

Origin and radiative forcing of black carbon aerosol: production and consumption perspectives

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7 figures

5 tables

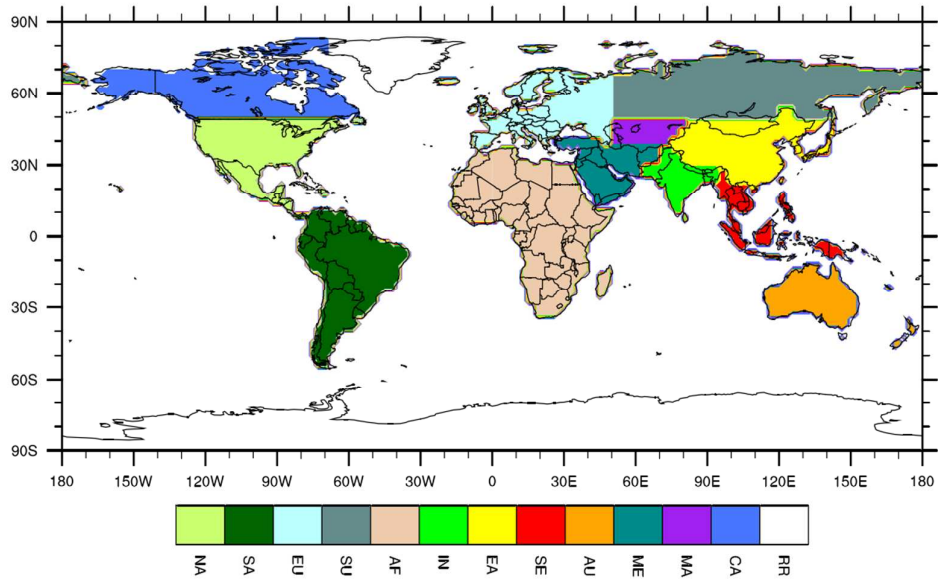


Figure S1. The thirteen continental regions tagged in our MOZART-4 simulations. Canada (CA), North America except Canada (NA), East Asia (EA), the former Soviet Union (SU), Europe (EU), Africa (AF), South America (SA), India (IN), Australia (AU), Middle Asia (MA), Southeast Asia (SE), the Middle East (ME), and the rest regions (RR).

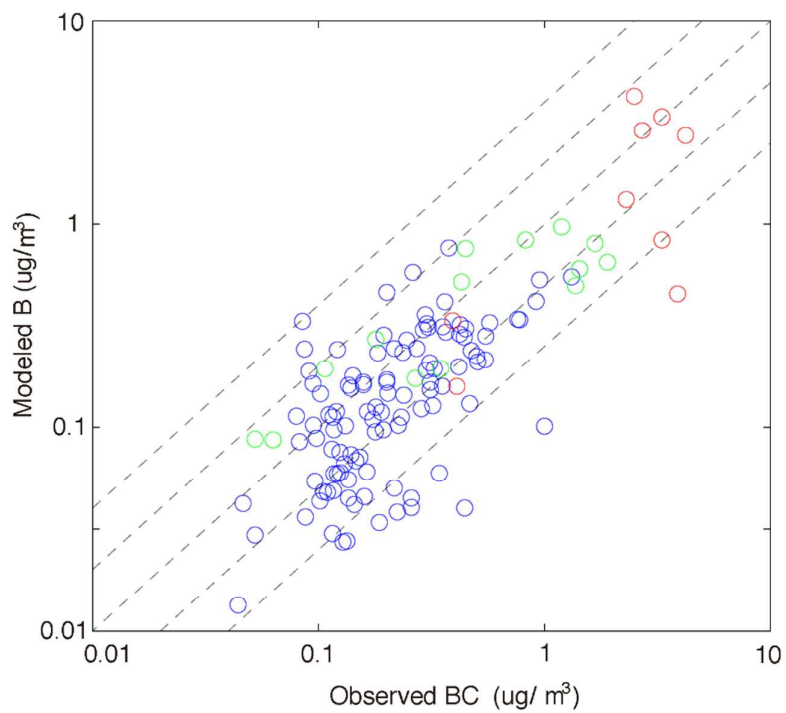


Figure S2. Modeled BC versus observed surface annual mean concentration of BC at sites in IMPROVE (blue), EMEP (green), and China (red). Dash lines are 1:4, 1:2, 1:1, 2:1, and 4:1 ratio lines. BC observations in China are attained from Zhang et al. (2008).

