Appendix A

1. Methods and data

1.1 Emission inventory

1.1.1 Beijing

Table A1. The method and source of emissions inventory data in Beijing.

Source	Sector	Emission Estimate	Emission factor source	Activity data sources
Power and heating	Power sector	(1) SO_2, NO_x and PM: CEM (2) VOCs: EF	MCUAPE	Beijing Municipal Statistics Bureau
	Industrial heating sector	EF	(1) NO_x: source test data (2) Others: MCUAPE	Beijing Municipal Statistics Bureau
Industry	Chemical industry, printing, pharmaceutical manufacturing, automobile manufacturing, appliance surface coating, semiconductor and electronics industries, other industrial surface coating and other manufacturing industries	MB	NA	NA
	Cement	(1) SO_2, NO_x and PM: CEM (2) VOCs: EF	MCUAPE	Annual Environmental Statistics
Residential	Residential heating sector, commercial/consumer solvent use, solvent degreasing, dry cleaning, building coatings, adhesives, hospital and breakdown service	EF	MCUAPE	Beijing Municipal Statistics Bureau
Fugitive dust	Road dust	EF	Source test data	Beijing Municipal Statistics Bureau

Source	Sector	Emission Estimate	Emission factor source	Activity data sources
	Construction dust, agricultural tilling operation	EF	MCUAPE	Remote Sensing Interpretation
Transportation	Vehicles	EF	MCUAPE	Beijing Municipal Commission of Transport
	Construction machinery	EF	MCUAPE	System for pollution emission control of non-road mobile machinery
	Farm machinery	EF	MCUAPE	Beijing Municipal Bureau of Agriculture and Rural Affairs
	Aviation	EF	MCUAPE	Civil Aviation Administration of China
	Railways	EF	MCUAPE	China Railway Beijing Croup Co., Ltd
	Transportation and marketing of petroleum liquids	EF	MCUAPE	Beijing Municipal Statistics Bureau
Cooking	Commercial kitchens	EF	Source test data	Beijing Municipal Market Regulation
	Residential cooking	EF	Literature data	Beijing Municipal Statistics Bureau
Waste disposal	Solid waste disposal, denitrification and wastewater handling	EF	MCUAPE	Beijing Municipal Statistics Bureau
Fireworks	-	EF	Literature data	News report
Biogenic	-	EF	Source test data	Beijing Municipal Forestry and Parks Bureau
Agriculture	Livestock and poultry breeding, fertilizer management, crop production and agricultural soils, use of pesticides	EF	MCUAPE	Beijing Municipal Bureau of Agriculture and Rural Affairs

Note:
(1) CEM: continuous emission monitoring
(2) MB: material balance
(3) NA: not applicable

(4) EF: emission factor

(5) MCUAPE: Manual for the Complication of Urban Air Pollutant Emission (He et al., 2019)

1.1.2 the surrounding area

Table A2. The method and source of emission inventory data in Tianjin and Hebei.

Source	**Sector**	**Emission Estimate**	**Emission factor source**	**Activity data sources**
Power and heating	Power sector, industrial heating sector	EF	MCUAPE	National Bureau of Statistics
Industry	All industries	EF	MCUAPE	National Bureau of Statistics
Residential	Residential heating sector, commercial/consumer solvent use, solvent degreasing, dry cleaning, coatings building coatings, adhesives, hospital and breakdown service	EF	MCUAPE	National Bureau of Statistics
Fugitive dust	Road dust, construction dust, agricultural tilling operation	EF	MCUAPE	National Bureau of Statistics
Transportation	Vehicles	Report on the Statistical Bulletin of the Ecology and Environment in China	NA	NA
	Construction machinery, farm machinery, railways, navigation, transportation and marketing of petroleum liquids	EF	MCUAPE	National Bureau of Statistics
	Aviation	EF	MCUAPE	Civil Aviation Administration of China
Cooking	Commercial kitchens	EF	MCUAPE	Dazhongdianping
	Residential cooking	EF	MCUAPE	National Bureau of Statistics

