu, Zhejiang, and Anhui provinces, as well as Shanghai municipality. The region has a land area of

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approximately 350,400 km^2, accounting for 3.7% of the whole China. However, the whole region produced a gross domestic product (GDP) of 2,893 billion USD, about 24% of the total national GDP in 2017, and growing at a rate of about 9.3% per year in the last decade (NBSC, 2018). Correspondingly, the region consumed 717.8 million tce of energy, about 17% of the national total in 2017. Coal is the main energy type in this region, contributing about 60% of total energy consumption (NBSC, 2018). The automobile population reached 40.9 million in 2017, occupying 19.6% of the total in China. The region also has a high concentration of traditional industries, producing 13.9%, 11.3%, 9.0%, 18.2% and 19.1% of the total products of gasoline, diesel, coke, cement, and crude steel in China in 2017 (NBSC, 2018). Figure 1 shows the domain of the YRD region in this study. The waters within the dashed line on the right figure are China's ship emission control areas. The ship emissions mentioned in this study are the summary of emissions in this region and inland waters in the YRD region.

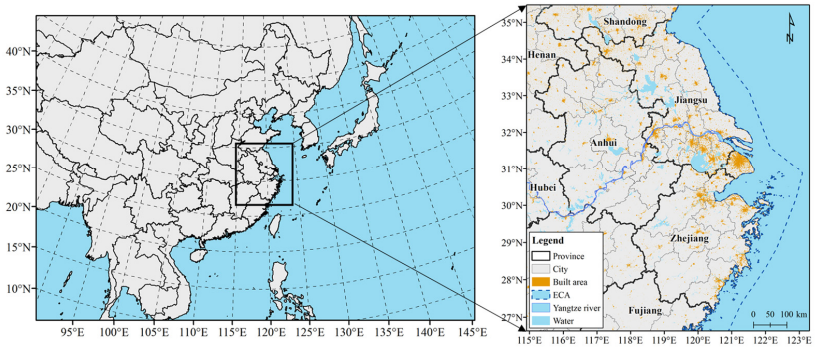

Figure 1. The domain of the YRD region in this study.

2.2 Sources classification

A total of 241 categories of emission sources in 4 levels were divided in this study. The first level is divided into 9 major sources, including stationary combustion sources, industrial process sources, industrial solvent-use sources, mobile sources, dust sources, oil storage and transportation sources, residential sources, waste treatment and disposal sources, and agricultural sources. The second level has a total of 36 source categories,

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mainly based on combustion facilities and industrial, transportation, residential, and agriculture sectors. The third-level classification is mainly based on fuel, product and material types, and contains a total of 127 categories. The fourth-level classification includes combustion types, emission segments, and control levels. Detailed classification is shown in Table S1 in the support information.

2.3 Emission estimation methods

The emissions of SO_2, PM_{10}, and $PM_{2.5}$ from stationary combustion sources are calculated using the mass balance method by Eq. (1) and (2). Other pollutant emissions are calculated using the EF method, as shown in Eq. (3).

$$E_{SO_2} = 2 \times S \times F \times C_s \times \left(1 - \eta_{SO_2}\right) \quad (1)$$

$$E_{PM} = A \times F \times C_A \times P_{ratio} \times (1 - \eta_{PM}) \quad (2)$$

$$E_{i,j} = AL_j \times EF_{i,j} \times \left(1 - \eta_{i,j}\right) \times 10^{-3} \quad (3)$$

Where, E_{SO2} and E_{PM} represent the emissions of SO_2 and PM_{10} or $PM_{2.5}$ (t). S and A represent fuel sulfur content and ash in fuel (%). F is the fuel consumption (t). Cs and C_A are the conversion efficiencies from sulfur and ash to SO_2 and PM (%). P_{ratio} is the mass percentage of PM_{10} or $PM_{2.5}$ in total PM. η_{SO2} and η_{PM} represent the removal efficiency of SO_2 and PM_{10} or $PM_{2.5}$. $E_{i,j}$ represents the emissions of pollutant i from source j (t). AL_j is the activity data of source j, such as fuel consumption, product output, and raw material consumption, etc. $EF_{i,j}$ is the EF of pollutant i from source j (kg per activity data). $H_{i,j}$ is the removal efficiency of pollutant i from source j.

Emissions from the industrial process sources are calculated using the EF method shown in Eq. (3). Emissions from industrial solvent-use sources are calculated using the mass balance method based on the consumption and VOC content of solvents, such as paints, coatings, inks, adhesives, thinners, etc. A small amount of VOC remaining in products, wastewater and waste was not considered in this calculation.

For motor vehicles, we use the International Vehicle Emission (IVE) model to calculate the emissions. However, the EFs and activity data including driving conditions,

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158 fleet composition, vehicle mileage travels (VMT), and meteorological parameters in the
159 model were localized via real-world measurements and surveys in this study. Non-road
160 machinery emissions are estimated with reference to the NONROAD model (USEPA,
161 2010), which is based on the fuel consumption and fuel-based emission factors. The
162 amount of fuel consumption is calculated based on the population, working hours and
163 fuel consumption rate per hour. Ship emissions are estimated using the approach based
164 on the Automatic Identification System (AIS) data. The detailed method has been
165 reported by Fan et al. (2016). Civil aviation aircraft source refers to aircraft emissions
166 under the land take-off (LTO) cycles, which include four operating modes, like
167 approaching, taxing, taking-off, and climbing. SO_2 emission from civil aviation aircraft
168 source is estimated using mass balance method. The sulfur content in aviation fuel is
169 0.068%, which is the default value provided in a previous study (Wayson et al., 2009).
170 NO_x, CO, and NMVOC emissions are estimated using the EF method, which multiplied
171 the fuel consumption rate by the EFs. PM emission is calculated using the FOA3.0
172 method (Wayson et al., 2009). The rated thrust and working hour of the aircraft in each
173 LTO mode are referenced to the recommended parameters by the International Civil
174 Aviation Organization (ICAO). The climbing mode specified by the ICAO refers to the
175 altitude of about 1 km from the end of take-off to the top of the boundary layer. However,
176 the height of boundary layer in the actual atmosphere will change with the
177 meteorological conditions. In this study, a meteorological model (WRF-v3.9.1) was
178 used to simulate the boundary layer height to correct the time of climbing mode.
179 Detailed description of the methodology for aviation emission estimation is provided
180 in our previous study (Wang et al., 2018b).

181 Emissions from the other sources (dust source, oil storage and transportation
182 source, residential source, waste treatment and disposal source, and agricultural source)
183 are all calculated using the EF method.

184 2.4 Activity data sources

185 The activity data related to the industrial sources (including stationary combustion

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sources, industrial process and solvent-use sources) of this study are mainly from the 2017 Environmental Statistics Database, which contains the information on fuel consumption, product output, raw material consumption, and removal technology and efficiencies. There are nearly 30,000 major point sources in the YRD region in the database. Considering that environmental statistics do not include all industrial sources, we take the difference between the total fuel consumption and product output in the statistical yearbook and the sum of environmental statistics for each city as an area source. To improve the accuracy of mobile source emissions, a number of local surveys on the activity data (such as population, vehicle or machine type, fuel type, and emission standard, etc.) were conducted for motor vehicles, non-road machinery, and aviation aircrafts. The activity data of ships come from the AIS data for the East China Sea in 2017. The activity data of area sources are derived from the statistical yearbooks of cities in the YRD region. For the sources whose activity data are not recorded in the statistical yearbooks (such as the number of construction sites, civil solvent usage, catering, biomass burning, etc.), we make some estimations based on statistical data, such as population, building area, and crop yield, etc. Table S2 in the support information summarizes the emission estimation methods and activity data sources for various sources and their reliability levels.

2.5 Determination of emission factors

The EFs of each specific emission source were determined by local measurements (or surveys) in the YRD region, domestic EI guidebook of China (MEP, 2014), and those recommended in USEPA's AP-42 (USEPA, 2002) and European's EMEP datasets (EEA, 2013) in turn. To minimize the uncertainty of the EI, this study localizes the EFs of 80 source categories, which include the majority of anthropogenic emission sources, such as coal-fired power plants and boilers (Yao et al., 2009; Zhao et al., 2010; Wang et al., 2011; Lou, 2014; Sun, 2015; Xu et al., 2018), petroleum refining and ferrous metal manufacturing (Guo et al., 2017), gasoline and diesel vehicles (Huang et al., 2016; Huang et al., 2017; Huang et al., 2018b; Huang et al., 2018c), non-road machinery (Fu

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et al., 2012; Fu et al., 2013; Ge et al., 2013; Qu et al., 2015; Li et al., 2016), and emissions from cooking (Wang et al., 2018a; Gao et al., 2019), livestock and poultry breeding (Chen, 2017; Zhou, 2019), N-fertilizer application (Chen et al., 2017; Xia et al., 2018), and biomass burning (Tang et al., 2014), etc. The NMVOC EFs for some evaporation loss sources, like industrial and residential solvent-use sources and oil storage and transportation sources, are estimated based on the results of field surveys of some typical sources in the YRD region. For the sources that have not been measured or investigated, the EFs recommended in the EI guidebook of China (MEP, 2014) are preferred, followed by the recommended factors in the USEPA's AP-42 (USEPA, 2002) and European's EMEP datasets (EEA, 2013). The EFs for each emission source and their references are provided in Table S1 in the supporting information.

2.6 $PM_{2.5}$ and NMVOC speciation

$PM_{2.5}$ and NMVOC emissions are further split into individual species to simulate $PM_{2.5}$ chemical components and O_3 mixing ratios in the atmosphere. There are 43 chemical species in $PM_{2.5}$, including OC, EC, sulfate (PSO4), nitrate (PNO3), ammonium (PNH4) and 36 elemental components such as Na, Mg, K, Ca, Al, and Si, etc. Additional species such as particulate water (H_2O), noncarbon organic matter (NCOM), metal bound oxygen (MO), and other unspeciated $PM_{2.5}$ (PMO) are calculated according to the method introduced by Reff et al. (2009). There are 424 species of VOCs, including 96 alkanes, 45 alkenes and alkynes, 44 aromatics, 164 OVOCs, 43 haloalkanes, and 32 other organic compounds.

The method for determining the $PM_{2.5}$ and NMVOC source profiles is similar to that for EFs. The results of local measurements are prioritized in this study, followed by domestic measurements in previous studies, and finally the USEPA's SPECIATE4.4 database (Hsu et al., 2014). To enhance the representativeness of source profiles in the inventory, the $PM_{2.5}$ chemical compositions of 34 sources and the NMVOC chemical compositions of 64 sources were localized according to the measurements in the YRD region. The source categories of localization for $PM_{2.5}$ profiles include power plants,

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coal-fired boilers, ferrous metal manufacturing, gasoline and diesel vehicles, non-road machinery, ships, catering, and biomass burning, etc. (Zheng et al., 2013; Tang et al., 2014; Huang et al., 2016; Xu et al., 2018). The localized NMVOC sources include coal combustion, gasoline and diesel vehicles, ships, catering, biomass burning, and the majority of industrial process and solvent-use sources, like petroleum refining, coke production, chemical manufacturing, textile, furniture manufacturing, package and printing, auto manufacturing, shipbuilding, and architectural coating, etc. (Wang et al., 2014a; Wang et al., 2014b; Wang et al., 2016; Wang et al., 2017b; Wang et al., 2017c; Huang et al., 2018d; Gao et al., 2019). Detailed information for the references, samples, and sampling and analytical methods for the sources are represented in Table S3. For the species which cannot be analyzed by the analytical methods, we supplement the mass fractions of these species from the SPECIATE database. Figure 2 and Figure 3 show the $PM_{2.5}$ and NMVOC speciation profiles of major sources in the YRD region, respectively.