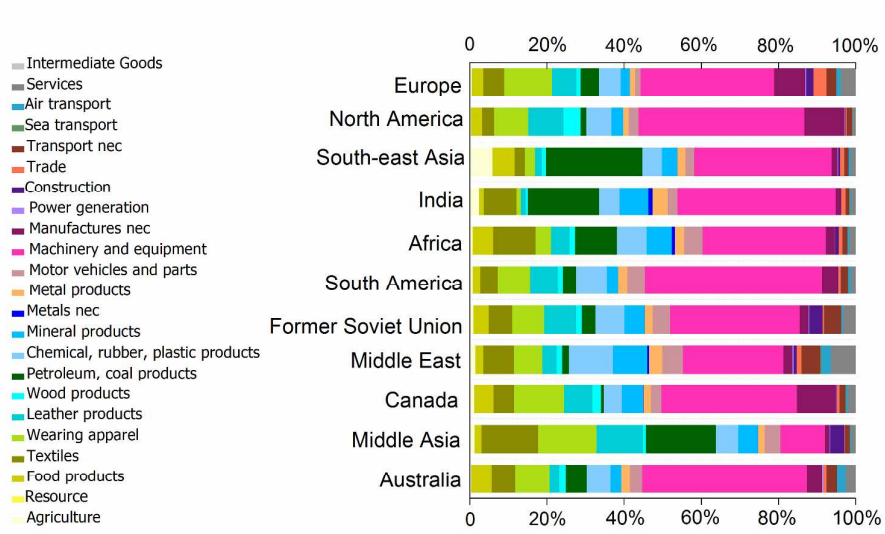


Figure S3. Sectoral contribution of emissions embodied in imports from East Asia.

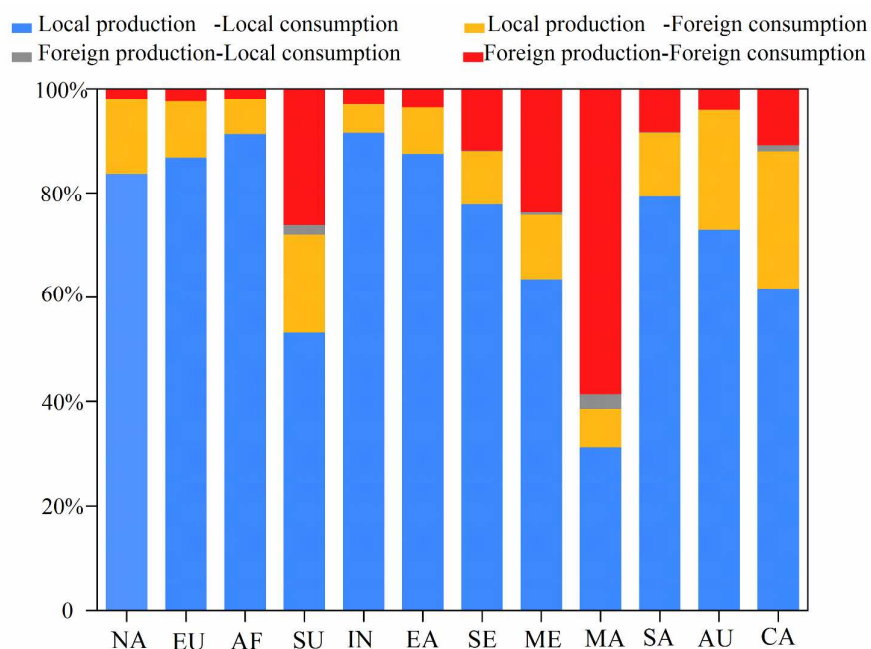


Figure S4. The composition of surface BC concentration in 12 regions from both production and consumption perspectives. Blue bars and orange bars refer to the percentage contribution from the emissions from local sites but the related products were consumed locally or by other regions, respectively; gray bars and red bars indicate the percentage contribution by the emissions from other regions but the related products were consumed by consumers locally or in other regions, respectively.