Source	**Sector**	**Emission Estimate**	**Emission factor source**	**Activity data sources**
Waste disposal	Solid waste disposal, denitration and wastewater handling	EF	MCUAPE	National Bureau of Statistics
Fireworks		EF	MCUAPE	News report
Biogenic		EF	MCUAPE	National Bureau of Statistics
Agriculture	Livestock and poultry breeding, fertilizer management, crop production and agricultural soils, use of pesticides	EF	MCUAPE	National Bureau of Statistics

1.2 Model validation

We used the normalized mean bias (NMB), normalized mean error (NME), mean fractional bias (MFB) and mean fractional error (MFE) to quantitatively evaluate the model performance. The observation data come from 12 national observation stations of the Beijing Municipal Environmental Monitoring Center (BMEMC, http://www.bjmemc.com.cn/).

2. Model validation

The model performance for the 2019 baseline and 2020 baseline scenarios was validated and the analysis of the results is shown in Table A. In general, the simulated $PM_{2.5}$ concentration is lower (~20%) compared to the observations, while the performance is acceptable. The validation results suggest that the $PM_{2.5}$ concentration is well reproduced and can be used for further analysis.

3. Emission reduction in Beijing

3.1 Power and heating

The emissions from the power sector were significantly reduced as a result of the decline in power production and demand. According to the monthly reports of power plants from the emission permit system, the emissions during the quarantine period declined by 22.2% compared with 2019.

The emissions for heating were reduced, which come from residential boilers and industrial boilers. Firstly, during the pandemic, people no longer needed to work or go to school, so the heating in office or school buildings could be entirely shut off, which reduced energy consumption. Nearly 0.6 million students in college did not come back to Beijing until March. The energy use was reduced due to the fall in heating demand by about 3%. Secondly, the energy use for industrial heating was reduced due to the slowdown in economic growth. The value added of industrial enterprises above a designated size was used to illustrate the changes in the energy consumption of industry during the pandemic, which decreased by 14.7% year on year by price comparison.

3.2 Industry

During the pandemic, the production activities of industries and pollutant emissions were not exactly at full capacity. A series of industrial indicators were used to illustrate the changes in Beijing's industrial emissions during the pandemic. Firstly, the emission of individual enterprises from the petrochemical industry and cement sector come from the monthly reports of the emission permit system. The results indicate that the emissions from the petrochemical sector fell by 65.20%, and those of the cement sector decreased by 71.6% during the pandemic. Secondly, in key sectors, Beijing Municipal Bureau of Statistics (BMBS) released their production. Assuming that emission factors and control efficiency are frozen at their 2019 levels, the response of emissions is linear to the production. The production of motor vehicles, liquor, microcomputer equipment and mobile telephones above a designated size decreased by 68%, 70%, 21% and 27%, respectively, while the production of integrated circuits increased by 42%. Finally, for industries without production data, a linear additive relationship was assumed between the emissions and value added of industrial enterprises above a designated size. According to the data releases from BMBS , the added value of the mining and processing of nonmetal ores, printing, manufacture of foods, beverages, furniture, raw chemical materials and other industries fell by 65%, 40%, 27%, 74%, 70%, 34% and 22%, respectively, while that of medicines increased by 9.1%.

3.3 Residential

The residential energy use for heating and solvent use for consumer, commercial and laundry purposes were reduced during the pandemic, resulting from population confinement. The use of organic solvent coatings for buildings falls due to the decrease in area of newly built houses, which was reduced by 27% during the pandemic according to the data of BMBS. The use of solvents in automobile service, renovation and refurbishment was reduced by nearly 28% due to the sharp decline in vehicle operation during the pandemic. There was an observable increase in the use of solvents and VOC emissions in the hospital, with a lift of 8%.

3.4 Transportation

A report published by AutoNavi Holdings Limited showed that passenger traffic dropped significantly by 52% in February 2020 compared to 2019. Data released by BMBS revealed that the freight traffic of highways fell by 49.1% in February. As a result, the emissions reduction in pollutants from road traffic decreased by ~50% during the pandemic. A decrease of 30% in the use of non-road mobile machinery was observed during the pandemic due to the stoppage of construction sites according to the news reports. According to data published by Civil Aviation Administration of China (CAAC), the total aircraft movements fell by 70.6% in February. The diesel consumption of trains decreased by 25% due to the integrated effects of railway freight and passenger traffic, with an increase ratio of 3.8% for railway freight traffic and decline ratio of 86.4% for railway passenger traffic, respectively.