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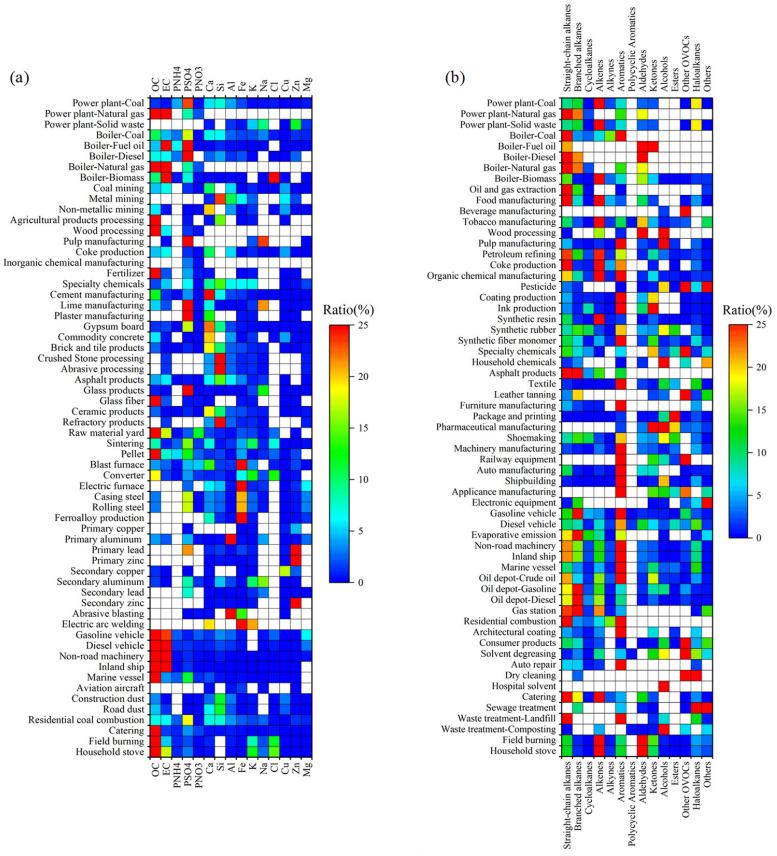

Figure 2. The speciation profile of $PM_{2.5}$ (a) and NMVOCs (b) for major emission sources.

2.7 Spatial distributions

Emissions from industrial sources, including power plants, boilers, industrial process and solvent-use sources, were allocated based on their latitude and longitude coordinates from Environmental Statistics Database. Vehicle emissions were determined based on the mileage sharing of various vehicle types on different levels of roads. The composition of traffic flow on different levels of roads was obtained from the surveys in Shanghai and Hangzhou (Huang et al., 2015; Yang et al., 2017). The approach of spatial allocation for road dust was consistent with vehicle emissions. The spatial distribution of emissions from non-road machinery varies in different ways depending on the type of machinery. The emissions from construction and agricultural machinery were allocated according to the built-up and farmland areas in the 2015 land

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use data released by European Space Agency (ESA) (https://www.esa-landcover-cci.org/). Emissions from port and factory machinery, and airport ground handling equipment were allocated according to their latitude and longitude coordinates. Emissions from residential sources were allocated based on 1 km resolved population distribution data. Those of agriculture sources were allocated based on the farmland areas in the land-use data.

2.8 Uncertainty analysis

The uncertainty is mainly derived from the activity data and EFs in the EI. In this study, we classify the coefficients of variation of the activity data and EFs of each source into seven grades in the range of 2%–100% based on expert judgment. The coefficient of activity data is determined based on the data source. The environmental statistic data with individual source information is assigned the lowest coefficient of uncertainties, while the estimated activity data based on statistical yearbooks such as biomass burning are assigned the highest values. The EFs derived from local measurements in the YRD region with large samples are assigned the lowest values, while those from USEPA's or European's datasets are assigned high coefficients. Detailed analysis method can be found in our previous study (Huang et al., 2011).

3. Results and discussion

3.1 Emission and source contributions

3.1.1 Emissions and their comparisons with previous studies

The total emissions of SO_2, NO_x, CO, NMVOCs, PM_{10}, $PM_{2.5}$, and NH_3 in the YRD region for the year of 2017 were 1,552, 3,235, 38,507, 4,875, 3,770, 1,597 and 2,467 Gg, respectively. If ship emissions were not included, the air pollutant emissions above would be 1,437, 2,936, 38,486, 4,867, 3,754, 1,583 and 2,467 Gg, respectively. Detailed information of air pollutant emissions for each city is shown in Table S1 in the Supplement.

Table 1 shows the emissions in the YRD region estimated in this study and their

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296 comparisons with previous studies. SO_2 emissions were close to the result in MEIC
297 2016, and were much lower than those reported in other studies in the past few years.
298 Emission reductions on coal-fired facilities including power plants and boilers were the
299 main reason for the significant decline in SO_2 emissions (Zheng et al., 2018). NO_x
300 emissions were generally lower than the results in previous studies. Some modeling and
301 satellite studies verified that the NO_x emissions in previous studies were overestimated
302 partly due to the failure to consider the improved NO_x control measures for power sector
303 (Zhao et al., 2018; Sha et al., 2019). The NO_x emission factors for coal-fired power
304 plants and boilers in this study were derived from local measurements which were
305 generally lower than those in previous studies, so the NO_x emissions from power sector
306 were 47% lower than MEIC. CO emissions were higher than MEIC's results but close
307 to those reported by Sun et al. (2018a). NMVOC emissions for key sources in this study
308 were individually estimated base on "bottom-up" method, so the estimates were lower
309 than the others who used "top-down" approach. Another reason is the majority of
310 emission factors selected in this study were detailed into different process segments,
311 which are generally lower than the comprehensive factors for whole industrial sectors
312 in the previous studies. Since dust sources were not included in MEIC inventory, PM_{10}
313 and $PM_{2.5}$ emissions estimated in this study were 1.7 and 0.5 times higher than the
314 results in MEIC, respectively. A previous study has pointed out that the existing NH_3
315 emissions in China were underestimated mainly due to the underestimate of NH_3
316 emission rates from fertilizer application and livestock and missing of some emission
317 sources (Zhang et al., 2017). Therefore, we used the local measured NH_3 emission
318 factors for fertilizer application and part of livestock breeding in the YRD region instead
319 in this study. Another difference came from transportation sector. NH_3 emissions from
320 transportation sector were 2.8 times higher than those in MEIC when localized NH_3
321 emission factors form light-duty gasoline vehicles (Huang et al., 2018) were used in
322 this study. In addition, NH_3 slip from selective catalyst reduction (SCR) devices in
323 power sector was also considered in this study. However, this emission source has not

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been included in previous studies.

Table 1. Air pollutant emissions in the YRD region in this study and their comparisons with other studies.

Regions	Data source	Base year	Annual air pollutant emissions (Gg/year)						
			SO_2	NO_x	CO	NMVOCs	PM_{10}	$PM_{2.5}$	NH_3
YRD	This study	2017	1437	2936	38486	4867	3754	1583	2467
	MEIC	2016	1136	3753	19560	5527	1374	1025	1153
	Simayi et al., 2019	2016				4984			
	Sun et al., 2018a	2015	3050	4160	30210	5490			
	Zhang et al., 2017b	2015							1632
	Wu et al., 2018	2013				6198			
Shanghai	This study	2017	57	225	1393	418	124	56	54
	MEIC	2016	168	345	1192	683	69	51	25
	Simayi et al., 2019	2016				728			
	Sun et al., 2018a	2015	550	470	2250	580			
	Zhang et al., 2017b	2015							50
	Wu et al., 2018	2013				838			
	Fu et al., 2013	2010	260	453		422	86	59	65
Jiangsu	This study	2017	619	1165	17309	2056	1440	577	1093
	MEIC	2016	468	1586	8191	2128	516	388	532
	Simayi et al., 2019	2016				2024			
	Sun et al., 2018a	2015	1230	1700	13780	2000			
	Zhang et al., 2017b	2015							703
	Wu et al., 2018	2013				2240			
	Zhou et al., 2017	2012	1142	1642	7680	1747	1394	941	1100
	Fu et al., 2013	2010	1126	1257		1759	619	401	976
Zhejiang	This study	2017	339	676	7036	1484	775	308	363
	MEIC	2016	280	867	3779	1671	219	151	159
	Simayi et al., 2019	2016				1624			
	Sun et al., 2018a	2015	730	980	5110	1810			
	Zhang et al., 2017b	2015							257
	Wu et al., 2018	2013				2214			
	Fu et al., 2013	2010	762	1067		1641	301	184	398
Anhui	This study	2017	422	869	12748	910	1415	642	957
	MEIC	2016	221	954	6398	1045	570	435	437
	Simayi et al., 2019	2016				608			
	Sun et al., 2018a	2015	540	1010	9070	1100			
	Sun et al., 2018b	2015	434	688				323	422
	Zhang et al., 2017b	2015							622
	Wu et al., 2018	2013				906			

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327 3.1.2 Source contributions

328 Figure 3 shows the contributions of emission sources divided by different source
329 categories (a), industrial sectors (b), and mobile source types (c). Detailed information
330 of the emissions from each source was provided in Table S5. SO_2 and CO emissions
331 were mainly from boilers, accounting for 49% and 73% of the total, respectively.
332 Notably the emission contributions of power plants were much lower than those in other
333 inventories (MEIC, http://meicmodel.org/; Zhou et al., 2017), resulting mainly from the
334 significant reduction in power plant emissions due to the implementation of ultra-low
335 emission reduction measures in recent years (Wu et al., 2019; Zhang et al., 2019).

336 Mobile sources dominated the NO_x emissions in the YRD region, which
337 contributed 57% of the total. This estimate was generally higher than the proportion of
338 mobile sources in MEIC and other inventories (Zhou et al., 2017; Sun et al., 2018a).
339 Emission control measures for power plants played an important role in reducing their
340 contributions on NO_x emissions. In addition, other studies did not include ship
341 emissions, which accounted for 16% of NO_x emissions from mobile sources in the YRD
342 region, as shown in Figure 3(c). Another reason that cannot be ignored was the NO_x
343 emission factors from gasoline and diesel vehicles were modified based on local
344 measurements in this study, which were generally higher than those recommended by
345 MEP (2014). Some real-world measurements based on portable emission measurement
346 system (PEMS), on-road chasing, and tunnel experiments also indicate that the NO_x
347 emissions from vehicles in China were higher than expected due to the existence of
348 high-emitting vehicles (Wu et al., 2012; Huang et al., 2017; Song et al., 2018; Wen et
349 al., 2019).

