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An Asian emission inventory of anthropogenic emission sources for the period 1980–2020

T. Ohara[1,2], H. Akimoto[2], J. Kurokawa[1], N. Horii[3], K. Yamaji[2], X. Yan[4], and T. Hayasaka[5]

[1]National Institute for Environmental Studies, Tsukuba, Ibaraki, Japan
[2]Frontier Research Center for Global Change, Japan Agency for Marine Science and Technology, Yokohama, Japan
[3]Faculty of Economics, Kyushu University, Fukuoka, Japan
[4]State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, Nanjing, China
[5]Research Institute for Humanity and Nature, Kyoto, Japan

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Abstract. We developed a new emission inventory for Asia (Regional Emission inventory in ASia (REAS) Version 1.1) for the period 1980–2020. REAS is the first inventory to integrate historical, present, and future emissions in Asia on the basis of a consistent methodology. We present here emissions in 2000, historical emissions for 1980–2003, and projected emissions for 2010 and 2020 of SO_2, NO_x, CO, NMVOC, black carbon (BC), and organic carbon (OC) from fuel combustion and industrial sources. Total energy consumption in Asia more than doubled between 1980 and 2003, causing a rapid growth in Asian emissions, by 28% for BC, 30% for OC, 64% for CO, 108% for NMVOC, 119% for SO_2, and 176% for NO_x. In particular, Chinese NO_x emissions showed a marked increase of 280% over 1980 levels, and growth in emissions since 2000 has been extremely high. These increases in China were mainly caused by increases in coal combustion in the power plants and industrial sectors. NMVOC emissions also rapidly increased because of growth in the use of automobiles, solvents, and paints. By contrast, BC, OC, and CO emissions in China showed decreasing trends from 1996 to 2000 because of a reduction in the use of biofuels and coal in the domestic and industry sectors. However, since 2000, Chinese emissions of these species have begun to increase. Thus, the emissions of air pollutants in Asian countries (especially China) showed large temporal variations from 1980–2003. Future emissions in 2010 and 2020 in Asian countries were projected by emission scenarios and from emissions in 2000. For China, we developed three emission scenarios: PSC (policy success case), REF (reference case), and PFC (policy failure case). In the 2020 REF scenario, Asian total emissions of SO_2, NO_x, and NMVOC were projected to increase substantially by 22%, 44%, and 99%, respectively, over 2000 levels. The 2020 REF scenario showed a modest increase in CO (12%), a lesser increase in BC (1%), and a slight decrease in OC (−5%) compared with 2000 levels. However, it should be noted that Asian total emissions are strongly influenced by the emission scenarios for China.

Correspondence to: T. Ohara
(tohara@nies.go.jp)

1 Introduction

Anthropogenic emissions in Asia are larger than those in Europe and North America today and will continue to increase in the future (Akimoto, 2003). In fact, recent tropospheric satellite observations have demonstrated that NO_x emissions in China have accelerated impressively since 2000 (Irie et al., 2005; Richter et al., 2005). In light of this situation, the development of Asian emission inventories for the past, present, and future is very important for the understanding and management of the regional and global atmospheric environment.

There are comparatively few Asian inventories of anthropogenic emission sources from East, Southeast, or South Asia. The first Asian inventory was developed by Kato and Akimoto (1992) and Akimoto and Narita (1994); it reported SO_2 and NO_x emissions for 1975, 1980, and 1985–1987. Recently, Streets et al. (2003) developed an emission inventory for use during the ACE-Asia (Asian Pacific Regional Aerosol Characterization Experiment) and TRACE-P (Transport and Chemical Evolution over the Pacific) field campaigns carried out in the East Asia and the Western Pacific region in spring 2001. The campaigns focused on the characterization of gaseous and aerosol species in Asian outflows to the western

Table 1. Summary of species and emission sources in REAS version 1.1.

Sector			SO_2	NO_x	CO	BC	OC	NMVOC	CO_2	N_2O	NH_3	CH_4
Anthropogenic	Combustion	Fossil fuel + biofuel	●	●	●	●	●	●	●	●	●	●
	Non-combustion	Industrial processes	●		●			●	●			
		Oil, solvents etc						●				
	Agriculture	Agricultural soil		●						●	●	●
		Livestock								●	●	●
Natural soils				●						●	●	

• Data available.