3.5 Fugitive dust

The emission of road dust was reduced by 52% due to the decreased traffic on the road during the pandemic. The emission from construction sites fell by nearly 30% due to the stoppage of construction sites during the pandemic, according to the news reports.

3.6 Cooking

The emissions from cooking were reduced, resulting from the integrated effects of household cooking and catering services. The revenue was applied to illustrate the emission change in catering services, which fell by 62% during the pandemic according to the data released by BMBS. A growth in emissions occurred in the household cooking due to the population confinement and offset the decrease in emissions from catering services. The emissions from household cooking increased by 88% due to the increase in edible oil resulting from population confinement. The edible oil use for urban areas during the pandemic was double than that of the previous year, attributed to the population confinement, while that of rural areas remained the same.

3.7 Municipal waste disposal

The generation of municipal waste fell by nearly 5% due to the decreased population in Beijing during the pandemic, and it drove down the emissions resulting from solid waste disposal operations.

3.8 Fireworks

Emissions are released from fireworks, which are usually used to celebrate Spring Festival. The Spring Festival occurred in February in 2020, while in January in 2019. The SO_2, PM_{10} and $PM_{2.5}$ emissions from fireworks in February increased from 0 t, 0 t and 0 t in 2019 to 11 t, 100 t and 72 t in 2020, respectively.

4. Emission reduction in surrounding regions

According to our study, the outbreak of the pandemic has caused conspicuous emission reductions in Beijing's surrounding regions (including Tianjin, Hebei). Figure A1 shows the updated emission inventory of Beijing's surrounding regions by month and sector.

The emissions presented decreasing trends from 2019 to 2020 in February. The major air pollutant emissions in the surrounding region in February of 2020 are estimated as follows: 43 kt of SO_2, 86 kt of NO_x, 125 kt of PM_{10}, 65 kt of $PM_{2.5}$, 89 kt of VOCs and 47 kt of NH_3. Compared with 2019, SO_2, NO_x, PM_{10}, $PM_{2.5}$, VOCs and NH_3 emissions in the surrounding regions were estimated to decrease by 4%, 23%, 21%, 14%, 15% and 1%, with a decrease of 8, 16, 15, 21, 8 and 6 percentage points compared with those of Beijing, respectively, indicating that the emission reductions in the surrounding area were lower than those of Beijing.

The most important sector identified by our estimates is the industry sector, which was the dominant source of SO_2, VOCs, PM_{10} and $PM_{2.5}$ emissions during the pandemic in 2019 and 2020, accounting for average values of 40%, 53%, 39% and 48% of total emissions, respectively, and is the second most important source of NO_x (35%) and NH_3 (5%). It is the dominant contributor to the reduction in SO_2 emissions, which accounted for 51% of SO_2 emission reduction. It is the second most important driver of NO_x, PM_{10}, $PM_{2.5}$, VOC and NH_3 emission reductions, contributing to 7%, 10%, 21%, 45% and 21% of their reductions. The emission reduction attributed to the operating level of major industries was much lower during the quarantine period than at the same time in 2019.

The fugitive dust sector is the dominant source of PM_{10}, to which it contributes average values of 38%. It is the third most important source of $PM_{2.5}$, accounting for 17% of the emissions. The fugitive dust sector was the driver of emission changes for PM_{10} and $PM_{2.5}$ in the pandemic of 2019–2020, which accounted for 82% and 59% of emission reductions, respectively. The reason for this is that the construction sites partially closed during the quarantine period.