350 VOC emissions were mainly contributed by industrial sources, accounting for 61%
351 of the total, of which industrial process and solvent-use sources accounted for 34% and
352 27%, respectively. Mobile and residential sources contributed 20% and 10%,
353 respectively. Dust sources were main contributors to PM_{10} and $PM_{2.5}$ emissions,
354 occupied 55% and 28%, respectively. Agricultural sources contributed up to 91% of

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355 NH_3 emissions. In addition, residential and mobile sources contributed 3% and 1% of
356 NH_3 emissions, respectively. Although NH_3 emission factors from vehicles have been
357 considered in this study, their NH_3 emission was still significantly lower than
358 agricultural sources. However, vehicle emissions were mainly concentrated in urban
359 areas, and their contribution to NH_3 emissions in urban areas would be considerable.

360 Industrial SO_2 and CO emissions mainly came from five major sectors, including
361 petroleum refining, coking, chemical manufacturing, non-metallic mineral
362 manufacturing, and ferrous metal manufacturing. Non-metallic mineral manufacturing
363 and ferrous metal manufacturing dominated the industrial NO_x, PM_{10}, and $PM_{2.5}$
364 emissions. The top five sectors of industrial VOCs emissions in the YRD region were
365 chemical manufacturing, Furniture and wood manufacturing, Appliance manufacturing,
366 rubber and plastic manufacturing, and non-metallic mineral manufacturing, accounting
367 for 27%, 12%, 9%, 9%, and 6% of the total, respectively. Chemical manufacturing
368 contributed the majority of industrial NH_3 emissions in the YRD region.

369 The YRD region has the largest port group in the world, so the emissions from the
370 transportation of ships and heavy-duty trucks dominate the mobile source emissions.
371 Among them, ships accounted for 94%, 16%, 12%, and 12% of mobile source SO_2,
372 NO_x, PM_{10}, and $PM_{2.5}$ emissions, and heavy-duty trucks occupied 31%, 37%, and 36%
373 of mobile source NO_x, PM_{10}, and $PM_{2.5}$ emissions, respectively. Light-duty vehicles
374 contributed significantly to CO, VOCs, and NH_3 emissions, accounting for 61%, 46%,
375 and 90%, respectively. Non-road machinery accounted for 27%, 18%, 12%, 21%, and
376 22% of NO_x, CO, VOCs, PM_{10}, and $PM_{2.5}$ emissions from mobile sources, respectively.
377 Construction and agriculture machinery were major contributors.

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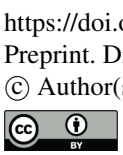

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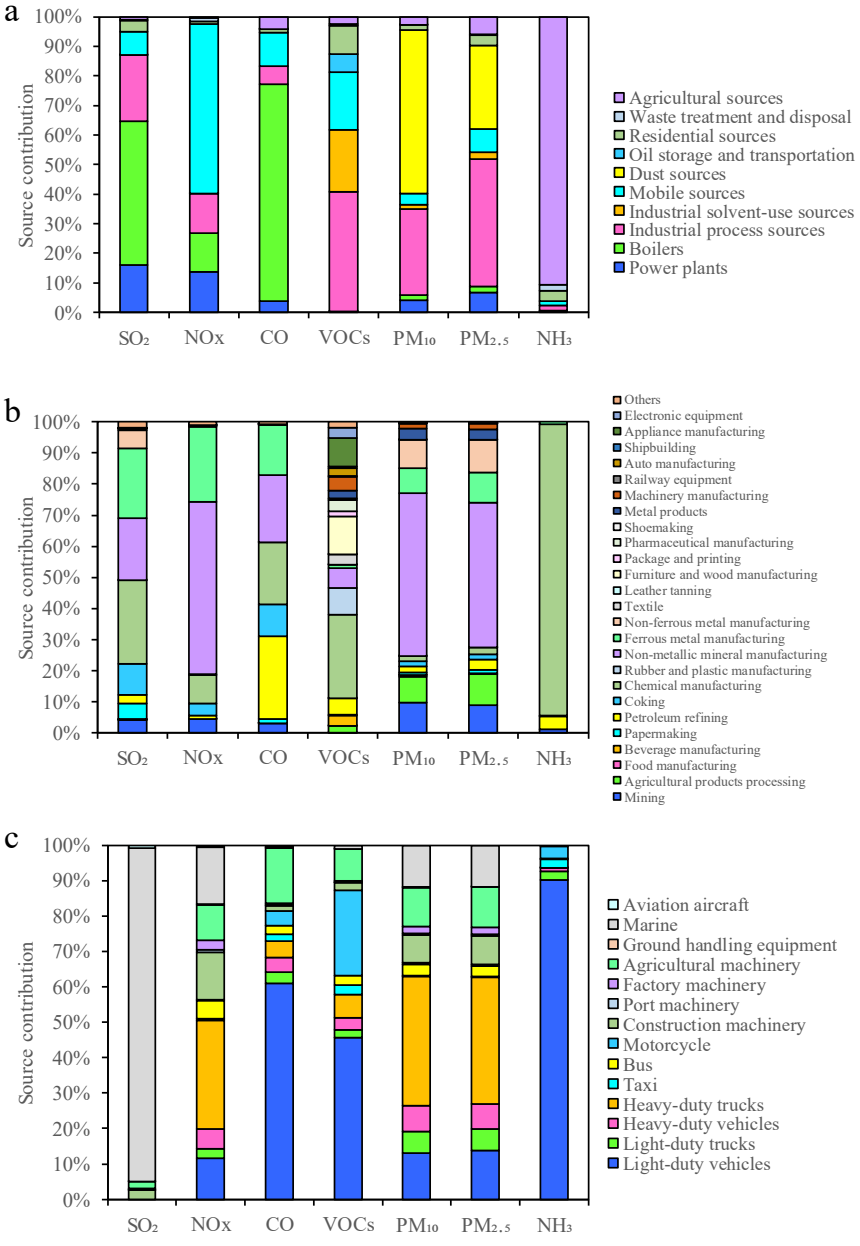

Figure 3. Source contributions of major air pollutant emissions in the YRD region. (a) Divided by major source categories; (b) Divided by detailed industrial sectors; (c) Divided by detailed mobile sources.

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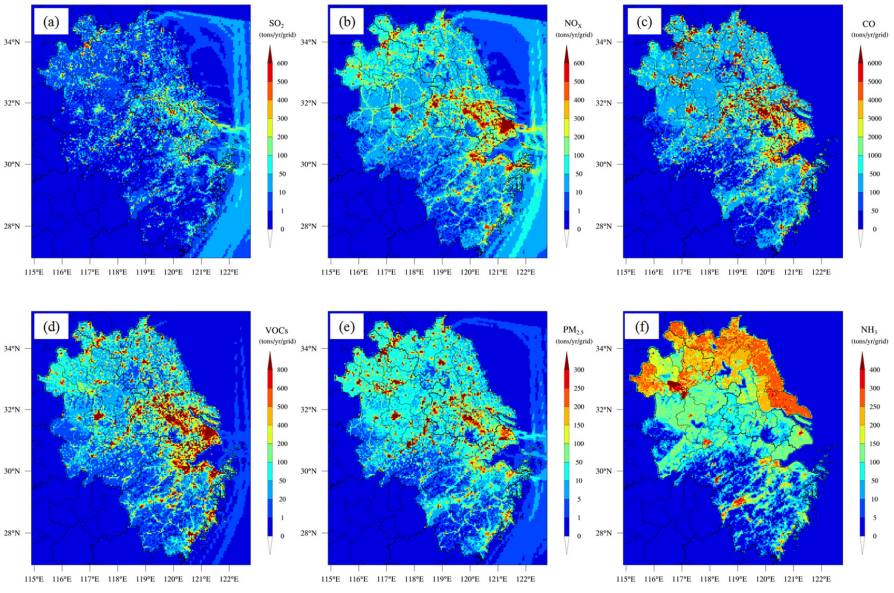
382 3.1.3 Spatial distribution

383 Fig. 4 shows the spatial allocation of SO_2, NO_x, CO, NMVOCs, $PM_{2.5}$, and NH_3
384 emissions in the YRD region. SO_2 emissions were mainly concentrated in the Yangtze
385 River and East China Sea estuary, where ships were densely populated. SO_2 emissions
386 along the Yangtze River and in the cities of northern Anhui and Jiangsu provinces were
387 also dense, mainly from power plants and boilers in these regions. The spatial
388 distribution of NO_x and NMVOCs was similar, mainly concentrated along the Yangtze
389 River and Hangzhou Bay, where the industries and logistics were most developed. CO
390 and $PM_{2.5}$ emissions were mainly concentrated in the built-up areas of cities due to
391 intensive road traffic and human activities such as construction sites. NH_3 emissions
392 were relatively high in northern Anhui and Jiangsu provinces, resulting mainly from
393 their developed agriculture. The contribution of NH_3 emissions from residential and
394 mobile sources has led to higher NH_3 emission densities for large cities such as
395 Shanghai.



396

397 **Figure 4.** Spatial distribution of major air pollutant emissions in the YRD region. (a)~(f) refer to
398 SO_2, NO_x, CO, VOCs, $PM_{2.5}$, and NH_3 in turn.