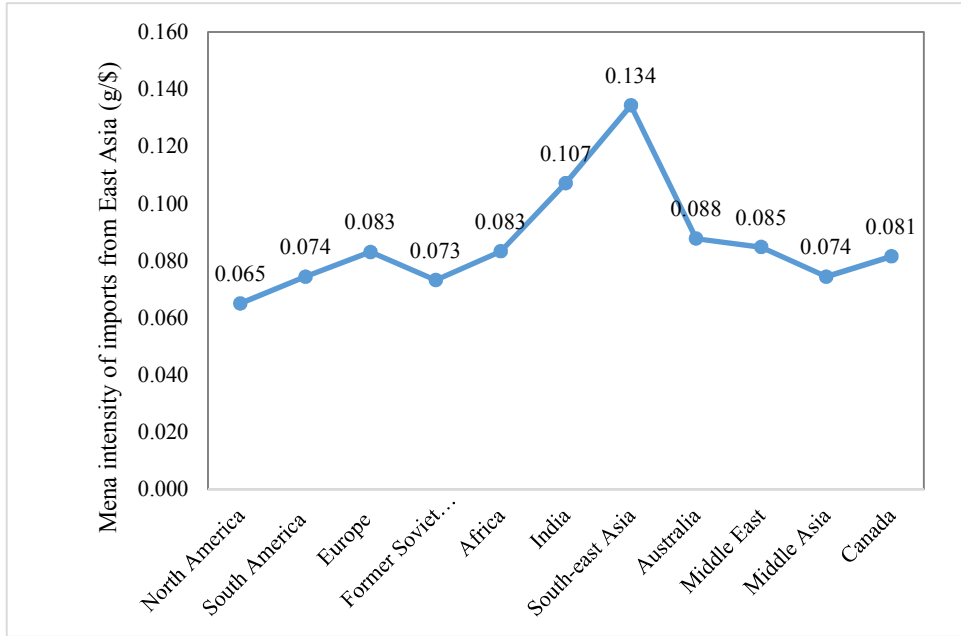


Fig. S5. Mean BC intensity of imports from East Asia (g/\$).