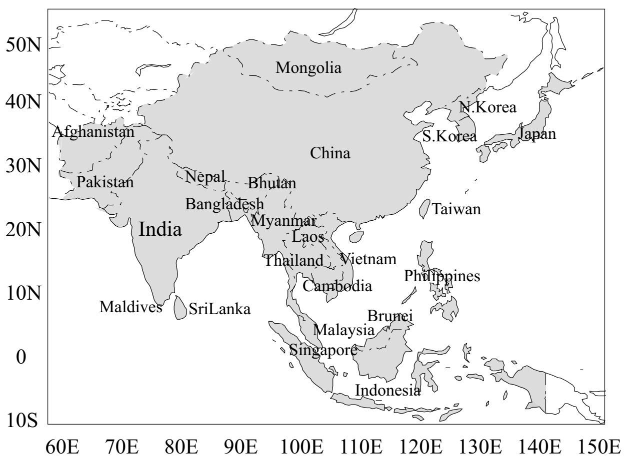

Fig. 1. Inventory domain.

Pacific Ocean, and the inventories included SO_2, NO_x, CO, nonmethane volatile organic compounds (NMVOC), black carbon (BC), organic carbon (OC), NH_3, and CH_4. Twenty-two countries and regions in East, Southeast, and South Asia were included, and $1^\circ \times 1^\circ$ grid maps for the base year (2000) were provided. The Regional Air Pollution Information and Simulation (RAINS-Asia) is a project organized by the International Institute for Applied Systems Analysis (IIASA) and funded by the World Bank for the purpose of constructing a policy tool for the mitigation of acid rain in Asia (Downing et al., 1997). In this study, emission inventories for SO_2 with base years of 1990 and 1995, and also projections from 2000 to 2030, were estimated, and the results are available on a CD-ROM (IIASA, 2001). The global emission inventories EDGAR (Emission Database for Global Atmospheric Research; Olivier et al., 1999) and the IIASA inventory (Cofala et al., 2006) naturally include Asian emissions.

Despite the importance of understanding annual variations in past air quality, only a few attempts have been made to estimate the time series of historical Asian emissions. Streets et al. (2000, 2001a) reported trends in country-based emissions of SO_2 and NO_x in Asia during 1985 and 1997; their data were based on the RAINS-Asia emission inventory. Global gridded emissions of CO_2, CO, CH_4, NMVOC, SO_2, NO_x, N_2O, and NH_3 by sector for the period 1890–1990 have been estimated by Van Aardenne et al. (2001). The emissions data set EDGAR-HYDE was estimated by using historical activity data from the HYDE database (Klein Goldewijk and Battjes, 1997) and historical emission factors based on the uncontrolled emission sources included in EDGAR. However, year-by-year emissions after 1990, which can be expected to show marked variations in Asian countries, were not included.

Future changes in the air quality in Asia will be affected strongly by the expected growth in anthropogenic emissions, which are controlled by economic growth, environmental policy, and future implementation of emissions controls. Projections of Asian emissions have been made by Van Aardenne et al. (1999) for NO_x, Streets and Waldhoff (2000) for SO_2, NO_x, and CO, and Klimont et al. (2001) for SO_2, NO_x, NH_3, and NMVOC. Additionally, Asian emissions have been projected as part of the estimations of global emissions of SO_2, NO_x, CO, and NMVOC (Cofala et al., 2006) and of carbonaceous particles (Streets et al., 2004).

Thus, it is very important to develop a historical and future emission inventory for multiple species and years covering the whole of Asia. We have developed a new Asian emission inventory (Regional Emission inventory in ASia (REAS), Version 1.1) for the 40 years from 1980 to 2020. REAS is the first inventory to integrate historical, current, and future emissions data for Asia on the basis of a consistent methodology. Table 1 demonstrates the emission sources and chemical species targeted by REAS. The REAS inventory includes NO_x, SO_2, CO, BC, OC, CO_2, N_2O, NH_3, CH_4, and NMVOC from anthropogenic activities (combustion, non-combustion, agriculture, and others). The methodology and results for NO_x, N_2O, NH_3, and CH_4 emissions from agricultural sources are explained by Yamaji et al. (2003, 2004) and Yan et al. (2003a, b, c). Open biomass burning is not yet included in REAS.