399 Figure 5 shows the spatial distribution of major industrial sectors of NO_x and

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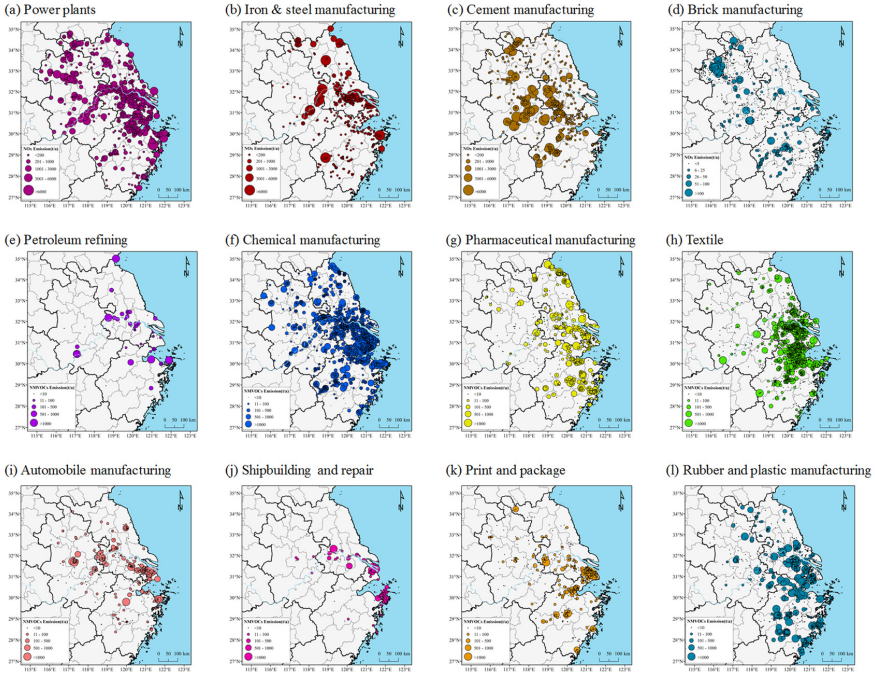
400 VOCs emissions in the YRD region. There were large differences in the spatial
401 distribution of different industrial sectors. The power plants were mainly distributed
402 along the Yangtze River and Hangzhou Bay and the northern part of the YRD region.
403 The iron & steel manufacturing sector was concentrated along the Yangtze River.
404 Cement and brick manufacturing sectors were mainly distributed in the western and
405 northern regions of the YRD. In comparison, the key sectors of VOC emissions (Figure
406 5(e)~(l)) were mainly concentrated in the central and eastern regions of the YRD,
407 including Shanghai, Suzhou, Wuxi, Changzhou, Nanjing, Hangzhou, Ningbo, Jiaxing,
408 and Shaoxing, etc., which also had the strongest NO_x emission intensities in the YRD
409 region. High intensities of NO_x and VOC emissions are the key factors leading to
410 serious pollution of ozone and secondary particulate matter in this region (Li et al., 2018;
411 Li et al., 2019). Refining the specific industrial sectors of emissions can help to find out
412 the detailed sources inducing air pollution.



413
414 **Figure 5.** Spatial distribution of major NO_x and VOC emission sources in the YRD region.

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415 3.1.4 Uncertainty assessment

416 The inventory was compiled using a "bottom-up" approach based on local
417 emission factors and activity data in the region. The activity data of industrial sources,
418 including fuel consumption, sulfur content, ash content, raw material used, and control
419 efficiency, were collected from Environmental Statistics Database. Emission factors
420 from some key sources, such as coal-fired power plants and boilers, iron & steel
421 manufacturing, gasoline and diesel vehicles, non-road machinery, catering, and
422 agricultural sources, etc., have been modified based on the local measurements. These
423 all help to reduce the uncertainty of the emission estimates. Table 2 shows the
424 uncertainties of major sources at the 95% confidence interval in this inventory. The
425 average uncertainties of emissions from the YRD region were estimated as -29 to 36%
426 for SO_2, -28 to 33% for NO_x, -42 to 75% for CO, -44 to 68% for NMVOCs, -36 to 62%
427 for PM_{10}, -30 to 46% for $PM_{2.5}$, and -58 to 117% for NH_3. The uncertainty of this
428 inventory was reduced compared to our previous inventory for the YRD region (Huang
429 et al., 2011).

430 The uncertainty assessment indicates that the stationary combustion sources
431 including power plants and boilers were more reliable, because the emissions were
432 estimated based on the detailed activity data and local measurements. The uncertainties
433 of major industrial sectors, such as ferrous metal manufacturing, non-ferrous metal
434 manufacturing, and non-metallic mineral manufacturing, were greatly improved when
435 using detailed emission estimation approach for different process segments. In
436 comparison, the emissions from chemical manufacturing still have large uncertainties
437 since there are a large number of process segments and unorganized emissions. The
438 uncertainties of emissions from vehicles and non-road machinery in this study mainly
439 came from the activity data. Although their population could be obtained from the
440 statistical yearbooks, their mileage travels or working hours were still difficult to
441 estimate accurately. Dust emissions including construction and road dust have much
442 higher uncertainties due to less information of their activity data and emission factors

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was available. Most of the area sources, like residential and agricultural sources, were estimated based on the activity data from statistical yearbooks, resulting in higher uncertainties of their emission estimates. Overall, using of emission estimation approach based on refined process segments and local measurements can help to reduce the uncertainties of EI. However, more detailed activity data and accurate emission factors are still very critical to improve the EI in the future.

Table 2. Uncertainty assessment of major emission sources in the YRD region.

Sources	SO_2	NOx	CO	NMVOCs	PM_{10}	$PM_{2.5}$	NH_3
Power plants	(-25%, 28%)	(-33%, 15%)	(-26%, 27%)	(-28%, 22%)	(-24%, 29%)	(-25%, 28%)	(-45%, 76%)
Boilers	(-29%, 38%)	(-23%, 27%)	(-24%, 30%)	(-19%, 23%)	(-24%, 30%)	(-24%, 30%)	(-46%, 56%)
Petroleum refining	(-49%, 84%)	(-45%, 72%)	(-51%, 90%)	(-40%, 57%)	(-53%, 60%)	(-53%, 64%)	(-39%, 62%)
Chemical manufacturing				(-71%, 167%)			
Ferrous metal manufacturing				(-41%, 61%)	(-23%, 48%)	(-12%, 34%)	
Non-ferrous metal manufacturing	(-37%, 78%)	(-42%, 62%)		(-44%, 70%)	(-38%, 60%)	(-52%, 94%)	
Non-metallic mineral manufacturing	(-48%, 75%)	(-46%, 71%)	(-47%, 72%)	(-45%, 69%)	(-44%, 74%)	(-43%, 68%)	
Vehicles		(-38%, 55%)	(-48%, 73%)	(-46%, 69%)	(-50%, 83%)	(-44%, 67%)	(-55%, 98%)
Non-road machinery	(-47%, 75%)	(-44%, 66%)	(-57%, 112%)	(-50%, 86%)	(-46%, 76%)	(-45%, 77%)	
Construction dust					(-56%, 104%)	(-57%, 102%)	
Road dust					(-35%, 71%)	(-43%, 68%)	
Oil storage and transportation sources				(-43%, 69%)			
Residential solvent-use				(-57%, 116%)			
Residential combustion	(-64%, 143%)	(-44%, 79%)	(-70%, 88%)	(-68%, 165%)	(-43%, 66%)	(-43%, 66%)	(-44%, 72%)
Biomass burning	(-66%, 171%)	(-62%, 124%)	(-67%, 153%)	(-65%, 142%)	(-66%, 149%)	(-66%, 152%)	(-68%, 159%)
Livestock and poultry farming							(-67%, 148%)
Fertilizer application							(-78%, 213%)
Overall	(-29%, 36%)	(-28%, 33%)	(-42%, 75%)	(-44%, 68%)	(-36%, 62%)	(-30%, 46%)	(-58%, 117%)

3.2 $PM_{2.5}$ and VOC species emissions

3.2.1 $PM_{2.5}$ species

Figure 6 shows the emissions and source contributions of major $PM_{2.5}$ species in the inventory. OC, Ca, Si, PSO4, and EC were top five components in primary $PM_{2.5}$ in the YRD region, accounting for 9.0%, 7.0%, 6.4%, 4.6%, and 4.3% of $PM_{2.5}$ emissions, respectively. There were large differences in the emission contributions of different $PM_{2.5}$ species. Among the industrial sources, non-metallic mineral manufacturing sector had largest contributions to Ca, Si, and Al emissions, accounting for 51.6%,

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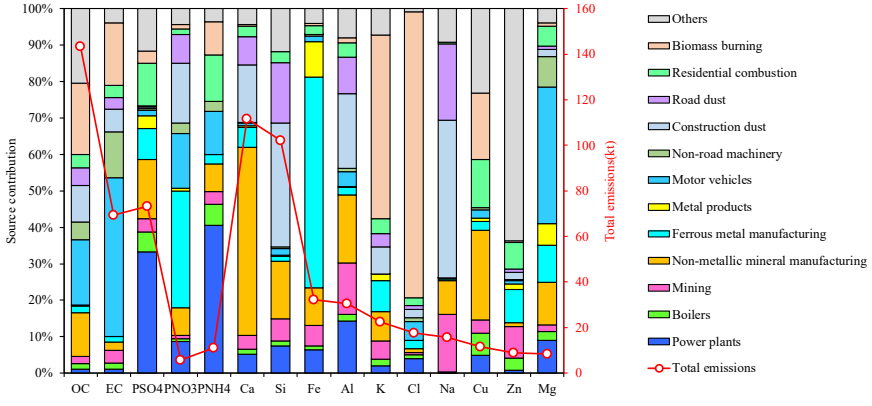
458 15.9%, and 18.8% of these species, respectively. Ferrous metal manufacturing was the
459 main source of Fe emissions, accounting for 57.9%. Vehicles was major contributors to
460 OC and EC emissions, taking up 18.0% and 43.5%, respectively. K and Cl emissions
461 mainly came from biomass burning, accounting for 50.4% and 78.5%, respectively.
462 Construction dust was also an important source of $PM_{2.5}$ components, accounting for
463 15.9%, 34.1% and 20.4% of Ca, Si, and Al emissions, respectively.



464
465 **Figure 6.** Emissions and source contributions of major $PM_{2.5}$ species in the YRD region.

466 3.2.2 VOC species

467 Figure 7 shows VOC species emissions and their source contributions. The
468 aromatics dominated the VOC species, accounting for 25.3% of the total VOC
469 emissions in the YRD region, followed by the alkanes, occupying 24.7%. Among them,
470 the straight-chain, branched, and cycloalkanes took up 11.9%, 9.9%, and 2.8%,
471 respectively. OVOCs also accounted for a considerable proportion of VOC emissions
472 in the YRD region, about 21.9% of the total. Among them, the aldehydes, ketones,
473 alcohols and esters took up 5.0%, 4.4%, 9.0% and 3.5%, respectively. In addition, the
474 haloalkanes occupied about 3.1% of the total VOC emissions. The aromatics were also
475 dominant species in VOC emissions in the YRD region in a previous study reported by
476 Wu et al. (2017), even higher (40%) than the proportion in ours. The proportion of
477 OVOCs was quite close to our study, while the proportion of alkenes and haloalkanes
478 were generally lower than ours.

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The chemical manufacturing accounted for a considerable proportion of various VOC species in the YRD region, accounting for 12.7%, 21.5%, 13.7%, and 10.8% of the alkanes, alkenes, aromatics, and OVOC emissions, respectively. Industrial solvent-use sources, including furniture and wood processing, textile, package and printing, pharmaceutical manufacturing, metal products, auto manufacturing, and appliance manufacturing, etc., were also an important source of VOC emissions in this region, which occupied 29.3% and 33.3% of the aromatics and OVOC emissions, while residential solvent-use sources accounted for 23.7% and 4.9% of the aromatics and OVOC emissions in the YRD region. Motor vehicles also have a very important contribution to various VOC species in the YRD region, occupying 31.2%, 10.4%, 15.1%, and 10.5% of the alkanes, alkenes, aromatics, and OVOC emissions in the region. Biomass burning contributed 12.0% of the aldehyde emissions, although it accounted for only 2.5% of the total VOC emissions in the region.

Overall, the refinement of VOC source profiles can help to provide an important support for assessing the impacts of VOC emissions on ambient air quality in the region. However, there are still considerable differences of VOC composition in different studies. It is necessary to strengthen the verification of VOC species emissions in the future.