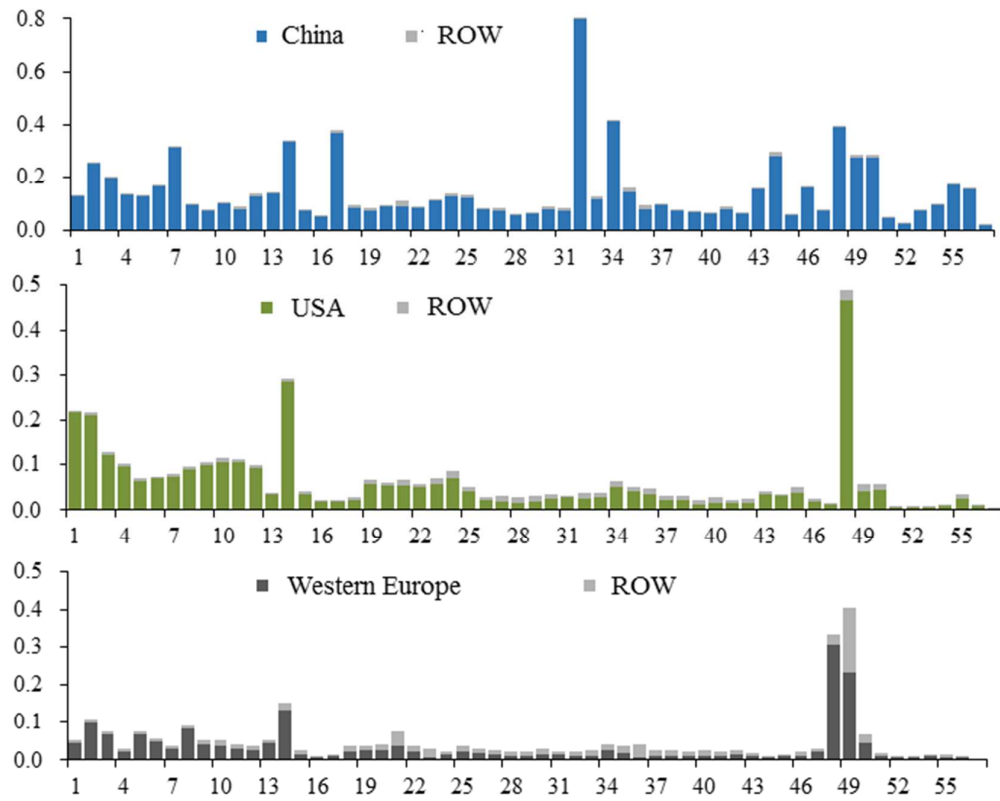


Figure S6. Mean embodied BC emission intensity (g per \$) for 57 sectors of China, USA and Western Europe. Embodied Intensity includes contributions from domestic and rest of the world (ROW) supply chains.

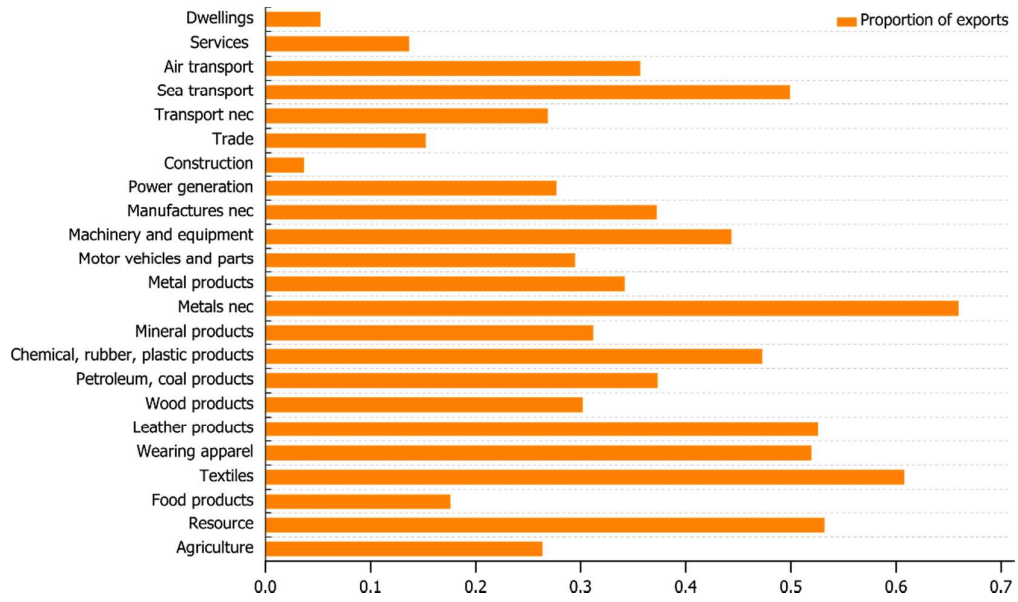


Figure S7 Global averaged proportion of emissions associated with exported products in each sector.

Table S1. Abbreviation and concordance of world regions.

World region	Abbreviation	GTAP regions
East Asia (China, Korea, Mongolia)	EAS	4,5,7,8,9,10
Economies in Transition (Eastern Europe and former Soviet Union)	EIT	52,54,59,62,63,67,69,70,78,79,80,81,82,83,84,85,86,87,88,89,90,91
Latin America and Caribbean	LAM	28,29,30,31,32,33,34,35,36,37,38,39,40,41,42,43,44,45,46,47,48
Middle East and North Africa	MNA	92,93,94,95,96,97,98,99,100,101,102,103,104,105
North America (USA, Canada)	NAM	26,27
Pacific Organization for Economic Co-operation and Development 1990 (Japan, Australia, New Zealand)	POECD	1,2,6
South-East Asia and Pacific	PAS	3,11,12,13,14,15,16,17,18,19
South Asia	SAS	20,21,22,23,24,25
sub-Saharan Africa	SSA	106,107,109,108,110,111,112,113,114,115,116,117,118,119,120,121,122,123,124,125,126,127,128,12
Western Europe	WEU	49,50,51,53,55,56,57,58,60,61,64,65,66,68,71,72,73,74,75,76,77

Table S2. Definition of regions.