The transportation sector is the dominant source of NO_x, with an average proportion of 42%. Specifically, for Tianjin, ships were the dominant source of NO_x, with emissions of 2 kt and a proportion of 20%. The transportation sector drives NO_x, NH_3 and VOCs emissions down and contributes to the reduction in $PM_{2.5}$ and PM_{10}. The transportation sector contributed to 88% of NO_x, 68% of NH_3, 47% of VOCs, 8% of $PM_{2.5}$ and 3% of PM_{10} emission reductions, respectively. The transportation sector, though accounting for only

13% of the VOC emissions, is the dominant contributor to the emissions reduction, with a decrease of 47% in the pandemic compared with 2019 levels, which is faster than that of any other emission source sector. The flow of vehicles in Tianjin and Hebei decreased by 55.9% and 50%, with reductions of 5.7 kt and 1.2 kt VOCs from vehicles, and the transport and marketing of liquid energy during the quarantine period, compared with the same time in 2019. The operating level of construction machinery declined during the quarantine period, which led to a decrease of 274 t in VOCs compared with its level in 2019. The emissions from ships reduced by 58 t VOCs, which is attributed to the decrease in the freight turnover and passenger traffic turnover of waterways, with proportions of 13.6% and 54.8%. VOC emissions decreased by 49 t and 64 t, because of lower air and train traffic flow during the quarantine period.

The residential sector is the second most important source of SO_2, $PM_{2.5}$ and VOCs, which accounted for 38%, 29% and 18% of total emissions, respectively. It is the third most important source of PM_{10}, contributing to 19% of the total emissions. The residential sector, though an important sector, is not a dominant contributor to the emissions reduction in the other pollutants, except for VOCs. It drives VOC emissions down by 1.0 kt, mainly due to the fall in demand to coat buildings, accounting for 7% of the reduction.

The power and heating sector accounted for 22% of SO_2 emissions, 19% of NO_x emission, 2% of PM_{10} emissions, 3% of $PM_{2.5}$ emissions, 3% of VOC emissions and 2% of NH_3 emissiona. The power and heating sector drove SO_2, NO_x and NH_3 down by 730 t, 1217 t and 78 t, respectively, in the quarantine period compared with the same time during 2019, which contributed to 41%, 5% and 11% of the reductions.