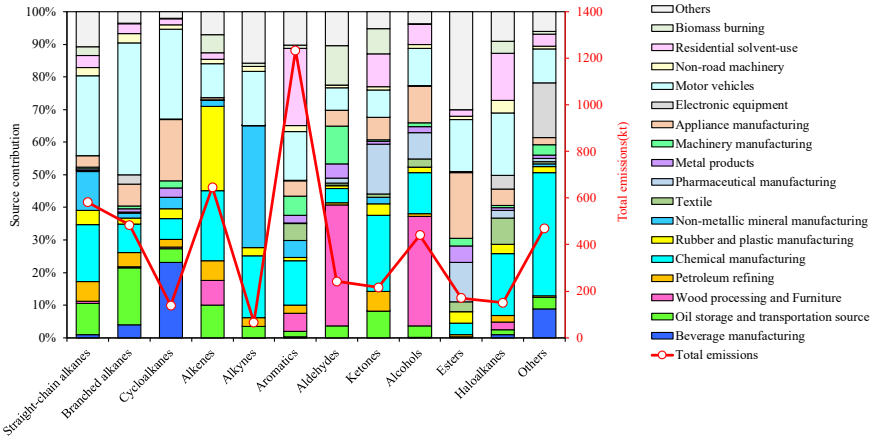

Figure 7. Emissions and source contributions of major VOC species in the YRD region.

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499 3.3 Model validation

500 To verify the reliability of the emission inventory, we used the Community
501 Modeling and Analysis System (CMAQ version 5.3) to simulate the concentrations of
502 SO_2, NO_2, $PM_{2.5}$, PM_{10}, O_3, and CO in the YRD region in January and July 2017, and
503 compared with the observation data in each city of the region. The Weather Research
504 and Forecast (WRF) version 3 supplied the meteorological field for CMAQ model. The
505 emission inventory developed in this study was used to produce the emission system in
506 the YRD region while emission beyond YRD was supplied by Multiresolution Emission
507 Inventory for China (MEIC-2016) (http://www.meicmodel.org). The anthropogenic
508 data was then combined with the biogenic data from Model for Emissions of Gases and
509 Aerosol from Nature (MEGAN version 2.10) as the final input of emission inventory
510 for the model. Figure S1 and Table S6 show the domain and settings of model system,
511 respectively. Detailed information is provided in the Supporting information Section 6.
512 Figure 8 compares the simulated concentration for SO_2, NO_2, $PM_{2.5}$, PM_{10}, O_3, and
513 CO in January and July 2017 in the YRD region with those of the observation data. The
514 simulated concentration distribution of various pollutants is consistent with the
515 observation results, which indicates the updated inventory generally reflects the
516 distribution of air pollution sources in the YRD region. Comparatively, the consistency
517 between the simulated concentration distribution and the observed results of the cities
518 in the central areas of the YRD region is stronger than those of the northern and southern
519 border areas. This is mainly because the concentration in the border areas is more
520 susceptible to the effects of emissions from the outer areas, which leads to greater
521 simulation results deviation. Detailed statistical results of the model performance for
522 simulating various pollutants in each city is shown in Table S7 of the supporting
523 information. Overall, the simulation results of O_3 were relatively high in January, while
524 SO_2, NO_2, $PM_{2.5}$, PM_{10}, and CO were relatively low. While in July, except that the O_3
525 simulation concentrations were slightly higher than the observed results, the average
526 NO_2 simulation values were consistent with the measured averages, other pollutants

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were relatively lower.

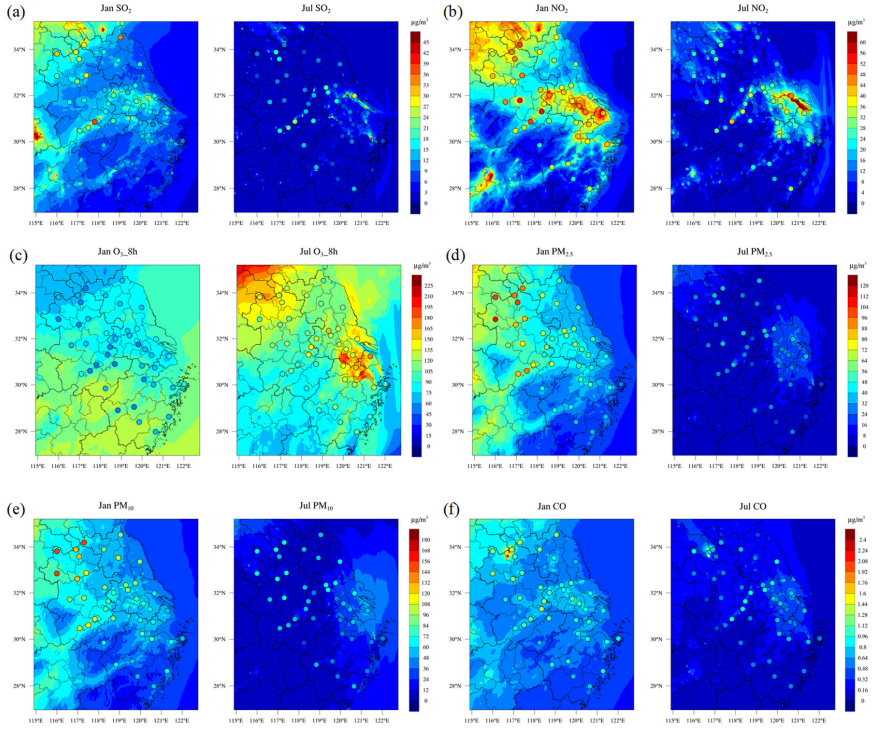

Figure 8. Comparisons of simulated and observed (circles) monthly average concentrations of SO_2, NO_2, daily maximum 8-hour of O_3 (O_3_8h), $PM_{2.5}$, PM_{10}, and CO in cities in the YRD region in January and July 2017.

3.4 Ozone and SOA formation potentials

To characterize the regional ozone and SOA formation contributions of different VOC species and their sources, we used ozone formation potential (OFP) and SOA formation potential (SOAP) methods to estimate. OFP and SOAP are the sum of individual VOC species emissions multiplied by maximum incremental reactivity (MIR) and SOA yield, respectively. The MIR and SOA yield of individual VOC species was referenced from previous studies (Carter, 1994; Wu and Xie, 2017).

Figure 9 shows the OFP and SOAP contributions from major VOC species, emission sources, and industrial sectors in the region. In terms of individual species, toluene is the most important species for both OFP and SOAP, which contributed 45.0%

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of the total (7.5% OFP and 37.5% SOAP), followed by 1,2,4-trimethylbenzene, contributing 29.1% of the total (2.1% OFP and 27.0% SOAP). Others were m/p-xylene, propylene, ethene, o-xylene, ethylbenzene, etc., their contributions to both OFP and SOAP were 14.9%, 16.6%, 10.7%, 5.7%, and 2.7% in turn. Their OFP contribution was relatively more prominent.

Industrial process sources dominated the OFP and SOAP in the region, which contributed 44.9% and 26.7%, respectively. Industrial solvent-use sources followed, with OFP and SOAP contributions of 15.0% and 33.8%, and their contribution to SOAP even exceeded the industrial process sources. The contributions of motor vehicles to regional OFP and SOAP were 13.9% and 13.5%, respectively, which was close to those from residential solvent-use sources. These two sources were major contributors of ozone and SOA formation in urban areas.

There are four major industrial sectors with significant potential contribution to ozone and SOA production in the YRD region. The chemical manufacturing sector contributed 16.4% and 14.8% of OFP and SOAP, respectively. The second was rubber & plastic manufacturing sector, with a SOAP contribution rate of 11.8%, while its OFP was relatively low, about 1.2%; the third and fourth were appliance manufacturing and textile sectors, accounting for 10.5% and 10.4% of both OFP and SOAP contributions.

Based on the above, it can be concluded that the reduction of aromatic emissions from industrial and vehicular sources were of vital importance for the YRD region, especially for the high reactivity species, such as toluene, xylene, and trimethylbenzene, etc., which should be the top priority on VOCs pollution control in the region.

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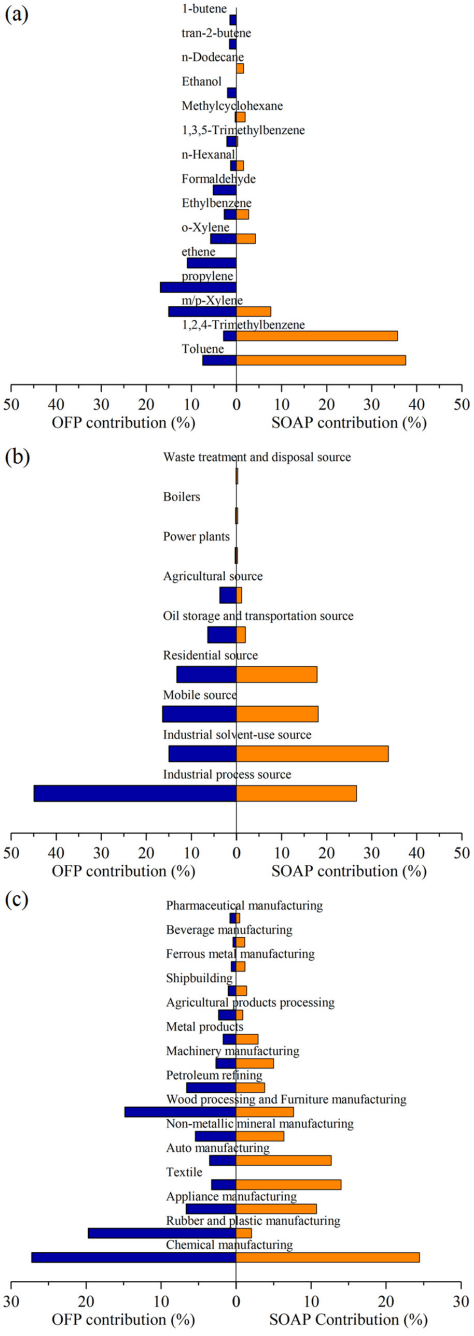

Figure 9. Ozone and SOA formation potentials from different (a) VOC species, (b) emission sources, and (c) industrial sectors.

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4. Conclusions

A high-resolution air pollutant emission inventory in the YRD region was updated using emission factors mainly from local measurements in this study. In addition to the conventional pollutants, 424 NMVOCs and 43 $PM_{2.5}$ components were also included. Source categories were divided into 4 levels and 259 specific sources. The results indicate that the total emissions of SO_2, NO_x, CO, NMVOCs, PM_{10}, $PM_{2.5}$, and NH_3 in the YRD region in 2017 are 1,552, 3,235, 38,507, 4,875, 3,770, 1,597, and 2,467 Gg, respectively. Overall, the SO_2 and NO_x emissions estimated in this study are lower than the existing EIs such as MEIC. The substantial reductions in power plants and boilers in recent years are the main reason. The VOC emissions is also slightly lower than the results of the previous studies, which is mainly due to the fact that this study uses emission factors refined to the process segments, which are usually lower than the comprehensive emission factors. Due to the consideration of dust sources, PM_{10} and $PM_{2.5}$ emissions are 1.7 times and 0.5 times higher than MEIC, respectively. The NH_3 emissions of this study are estimated using localized emission factors, and the results are significantly higher than those of previous studies.