Number	Code	Description	Member Countries
1	AUS	Australia	Australia, Cocos (Keeling) Islands, Christmas Island, Heard Island and McDonald Islands, Norfolk Island
2	NZL	New Zealand	New Zealand
3	XOC	Rest of Oceania	American Samoa, Cook Islands, Fiji, Micronesia Federated States of, Guam, Kiribati, Marshall Islands, Northern Mariana Islands, New Caledonia, Niue, Nauru, Palau, Papua New Guinea, French Polynesia, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis and Futuna, Samoa, Pitcairn, United States Minor Outlying Islands
4	CHN	China	China
5	HKG	Hong Kong	Hong Kong
6	JPN	Japan	Japan
7	KOR	Korea Republic of	Korea Republic of
8	MNG	Mongolia	Mongolia
9	TWN	Taiwan	Taiwan
10	XEA	Rest of East Asia	Macao, Korea Democratic Peoples Republic of
11	KHM	Cambodia	Cambodia
12	IDN	Indonesia	Indonesia
13	LAO	Lao People's Democratic Republic	Lao People's Democratic Republic
14	MYS	Malaysia	Malaysia
15	PHL	Philippines	Philippines
16	SGP	Singapore	Singapore
17	THA	Thailand	Thailand
18	VNM	Viet Nam	Viet Nam
19	XSE	Rest of Southeast Asia	Brunei Darussalam, Myanmar, Timor Leste
20	BGD	Bangladesh	Bangladesh
21	IND	India	India
22	NPL	Nepal	Nepal
23	PAK	Pakistan	Pakistan
24	LKA	Sri Lanka	Sri Lanka
25	XSA	Rest of South Asia	Afghanistan, Bhutan, Maldives
26	CAN	Canada	Canada
27	USA	United States of America	United States of America

Number	Code	Description	Member Countries
28	MEX	Mexico	Mexico
29	XNA	Rest of North America	Bermuda, Greenland, Saint Pierre and Miquelon
30	ARG	Argentina	Argentina
31	BOL	Bolivia, Plurinational Republic of	Bolivia, Plurinational Republic of
32	BRA	Brazil	Brazil
33	CHL	Chile	Chile
34	COL	Colombia	Colombia
35	ECU	Ecuador	Ecuador
36	PRY	Paraguay	Paraguay
37	PER	Peru	Peru
38	URY	Uruguay	Uruguay
39	VEN	Venezuela	Venezuela
40	XSM	Rest of South America	Falkland Islands (Malvinas), French Guiana, Guyana, Suriname, South Georgia and the South Sandwich Islands
41	CRI	Costa Rica	Costa Rica
42	GTM	Guatemala	Guatemala
43	HND	Honduras	Honduras
44	NIC	Nicaragua	Nicaragua
45	PAN	Panama	Panama
46	SLV	El Salvador	El Salvador
47	XCA	Rest of Central America	Belize
48	XCB	Caribbean	Aruba, Anguilla, Netherlands Antilles, Antigua & Barbuda, Bahamas, Barbados, Cuba, Cayman Islands, Dominica, Dominican Republic, Grenada, Haiti, Jamaica, Saint Kitts and Nevis, Saint Lucia, Montserrat, Puerto Rico, Turks and Caicos Islands, Trinidad and Tobago, Saint Vincent and the Grenadines, Virgin Islands British, Virgin Islands U.S.
49	AUT	Austria	Austria
50	BEL	Belgium	Belgium
51	CYP	Cyprus	Cyprus
52	CZE	Czech Republic	Czech Republic
53	DNK	Denmark	Denmark
54	EST	Estonia	Estonia
55	FIN	Finland	Finland, Aland Islands
56	FRA	France	France, Guadeloupe, Martinique, Reunion
57	DEU	Germany	Germany