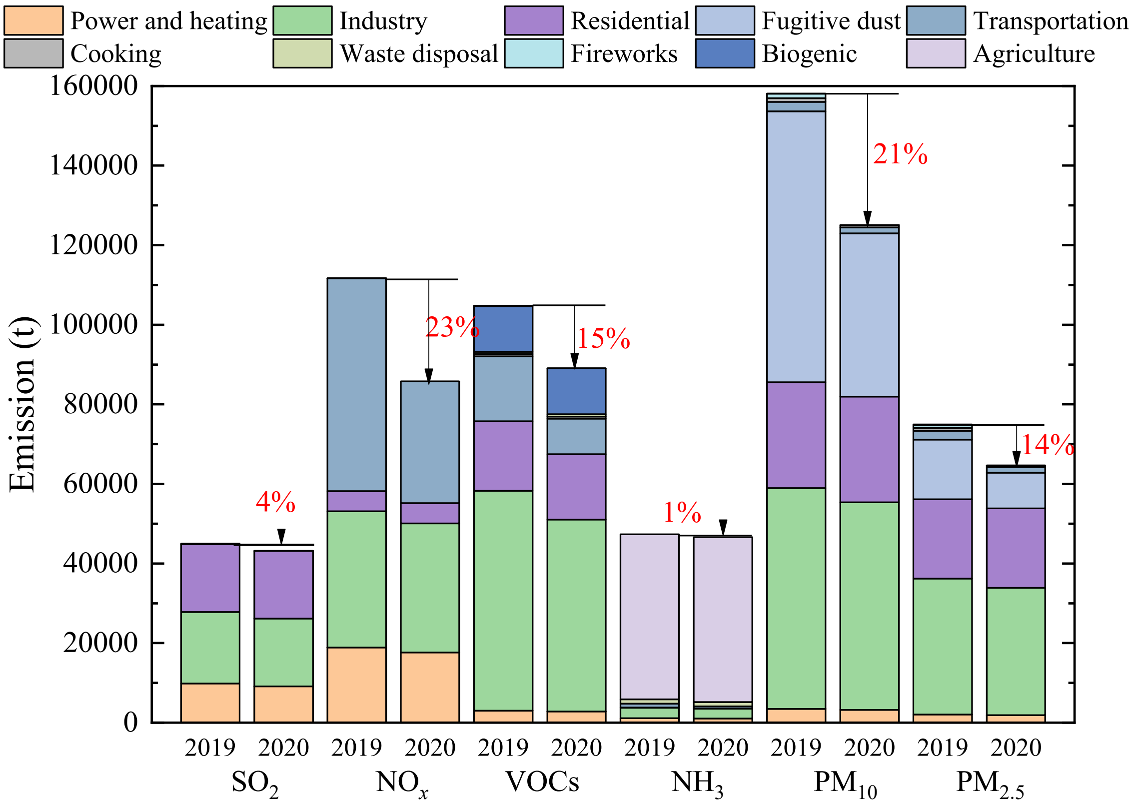

Figure A1. Changes in emissions of SO_2, NO_x, PM_{10}, $PM_{2.5}$, VOCs and NH_3 in Tianjing and Beijing during the quarantine period and at the same time in 2019.

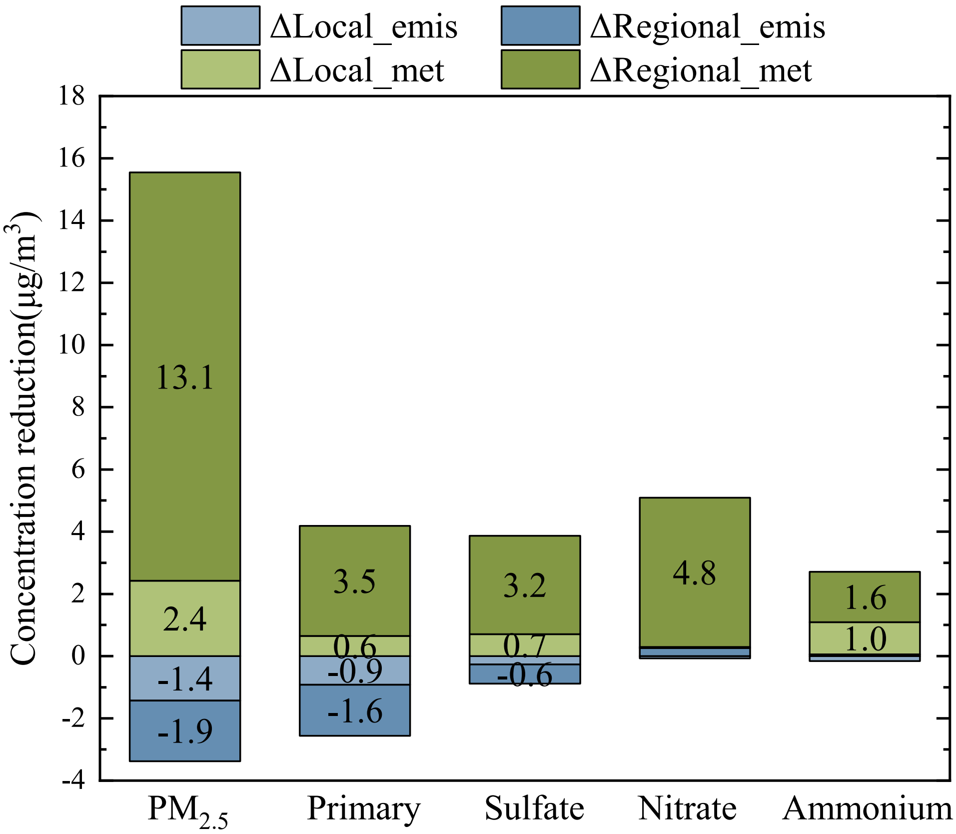

Figure A2. Contributions of different factors to the $PM_{2.5}$ concentrations.

Table A3. Comparisons of simulated 1-h $PM_{2.5}$ concentrations with observations (Obs: observation, Sim: simulation).

Baseline scenario	SIM	OBS	MFB	MFE	NMB	NME
2019	48	58	-4%	51%	-3%	54%
2020	59	64	16%	52%	1%	43%

Reference

He Kebing, 2017. Manual for the Complication of Urban Air Pollutant Emission, Beijing, China.