SO_2 and CO emissions are mainly from boilers, accounting for 49% and 73% of the total. Mobile sources dominate the NO_x emissions from anthropogenic sources in the YRD region, accounting for 57% of the total. VOC emissions mainly come from industrial sources, accounting for 61%. The main industrial sectors are chemical manufacturing and solvent-use sources like furniture manufacturing, appliance manufacturing, textile, package and printing, and machinery manufacturing. 55% and 28% of PM_{10} and $PM_{2.5}$ come from dust sources, respectively. Agricultural sources account for 91% of NH_3 emissions.

Major $PM_{2.5}$ species emitted from anthropogenic sources in the YRD region are OC, Ca, Si, PSO4 and EC, which account for 9.0%, 7.0%, 6.4%, 4.6% and 4.3% of total primary $PM_{2.5}$ emissions. The main species of VOCs are aromatics, accounting for 25.3%. OVOCs also occupy a relatively high proportion, accounting for 21.9%. Among

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595 them, aldehydes, ketones, alcohols, and esters account for 5.0%, 4.4%, 9.0% and 3.5%,
596 respectively. Toluene has the highest comprehensive contribution to ozone and SOA
597 formation potentials, and the others are 1,2,4-trimethylbenzene, m,p-xylene, propylene,
598 ethene, o-xylene, ethylbenzene and so on. Industrial process and solvent use sources
599 are the main sources of ozone and SOA formation potential, followed by motor vehicles.
600 Among industrial sources, chemical manufacturing, rubber & plastic manufacturing,
601 appliance manufacturing and textile have made relatively outstanding contributions.

602 In recent years, the ambient air quality in the YRD region has improved
603 significantly. At the same time, the contributions of air pollutant emissions have also
604 been subtly changing in these years. The emissions of primary pollutants such as SO_2
605 and NO_x from power plants and boilers have dropped significantly, but the contribution
606 of mobile sources has become increasingly prominent, and the emissions of reactive
607 organic compounds from industrial sources are still at a high level, resulting in
608 outstanding secondary pollution issues. We hope that the EI in detailed sources and
609 species established in this study can provide scientific guidance for future joint control
610 of air pollutants in the YRD region, China.

611 **Acknowledgement**

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614 2018YFC0213800), and the Shanghai Municipal Bureau of Ecology and Environment
615 Fund Project (Grant No. 2019-01).

616 **Data availability**

617 The gridded emissions of air pollutants for Yangtze River Delta developed by this
618 study at a horizontal resolution of 4 × 4km can be downloaded from website
619 (https://doi.org/10.6084/m9.figshare.12720938). Additional related data is available
620 upon request by contacting the corresponding author (Cheng Huang;
621 huangc@saes.sh.cn).

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Author contribution

C.H., H.W. and C.C. designed the research. J.A., Y.H., X.W., R.Y., Q.W., Y.L., and C.X. performed the research. H.W. and S.J. collected the NMVOC species data. L.Q., M.Z., and S.Z. collected the $PM_{2.5}$ species data. C.H., Q.H., and J.L. supported the emission factor data. J.A., Y.H., C.H., X.W., H.L., Y.Z., Y.C., and C.C. analyzed the results. J.A., Y.H, C.H., and X.W. wrote the paper.

Competing interests

The authors declare that they have no conflict of interest.

References

Cai, S. Y., Ma, Q., Wang, S. X., Zhao, B., Brauer, M., Cohen, A., Marting, R. V., Zhang, Q. Q., Li, Q. B., Wang, Y. X., Hao, J. M., Frostad, J., Forouzanfar, M. H., and Burnettk, R. T.: Impact of air pollution control policies on future $PM_{2.5}$ concentrations and their source contributions in China, J. Environ. Manage., 227, 124–133, 2018.

Carter, W. P. L.: Development of ozone reactivity scales for volatile organic compounds, J. Air Waste Manage. Assoc., 44, 881–899, 1994.

Chen, D. S., Tian, X. L., Lang, J. L., Zhou, Y., Li, Y., Guo, X. R., Wang, W. L., and Liu, B.: The impact of ship emissions on $PM_{2.5}$ and the deposition of nitrogen and sulfur in Yangtze River Delta, China, Sci. Total Environ., 649, 1609–1619, 2019.

Chen, Y.: Study on characteristics ammonia emission from typical large scale pig farm in Shanghai, Master Thesis, East China University of Science and Technology. (in Chinese).

Chen, Y., Fang, X. F., Shen, G. X., Xu, C., Qian, X. Y., Zhao, Z. G., Yu, S. F., Li, J. W., and Wang, Z. Q.: Research on ammonia emission characteristics and its influencing factors from paddy fields in Taihu Lake region, Acta Agriculturae Zhejiangensis, 29, 119−128, 2017 (in Chinese).

Crippa, M., Guizzardi, D., Muntean, M., Schaaf, E., Dentener, F., van Aardenne, J. A., Monni, S., Doering, U., Olivier, J. G. J., Pagliari, V., and Janssens-Maenhout, G.: Gridded emissions of air pollutants for the period 1970–2012 within EDGAR v4.3.2, Earth Syst. Sci. Data, 10, 1987–2013, 2018.

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020

European Environment Agency (EEA): EMEP/EEA air pollution emission inventory guidebook, http://www.eea.europa.eu/publications/emep-eea-emission-inventory-guidebook-2013, 2013.

Fan, Q. Z., Zhang, Y., Ma, W. C., Ma, H. X., Feng, J. L., Yu, Q., Yang, X., Ng, S. K. W., Fu, Q. Y., and Chen, L. M.: Spatial and seasonal dynamics of ship emissions over the Yangtze River Delta and East China Sea and their potential environmental influence, Environ. Sci. Technol., 50, 1322−1329, 2016.

Fiore, A. M., Naik, V., Spracklen, D. V., Steiner, A., Unger, N., Prather, M., Bergmann, D., Cameron-Smith, P. J., Cionni, I., Collins, W. J., Dalsøren, S., Eyring, V., Folberth, G. A., Ginoux, P., Horowitz, L. W., Josse, B., Lamarque, J., MacKenzie, I. A., Nagashima, T., O'Connor, F. M., Righi, M., Rumbold, S. T., Shindell, D. T., Skeie, R. B., Sudo, K., Szopa, S., Takemurat, T., and Zeng, G.: Global air quality and climate, Chem. Soc. Rev., 41, 6663–6683, 2012.

Fu, M. L., Ge, Y. S., Tan, J. W., Zeng, T., and Liang, B.: Characteristics of typical non-road machinery emissions in China by using portable emission measurement system, Sci. Total Environ., 437, 255–261, 2012.

Fu, M. L., Ding, Y., Yin, H., Ji, Z., Ge, Y. S., and Liang, B.: Characteristics of agricultural tractors emissions under real-world operating cycle, Transactions of the Chinese Society of Agricultural Engineering, 29, 42–48, 2013 (in Chinese).

Fu, X., Wang, S. X., Zhao, B., Xing, J., Cheng, Z., Liu, H., and Hao, J. M.: Emission inventory of primary pollutants and chemical speciation in 2010 for the Yangtze River Delta region, China, Atmos. Environ., 70, 39–50, 2013.

Gao, Y. Q., Wang, H. L., Xu, R. Z., Jing, S. A., Liu, Y. H., and Peng, Y. R.: Characterization of volatile organic compounds from cooking emissions, Huanjing Kexue, 40, 1627–1633, 2019 (in Chinese).

Ge, Y. S., Liu, H. K., Ding, Y., Yin, H., Fu, M. L., and Li, J. Q.: Experimental study on characteristics of emissions and fuel consumption for combines, Transactions of the Chinese Society of Agricultural Engineering, 29, 41–47, 2013 (in Chinese).

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020

Atmospheric Chemistry and Physics Discussions

678 Guan, W. J., Zheng, X. Y., Chung, K. F., and Zhong, N. S.: Impact of air pollution on the burden
679 of chronic respiratory diseases in China: time for urgent action, Lancet, 388, 1939–1951,
680 2016.
681 Guo, Y. Y., Gao, X., Zhu, T. Y., Luo, L., and Zheng, Y.: Chemical profiles of PM emitted from
682 the iron and steel industry in northern China, Atmos. Environ., 150, 187–197, 2017.
683 Hoesly, R. M., Smith, S. J., Feng, L., Klimont, Z., Janssens-Maenhout, G., Pitkanen, T., Seibert,
684 J. J., Vu, L., Andres, R. J., Bolt, R. M., Bond, T. C., Dawidowski, L., Kholod, N.,
685 Kurokawa, J. I., Li, M., Liu, L., Lu, Z., Moura, M. C. P., O'Rourke, P. R., and Zhang, Q.:
686 Historical (1750–2014) anthropogenic emissions of reactive gases and aerosols from the
687 Community Emissions Data System (CEDS), Geosci. Model Dev., 11, 369–408, 2018.
688 Huang, C., Chen, C. H., Li, L., Cheng, Z., Wang, H. L., Huang, H. Y., Streets, D. G., Wang, Y.
689 J., Zhang, G. F., and Chen, Y. R.: Emission inventory of anthropogenic air pollutants and
690 VOC species in the Yangtze River Delta region, China, Atmos. Chem. Phys., 11, 4105–
691 4120, 2011.
692 Huang, C., Wang, H. L., Li, L., Wang, Q., Lu, Q., de Gouw, J. A., Zhou, M., Jing, S. A., Lu, J.,
693 and Chen, C. H.: VOC species and emission inventory from vehicles and their SOA
694 formation potentials estimation in Shanghai, China, Atmos. Chem. Phys., 15, 11081–
695 11096, 2015.
696 Huang, C., Lou, S. R., Qiao, L. P., Jing, S. A., Tao, S. K., Zhou, M., and Chen, C. H.:
697 Physicochemical characteristics of real-world PM emissions from heavy-duty diesel buses,
698 Research of Environmental Sciences, 29, 1352–1361, 2016 (in Chinese).
699 Huang, C., Tao, S. K., Lou, S. R., Hu, Q. Y., Wang, H. L., Wang, Q., Li, L., Wang, H. Y., Liu,
700 J. G., Quan, Y. F., and Zhou, L. L.: Evaluation of emission factors for light-duty gasoline
701 vehicles based on chassis dynamometer and tunnel studies in Shanghai, China, Atmos.
702 Environ., 169, 193–203, 2017.
703 Huang, C., An, J. Y., and Lu, J.: Emission inventory and prediction of non-road machineries in
704 the Yangtze River Delta region, China, Huanjing Kexue, 39, 3965–3975, 2018a (in
705 Chinese).