Number	Code	Description	Member Countries
58	GRC	Greece	Greece
59	HUN	Hungary	Hungary
60	IRL	Ireland	Ireland
61	ITA	Italy	Italy
62	LVA	Latvia	Latvia
63	LTU	Lithuania	Lithuania
64	LUX	Luxembourg	Luxembourg
65	MLT	Malta	Malta
66	NLD	Netherlands	Netherlands
67	POL	Poland	Poland
68	PRT	Portugal	Portugal
69	SVK	Slovakia	Slovakia
70	SVN	Slovenia	Slovenia
71	ESP	Spain	Spain
72	SWE	Sweden	Sweden
73	GBR	United Kingdom	United Kingdom
74	CHE	Switzerland	Switzerland
75	NOR	Norway	Norway, Svalbard and Jan Mayen
76	XEF	Rest of EFTA	Iceland, Liechtenstein
77	ALB	Albania	Albania
78	BGR	Bulgaria	Bulgaria
79	BLR	Belarus	Belarus
80	HRV	Croatia	Croatia
81	ROU	Romania	Romania
82	RUS	Russian Federation	Russian Federation
83	UKR	Ukraine	Ukraine
84	XEE	Rest of Eastern Europe	Moldova Republic of
85	XER	Rest of Europe	Andorra, Bosnia and Herzegovina, Faroe Islands, Gibraltar, Monaco, Macedonia the former Yugoslav Republic of, San Marino, Serbia, Guernsey, Isle of Man, Jersey, Montenegro, Holy See (Vatican City State)
86	KAZ	Kazakhstan	Kazakhstan
87	KGZ	Kyrgyzstan	Kyrgyzstan
88	XSU	Rest of Former Soviet Union	Tajikistan, Turkmenistan, Uzbekistan
89	ARM	Armenia	Armenia
90	AZE	Azerbaijan	Azerbaijan
91	GEO	Georgia	Georgia
92	BHR	Bahrain	Bahrain
93	IRN	Iran Islamic Republic of	Iran Islamic Republic of

Number	Code	Description	Member Countries
94	ISR	Israel	Israel
95	KWT	Kuwait	Kuwait
96	OMN	Oman	Oman
97	QAT	Qatar	Qatar
98	SAU	Saudi Arabia	Saudi Arabia
99	TUR	Turkey	Turkey
100	ARE	United Arab Emirates	United Arab Emirates
101	XWS	Rest of Western Asia	Iraq, Jordan, Lebanon, Palestinian Territory Occupied, Syrian Arab Republic, Yemen
102	EGY	Egypt	Egypt
103	MAR	Morocco	Morocco
104	TUN	Tunisia	Tunisia
105	XNF	Rest of North Africa	Algeria, Libyan Arab Jamahiriya, Western Sahara
106	CMR	Cameroon	Cameroon
107	CIV	Cote d'Ivoire	Cote d'Ivoire
108	GHA	Ghana	Ghana
109	NGA	Nigeria	Nigeria
110	SEN	Senegal	Senegal
111	XWF	Rest of Western Africa	Benin, Burkina Faso, Cape Verde, Gambia, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, Ascension and Tristan Da Cunha, Sierra Leone, Togo
112	XCF	Central Africa	Central African Republic, Congo, Gabon, Equatorial Guinea, Sao Tome and Principe, Chad
113	XAC	South Central Africa	Angola, Congo the Democratic Republic of the
114	ETH	Ethiopia	Ethiopia
115	KEN	Kenya	Kenya
116	MDG	Madagascar	Madagascar
117	MWI	Malawi	Malawi
118	MUS	Mauritius	Mauritius
119	MOZ	Mozambique	Mozambique
120	TZA	Tanzania United Republic of	Tanzania United Republic of
121	UGA	Uganda	Uganda
122	ZMB	Zambia	Zambia
123	ZWE	Zimbabwe	Zimbabwe

Number	Code	Description	Member Countries
124	XEC	Rest of Eastern Africa	Burundi, Comoros, Djibouti, Eritrea, Mayotte, Rwanda, Sudan, Somalia, Seychelles
125	BWA	Botswana	Botswana
126	NAM	Namibia	Namibia
127	ZAF	South Africa	South Africa
128	XSC	Customs Union	Lesotho, Swaziland
129	XTW	Rest of the World	Antarctica, French Southern Territories, Bouvet Island, British Indian Ocean Territory

Table S3. Definition of sectors.

Number	Sector	Category
1	Paddy rice	Agriculture
2	Wheat	
3	Cereal grains nec	
4	Vegetables, fruit, nuts;	
5	Oil seeds	
6	Sugarcane, sugar beet	
7	Plant-based fibers	
8	Crops nec	
9	Cattle, sheep, goats, horses	
10	Animal products nec	
11	Raw milk	
12	Wool, silk-worm cocoons	
13	Forestry	
14	Fishing	
15	Coal	Resource
16	Oil	
17	Gas	
18	Minerals nec	
19	Meat: cattle, sheep, goats, horses	Food products
20	Meat products nec	
21	Vegetable oils and fats	
22	Dairy products	
23	Processed rice	
24	Sugar	
25	Food products nec	
26	Beverages and tobacco products	
27	Textiles	Textiles
28	Wearing apparel	Wearing apparel
29	Leather products	Leather products
30	Wood products	Wood products
31	Paper products, publishing	
32	Petroleum, coal products	Petroleum, coal products
33	Chemical, rubber, plastic products	Chemical, rubber, plastic products
34	Mineral products nec	Mineral products
35	Ferrous metals	
36	Metals nec	Metals nec
37	Metal products	Metal products
38	Motor vehicles and parts	Motor vehicles and parts
39	Transport equipment nec	Machinery and equipment
40	Electronic equipment	

41	Machinery and equipment nec	
42	Manufactures nec	Manufactures nec
43	Electricity	Power generation
44	Gas manufacture, distribution	
45	Water collection, purification, and distribution	
46	Construction	Construction
47	Trade	Services
48	Transport nec	Transport
49	Sea transport	
50	Air transport	
51	Communication	Services
52	Financial services nec	
53	Insurance	
54	Business services nec	
55	Recreation and other services	
56	Public Administration, Defense, Health, Education	
57	Dwellings	

Bridging emission inventories and GTAP classifications

In this study, we use the production-based emissions developed by researchers in Peking University (PKU-BC, <http://inventory.pku.edu.cn/home.html>). The inventory is based on a global $0.1^\circ \times 0.1^\circ$ fuel combustion dataset (PKU-FUEL-2011 covering 64 fuel combustion processes)¹ and an updated emission factor BC (EF_{BC}) dataset. Detailed source information, EFs, technology, technology splits, noncompliance rate and uncertainty analysis can be found in Wang et al.²

The PKU-inventory is expressed at a detail of 78 emission sources and 222 countries, which are different to the region and sector classifications of GTAP database. The 222 regions in PKU-inventory were aggregated into 129 regions according to the region definition. The mapping of 78 emission sources into sector-specific data which was compatible with MRIO table is provided as below.

Bridging the two databases was done by setting up concordance matrices between the 78 emission sources and each of GTAP's countries' sectors. Let C be such a concordance matrix, holding $C_{ij}=1$ if PKU-inventory class i corresponds to GTAP sector j , as shown in Table S1.

The original primary fuel type in GTAP database covers coal, oil, coal and oil products, and

gas (Table S1). As the emission factors of various types of fuel varies significant, the coal, oil, coal and oil products were split into seven types of fuel according to the energy statistics from International Energy Agency.³⁻⁷ The coal consumption was divided into: (1) Briquettes, coke; (2) Brown coal, peat; (3) Hard coal, coking coal. The consumption of coal and oil products was divided into: (1) Heavy fuel oil; (2) Gasoline, aviation fuel, kerosene; (3) Liquefied Petroleum Gas. For some developing countries without country-specific energy statistics, average proportion of different types of fuels of NON-OECD countries were used. Then the emissions from power generation were split into 2 sectors (Sector 43-44 in Table S5) according to the sectors' fuel consumption. For example, the emissions from coke used in power generation were C , the coke consumption in Sector 43 and Sector 44 was E_1 and E_2 , then the emissions from coke consumption in Sector 43 and Sector 44 was $C * E_1 / (E_1 + E_2)$ and $C * E_2 / (E_1 + E_2)$, respectively. Similarly, emissions from energy combustion in agriculture, industry, residential were split into 14 sectors (Sector 1-14 in Table S5), 30 sectors (Sector 15-42, 45-46 in Table S5), 8 sectors (Sector 47, 51-57 in Table S5) respectively. The emissions from industrial process were attributed to the corresponding sectors of the products.