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020

706 Huang, C., Hu, Q. Y., and Lu, J.: Measurements of OC and EC emission factors for light-duty
707 gasoline vehicles, Huanjing Kexue, 39, 3110–3117, 2018b (in Chinese).
708 Huang, C., Hu, Q. Y., Lou, S. R., Tian, J. J., Wang, R. N., Xu, C., An, J. Y., Ren, H. J., Ma, D.,
709 Quan, Y. F., Zhang, Y. J., and Li, L.: Ammonia emission measurements for light-duty
710 gasoline vehicles in China and implications for emission modeling, Environ. Sci. Technol.,
711 52, 11223−11231, 2018c.
712 Huang, C., Hu, Q. Y., Wang, H. Y., Qiao, L. P., Jing, S. A., Wang, H. L., Zhou, M., Zhu, S. H.,
713 Ma, Y. G., Lou, S. R., Li, L., Tao, S. K., Li, Y. J., and Lou, D. M.: Emission factors of
714 particulate and gaseous compounds from a large cargo vessel operated under real-world
715 conditions, Environ. Pollut., 242, 667−674, 2018d.
716 Hsu, Y., Divita, F., and Dorn, J.: SPECIATE version 4.4 database development documentation,
717 final report, EPA/600/R-13/307, 2014.
718 International Civil Aviation Organization (ICAO): ICAO Environmental Report 2013,
719 Montreal, Canada, 2014.
720 Janssens-Maenhout, G., Crippa, M., Guizzardi, D., Dentener, F., Muntean, M., Pouliot, G.,
721 Keating, T., Zhang, Q., Kurokawa, J., Wankmüller, R., Denier van der Gon, H., Kuenen,
722 J. J. P., Klimont, Z., Frost, G., Darras, S., Koffi, B., and Li, M.: HTAP_v2.2: a mosaic of
723 regional and global emission grid maps for 2008 and 2010 to study hemispheric transport
724 of air pollution, Atmos. Chem. Phys., 15, 11411–11432, 2015.
725 Jing, S. A., Wang, H. L., Zhu, H. L., Yang, Q., Lu, B., Xia, Y., Yu, C. G., Tao, S. K., Li, L., Lou,
726 S. R., Huang, C., Tang, W., and Jing, B. L.: Treatment status and emission characteristics
727 of volatile organic compounds from typical industrial sources, Huanjing Kexue, 39, 3091–
728 3095, 2018 (in Chinese).
729 Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., and
730 Schöpp, W.: Global anthropogenic emissions of particulate matter including black carbon,
731 Atmos. Chem. Phys., 17, 8681–8723, 2017.
732 Li, L., An, J. Y., Zhou, M., Qiao, L. P., Zhu, S. H., Yan, R. S., Ooi, C. G., Wang, H. L., Huang,
733 C., Huang, L., Tao, S. K., Yu, J. Z., Chan, A., Wang, Y. J., Feng, J. L., Chen, C. H.: An

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020

Atmospheric Chemistry and Physics Discussions

integrated source apportionment methodology and its application over the Yangtze River Delta region, China, Environ. Sci. Technol., 52, 14216−14227, 2018.

Li, L., An, J. Y., Huang, L., Yan, R. S., Huang, C., Yarwood, G.: Ozone source apportionment over the Yangtze River Delta region, China: Investigation of regional transport, sectoral contributions and seasonal differences, Atmos. Environ., 202, 269–280, 2019.

Li, M., Zhang, Q., Streets, D. G., He, K. B., Cheng, Y. F., Emmons, L. K., Huo, H., Kang, S. C., Lu, Z., Shao, M., Su, H., Yu, X., and Zhang, Y.: Mapping Asian anthropogenic emissions of non-methane volatile organic compounds to multiple chemical mechanisms, Atmos. Chem. Phys., 14, 5617–5638, 2014.

Li, Z., Zhang, K.S., Pang, K.L., and Di, B.F.: A fuel-based approach for emission factor development for highway paving construction equipment in China, J. Air Waste Manage. Assoc., 66, 1214–1223, 2016.

Liang, C. S., Duan, F. Q., He, K. B., and Ma, Y. L.: Review on recent progress in observations, source identifications and countermeasures of $PM_{2.5}$, Environ. Int., 86, 150–170, 2016.

Liu, Z. Q.: Study on the estimation of NO_x from thermal power industry in China, Master thesis, North China Electric Power University, China, Beijing, 2008 (in Chinese).

Lu, J., Huang, C., Hu, Q. Y., Yang, Q., Jing, B. L., Xia, Y., Lu, B., Tang, W., Lou, S. R., Tao, S. K., and Li, L.: Air pollutant emissions inventory of non-road machinery in typical cities in Eastern China, Huanjing Kexue, 38, 2738–2746, 2017 (in Chinese).

Lou, S. R.: Emission characteristics of $PM_{2.5}$ from medium and small capacity coal-fired boilers in service, Acta Scientiae Circumstantiae, 34, 3119–3125, 2014 (in Chinese).

Ministry of Environmental Protection (MEP), P.R. of China: Guidebooks for compiling air pollution emission inventories. Available via. http://www.zhb.gov.cn/gkml/hbb/bgg/201408/t20140828_288364.htm, 2014 (in Chinese).

Monks, P. S., Granier, C., Fuzzi, S., Stohl, A., Williams, M. L., Akimoto, H., Amann, M., Baklanov, A., Baltensperger, U., Bey, I., Blake, N., Blake, R. S., Carslaw, K., Cooper, O. R., Dentener, F., Fowler, D., Fragkou, E., Frost, G. J., Generoso, S., Ginoux, P., Grewe, V., Guenther, A., Hansson, H. C., Henne, S., Hjorth, J., Hofzumahaus, A., Huntrieser, H.,

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020


Atmospheric Chemistry and Physics Discussions

762 Isaksen, I. S. A., Jenkin, M. E., Kaiser, J., Kanakidou, M., Klimont, Z., Kulmala, M., Laj,
763 P., Lawrence, M. G., Lee, J. D., Liousse, C., Maione, M., McFiggans, G., Metzger, A.,
764 Mieville, A., Moussiopoulos, N., Orlando, J. J., O'Dowd, C. D., Palmer, P. I., Parrish, D.
765 D., Petzold, A., Platt, U., Pöschl, U., Prévôt, A. S. H., Reeves, C. E., Reimann, S., Rudich,
766 Y., Sellegri, K., Steinbrecher, R., Simpson, D., ten Brink, H., Theloke, J., van derWerf, G.
767 R., Vautard, R., Vestreng, V., Vlachokostas, C., and von Glasow, R.: Atmospheric
768 composition change – global and regional air quality, Atmos. Environ., 43, 5268–5350,
769 2009.
770 National Bureau of Statistics of China: China Statistical Yearbook 2018. China Statistics Press,
771 Beijing, 2018
772 Qiao, L. P., Cai, J., Wang, H. L., Wang, W. B., Zhou, M., Lou, S. R., Chen, R. J., Dai, H. X.,
773 Chen, C. H., and Kan, H. D.: $PM_{2.5}$ constituents and hospital emergency-room visits in
774 Shanghai, China, Environ. Sci. Technol., 48, 10406−10414, 2014.
775 Qu, L., He, L. Q., Hu, J. N., Jin, T. S., Zu, L., Wang, M. Y., and Song, J. H.: Characteristics of
776 $PM_{2.5}$ emissions and its carbonaceous components from construction machines under
777 different typical driving modes, Research of Environmental Sciences, 28, 1047–1052,
778 2015 (in Chinese).
779 Reff, A., Bhave, P. V., Simon, H., Pace, T. G., Pouliot, G. A., Mobley, J. D., and Houyoux, M.:
780 Emissions inventory of $PM_{2.5}$ trace elements across the United States, Environ. Sci.
781 Technol., 43, 5790–5796, 2009.
782 Requia, W. J., Adams, M. D., Arain, A., Papatheodorou, S., Koutrakis, P., and Mahmoud, M.:
783 Global association of air pollution and cardiorespiratory diseases: a systematic review,
784 meta-Analysis, and investigation of modifier variables. Am. J. Public Health, 108, S123–
785 S130, 2018.
786 Sha, T., Ma, X. Y., Jia, H. L., van der A, R. J., Ding, J. Y., Zhang, Y. L., Chang, Y. H.: Exploring
787 the influence of two inventories on simulated air pollutants during winter over the Yangtze
788 River Delta, Atmos. Environ., 206, 170–182, 2019.
789 Simayi, M., Hao, Y. F., Li, J., Wu, R. R., Shi, Y. Q., Xi, Z. Y., Zhou, Y., Xie, S. D.: Establishment

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020


Atmospheric Chemistry and Physics Discussions

790 of county-level emission inventory for industrial NMVOCs in China and spatial-temporal
791 characteristics for 2010–2016, Atmos. Environ., 211, 194–203, 2019.
792 Song, C. B., Ma, C., Zhang, Y. J., Wang, T., Wu, L., Wang, P., Liu, Y., Li, Q., Zhang, J. S., Dai,
793 Q. L., Zou, C., Sun, L. N., Mao, H. J.: Heavy-duty diesel vehicles dominate vehicle
794 emissions in a tunnel study in northern China, Sci. Total Environ., 637–638, 431–442,
795 2018.
796 Stroud, C. A., Makar, P. A., Zhang, J. H., Moran, M. D., Akingunola, A., Li, S. M., Leithead,
797 A., Hayden, K., and Siu, M.: Improving air quality model predictions of organic species
798 using measurement-derived organic gaseous and particle emissions in a petrochemical-
799 dominated region, Atmos. Chem. Phys., 18, 13531–13545, 2018.
800 Sun, W., Shao, M., Granier, C., Liu, Y., Ye, C. S., Zheng, J. Y.: Long-Term trends of
801 anthropogenic SO_2, NO_x, CO, and NMVOCs emissions in China, Earth's Future, 6, 1112–
802 1133, 2018a.
803 Sun, X. W., Cheng, S. Y., Lang, J. L., Ren, Z. H., Sun, C.: Development of emissions inventory
804 and identification of sources for priority control in the middle reaches of Yangtze River
805 Urban Agglomerations, Sci. Total Environ., 625, 155–167, 2018.
806 Sun, Y. Y.: Study on emission inventory and uncertainty assessment of multi-pollutants from
807 coal-fired power plants, Master thesis, Zhejiang University, China, Hangzhou, 2015 (in
808 Chinese).
809 Tang, X. B., Huang, C., Lou, S. R., Qiao, L. P., Wang, H. L., Zhou, M., Chen, M. H., Chen, C.
810 H., Wang, Q., Li, G. L., Li, L., Huang, H. Y., and Zhang, G. F.: Emission factors and PM
811 chemical composition study of biomass burning in the Yangtze River Delta Region,
812 Huanjing Kexue, 35, 1623–1632, 2014 (in Chinese).
813 U.S. Environmental Protection Agency (USEPA): Compilation of air pollutant emission Factors,
814 AP-42, 5th ed., Washington, DC, 2002.
815 U.S. Environmental Protection Agency (USEPA): Exhaust and crankcase emission factors for
816 non-road engine modeling-compression ignition, Washington, DC, 2010.
817 Wang, S., Zhu, F. H., Wang, H. M., Zuo, Y., Sun, X. L., Zhao, X. Y., Chen, H., and Liu, G.: Fine

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020


Atmospheric Chemistry and Physics Discussions

818 particle emission characteristics from coal-fired power plants based on field test, Acta
819 Scientiae Circumstantiae, 31, 630–635, 2011 (in Chinese).
820 Wang, J. D., Zhao, B., Wang, S. X., Yang, F. M., Xing, J., Morawska, L., Ding, A. J., Kulmala,
821 M., Kerminen, V., Kujansuu, J., Wang, Z. F., Ding, D., Zhang, X. Y., Wang, H. B., Tian,
822 M., Petäjä, T., Jiang, J. K., and Hao, J. M.: Particulate matter pollution over China and the
823 effects of control policies, Sci. Total Environ., 584–585, 426–447, 2017a.
824 Wang, H. L., Lou, S. R., Huang, C., Qiao, L. P., Tang, X. B., Chen, C. H., Zeng, L. M., Wang,
825 Q., Zhou, M., Lu, S. H., and Xu, X. N.: Source profiles of volatile organic compounds
826 from biomass burning in Yangtze River Delta, China, Aerosol and Air Quality Research,
827 14, 818–828, 2014a.
828 Wang, H. L., Qiao, Y. Z., Chen, C. H., Lu, J., Dai, H. X., Qiao, L. P., Lou, S. R., Huang, C., Li,
829 L., Jing, S. A., and Wu, J. P.: Source profiles and chemical reactivity of volatile organic
830 compounds from solvent use in Shanghai, China, Aerosol and Air Quality Research, 14,
831 301–310, 2014b.
832 Wang, H. L., Jing, S. A., Wang, Q., Huang, C., Lou, S. R., Qiao, L. P., and Li, L.: Measurement
833 and characterization of emissions of volatile organic compounds in solvent use, Research
834 of Environmental Sciences, 29, 1433–1439, 2016 (in Chinese).
835 Wang, H. L., Yang, Z. X., and Jing, S. A.: Volatile organic compounds (VOCs) source profiles
836 of industrial processing and solvent use emissions: a review, Huanjing Kexue, 38, 2617–
837 2628, 2017b (in Chinese).
838 Wang, H. L., Jing, S. A., Lou, S. R., Hu, Q. Y., Li, L., Tao, S. K., Huang, C., Qiao, L. P., and
839 Chen, C. H.: Volatile organic compounds (VOCs) source profiles of on-road vehicle
840 emissions in China, Sci. Total Environ., 607–608, 253–261, 2017c.
841 Wang, H. L., Jing, S. A., Lou, S. R., Tao, S. K., Qiao, L. P., Li, L., Huang, C., Lin, L., and Chen,
842 C. H.: Estimation of fine particle ($PM_{2.5}$) emission inventory from cooking: case study for
843 Shanghai, Huanjing Kexue, 39, 1971–1977, 2018a (in Chinese).
844 Wang, R. N., Huang, C., Ren, H. J., Yan, R. S., Hong, Z., Xu, C., Hu, Q. Y., An, J. Y., Dong, B.
845 N., and Li, L.: Air pollutant emission inventory from LTO cycles of aircraft in civil aviation

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020

Atmospheric Chemistry and Physics Discussions

846 airports in the Yangtze River Delta region, China, Acta Scientiae Circumstantiae, 38,
847 4472–4479, 2018b (in Chinese).
848 Wang, P., Ying, Q., Zhang, H. L., Hu, J. L., Lin, Y. C., and Mao, H. J.: Source apportionment
849 of secondary organic aerosol in China using a regional source-oriented chemical transport
850 model and two emission inventories, Environ. Pollut., 237, 756–766, 2018c.
851 Wayson, R. L., Fleming, G. G., and Lovinelli, R.: Methodology to estimate particulate matter
852 emissions from certified commercial aircraft engines, J. Air Waste Manage, 59, 91–100,
853 2009.
854 Wen, Y. F., Wang, H., Larson, T., Kelp, M., Zhang, S. J., Wu, Y., Marshall, J. D.: On-highway
855 vehicle emission factors, and spatial patterns, based on mobile monitoring and absolute
856 principal component score, Sci. Total Environ., 676, 242–251, 2019.
857 Wu, R. R. and Xie, S. D.: Spatial distribution of ozone formation in China derived from
858 emissions of speciated volatile organic compounds, Environ. Sci. Technol., 52, 8146−8156,
859 2018.
860 Wu, R. R. and Xie, S. D.: Spatial distribution of secondary organic aerosol formation potential
861 in China derived from speciated anthropogenic volatile organic compound emissions,
862 Environ. Sci. Technol., 52, 8146−8156, 2018.
863 Wu, R. L., Liu, F., Tong, D., Zheng, Y. X., Lei, Y., Hong, C. P., Li, M., Liu, J., Zheng, B., Bo,
864 Y., Chen, X. T., Li, X., Zhang, Q.: Air quality and health benefits of China's emission
865 control policies on coal-fired power plants during 2005–2020, Environ. Res. Lett., 14,
866 094016, 2019.
867 Wu, Y., Zhang, S. J., Li, M. L., Ge, Y. S., Shu, J. W., Zhou, Y., Xu, Y. Y., Hu, J. N., Liu, H., Fu,
868 L. X., He, K. B., Hao, J. M.: The challenge to NO_x emission control for heavy-duty diesel
869 vehicles in China, Atmos. Chem. Phys., 12, 9365–9379, 2012.
870 Xia, Y., Yang, Q., Xu, C., Lu, B., Tang, W., Jing, B. L., Lu, Q., Huang, C., and Lu, J.: Study on
871 high resolution NH_3 emission inventory based on analysis of large data for agriculture in
872 Hangzhou, Acta Scientiae Circumstantiae, 38, 661–668, 2018 (in Chinese).
873 Xu, J., Huang, C., Li, L., Chen, Y. H., Lou, S. R., Qiao, L. P., and Wang, H. Y.: Chemical

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020

Atmospheric Chemistry and Physics Discussions

composition characteristics of $PM_{2.5}$ emitted by medium and small capacity coal-fired boilers in the Yangtze River Delta Region, Huanjing Kexue, 39, 1493–1501, 2018 (in Chinese).

Yang, Y. and Zhao, Y.: Quantification and evaluation of atmospheric pollutant emissions from open biomass burning with multiple methods: a case study for the Yangtze River Delta region, China, Atmos. Chem. Phys., 19, 327–348, 2019.

Yang, Q., Huang, C., Lu, B., Jing, B. L., Xia, Y., Tang, W., Lu, Q., Lu, J., Xu, C., Gu, Z. Y.: Air pollutant emission inventory based on local emission source surveys in Hangzhou, China, Acta Scientiae Circumstantiae, 37, 3240–3254, 2017 (in Chinese).

Yao, Z. M., Teng, Y., Li, J., Wu, X. F., and Duan, N.: NO_x emission factors from medium and small layer burning boilers firing soft coal, Research of Environmental Sciences, 22, 1263–1268, 2009 (in Chinese).

Ying, Q., Feng, M., Song, D. L., Wu, L., Hu, J. L., Zhang, H. L., Kleeman, M. J., and Li, X. H.: Improve regional distribution and source apportionment of $PM_{2.5}$ trace elements in China using inventory-observation constrained emission factors, Sci. Total Environ., 624, 355–365, 2018.

Zhang, S. J., Wu, Y., Zhao, B., Wu, X. M., Shu, J. W., and Hao, J. M.: City-specific vehicle emission control strategies to achieve stringent emission reduction targets in China's Yangtze River Delta region, J. Environ. Sci., 51, 75–87, 2017a.

Zhang, X. M., Wu, Y. Y., Liu, X. J., Reis, S., Jin, J. X., Dragosits, U., van Damme, M., Clarisse, L., Whitburn, S., Coheur, P., Gu, B. J.: Ammonia emissions may be substantially underestimated in China, Environ. Sci. Technol., 51, 12089-12096, 2017b.

Zhang, Y., Bo, X., Zhao, Y., Nielsen, C. P.: Benefits of current and future policies on emissions of China's coalfired power sector indicated by continuous emission monitoring, Environ. Pollut., 251, 415–424, 2019.

Zhao, Y., Wang, S. X., Nielsen, C. P., Li, X. H., and Hao, J. M.: Establishment of a database of emission factors for atmospheric pollutants from Chinese coal-fired power plants, Atmos. Environ., 44, 1515–1523, 2010.

https://doi.org/10.5194/acp-2020-582
Preprint. Discussion started: 17 August 2020

902 Zhao, Y., Mao, P., Zhou, Y. D., Yang, Y., Zhang, J., Wang, S. K., Dong, Y. P., Xie, F. J., Yu, Y.
903 Y., and Li, W. Q.: Improved provincial emission inventory and speciation profiles of
904 anthropogenic non-methane volatile organic compounds: a case study for Jiangsu, China,
905 Atmos. Chem. Phys., 17, 7733–7756, 2017.
906 Zhao, Y., Xia, Y. M., Zhou, Y. D.: Assessment of a high-resolution NO_x emission inventory
907 using satellite observations: A case study of southern Jiangsu, China, Atmos. Environ., 190,
908 135–145, 2018.
909 Zheng, B., Tong, D., Li, M., Liu, F., Hong, C. P., Geng, G. N., Li, H. Y., Li, X., Peng, L. Q., Qi,
910 J., Yan, L., Zhang, Y. X., Zhao, H. Y., Zheng, Y. X., He, K. B., and Zhang, Q.: Trends in
911 China's anthropogenic emissions since 2010 as the consequence of clean air actions,
912 Atmos. Chem. Phys., 18, 14095–14111, 2018.
913 Zheng, J. J., Jiang, P., Qiao, W., Zhu, Y., and Kennedy, E.: Analysis of air pollution reduction
914 and climate change mitigation in the industry sector of Yangtze River Delta in China, J.
915 Clean Prod., 114, 314–322, 2016.
916 Zheng, M., Zhang, Y. J., Yan, C. Q., Fu, H. Y., Niu, H. Y., Huang, K., Hu, M., Zeng, L. M., Liu,
917 Q. Z., Pei, B., and Fu, Q. Y.: Establishing $PM_{2.5}$ industrial source profiles in Shanghai,
918 China Environmental Science, 33, 1354–1359, 2013 (in Chinese).
919 Zhou, Y. D., Zhao, Y., Mao, P., Zhang, Q., Zhang, J., Qiu, L. P., and Yang, Y.: Development of
920 a high-resolution emission inventory and its evaluation and application through air quality
921 modeling for Jiangsu Province, China, Atmos. Chem. Phys., 17, 211–233, 2017.
922 Zhou, Z. Q.: Study on characteristics ammonia emission from typical large scale dairy cow
923 farm in Shanghai, Master Thesis, East China University of Science and Technology, 2019
924 (in Chinese).
925