Table S4 Sources information of PKU-inventory and classification to the GTAP database aggregated categories.

Category	Activity included	Sector
Coal	anthracite consumed	Power coal
	coking coal consumed	Power coal
	bituminous coal consumed	Power coal
	lignite consumed	Power coal
	peat consumed	Power coal
	anthracite consumed	Industry coal
	coking coal consumed	Industry coal
	bituminous coal consumed	Industry coal
	lignite consumed	Industry coal
	peat consumed	Industry coal
	anthracite consumed	residential & commercial
	coking coal consumed	residential & commercial
	bituminous coal consumed	residential & commercial
	lignite consumed	residential & commercial
	peat consumed	residential & commercial
	patent fuel	residential & commercial
	brown coal briquettes	residential & commercial
Oil	gas/diesel consumed	Power coal and oil product
	residue fuel oil consumed	Power oil
	natural gas liquid consumed	Power coal and oil product
	gas/diesel	agriculture
	gas/diesel consumed	Industry coal and oil product
	residue fuel oil consumed	Industry oil
	natural gas liquid consumed	Industry coal and oil product
	natural gas liquid consumed	residential & commercial
	kerosene consumed	residential & commercial
	gas/diesel consumed	residential & commercial
	fuel oil consumed	residential & commercial
	vehicle gasoline	transportation
	vehicle diesel	transportation
	ocean tanker	ship
	ocean container	ship
	ocean bulk & combined carries	ship
	general-cargo vessels	ship
non-cargo vessels	ship	
auxiliary engines	ship	
military vessels	ship	
Gas	dry natural gas consumed	energy gas
	gas flaring	Industry gas
	dry natural gas consumed	Industry gas
	liquid petroleum gas consumed	residential & commercial
	dry natural gas consumed	residential & commercial
	gas works gas	residential & commercial
	coke oven gas	residential & commercial
biogas consumed	residential & commercial	
Biomass	solid biomass consumed	Power coal and oil product
	biogas consumed	Power coal and oil product
	solid biomass consumed	Industry coal and oil product
	biogas consumed	Industry coal and oil product
	indoor firewood burning	residential & commercial
charcoal burning	residential & commercial	

	indoor crop residue burning	residential & commercial
	indoor dung cake burning	residential & commercial
	vehicle liquid biofuels	transportation
	coke production	Sector 32
	brick production	Sector 34
	primary Al production	Sector 36
	iron sintering	Sector 35
	electric arc furnace	Sector 35
	open hearth furnace	Sector 35
	oxygen blown converter	Sector 35
	hot rolling	Sector 35
Process	petroleum catalytic cracking	Sector 35
	lime production	Sector 34
	glass production	Sector 34
	fertilizer production	Sector 33
	ferroalloy production	Sector 36
	lead production	Sector 36
	magnesium production	Sector 36
	zinc production	Sector 36
	ammonia production	Sector 33

Table S5 Comparisons of Top-of-Atmosphere BC Direct Radiative Forcing (DRF) and Driving Variables.

Reference	Emission (Tg)	Lifetime (d)	Load (mg m ⁻²)	DRF
This work	9.5	4.9 ^a	0.28	0.275
Wang et al. 2014 ⁹	6.5	4.2	0.15	0.19 (0.17-0.31)
Jacobson (2000) ¹⁰			0.45	0.54
Schulz et al. (2006) ¹¹	6.3	6.8± 1.8	0.23±0.07	0.27 ± 0.06
Ramanathan and Carmichael, 2008 ¹²				0.9
Chung et al., 2012 ¹³				0.65
Jacobson, 2012 ¹⁴	9.3	3.2	0.18	
Bond et al., 2013 ¹⁵	17	6.1	0.55	0.88

^a Lifetime of BC varies significantly by source region, ranging from 2 to 10 days. Zhang et al., 2015.⁸

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