Here, we focus on the emissions of NO_x, SO_2, BC, OC, CO, and NMVOC from fuel combustion and non-combustion sources. Section 2 describes the methodology used in REAS to estimate emissions, including activity data, emission factors, emission scenarios in 2010 and 2020, and grid allocation. Section 3, the results and discussion, covers four topics: (1) Asian and national emissions in 2000; (2) historical emissions between 1980 and 2003; (3) projections of future emissions in 2010 and 2020; and (4) gridded emissions in Asia. Conclusions and a summary are given in Sect. 4.

2 Methodology

2.1 Basic methodology

The target domain of REAS covers 24 countries in East, Southeast, and South Asia (Fig. 1). Emissions were estimated on the basis of activity data at district levels for China (30 provinces), India (20 states), Japan (6 sub-regions), South Korea (4 sub-regions), and Pakistan (5 sub-regions). For the other countries, national emissions were estimated on the basis of activity data at the national level.

Figure 2 demonstrates the general methodology for the emission estimates in REAS. We estimated the emissions from fuel combustion sources and non-combustion sources as part of anthropogenic activities: transformation (power) sectors (electricity and heat production, oil refineries, manufacture of solid fuels, and other energy and transformation industries); industry sectors (including iron and steel, chemical and petrochemical, non-ferrous metals, and non-metallic minerals); transport sectors (including aviation, roads, railways, and shipping); and other (mainly domestic) sectors (including agriculture, commerce and public, and residential). Emissions of a particular species were estimated as a product of the activity data, emission factors, and removal efficiency of emission controls. Region-specific emission factors for several emission species from subdivided source sectors were developed from a wide range of sources (published or unpublished information) and were used to estimate emissions on district and country levels. These emissions, estimated on district and country levels, were divided into a 0.5°×0.5° grid by using index databases, i.e. population data; information on the positions of large point sources (LPSs); land cover data sets; and land area data sets. Here, we give the methodology, data, and data sources of the emission estimations in this inventory. Emissions from fuel combustion sources, including 20 economic sectors and 36 fuel types, were estimated in REAS. Emissions of SO_2 and other species (except NMVOC) from stationary sources were estimated by using Eqs. (1) and (2), respectively.

$$E = (A/NCV) \times S \times (1 - SR) \times (1 - R) \quad (1)$$

E: SO_2 emissions [kg]
A: Energy consumption [J]

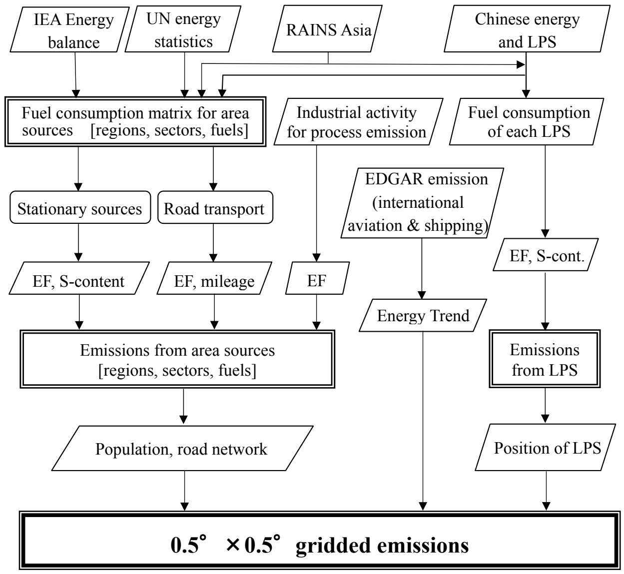

Fig. 2. Flow chart for the estimation of emissions.

NCV: Net calorific value [J kg^{-1}]
S: Sulfur content of fuel [kg kg^{-1}]
SR: Sulfur retention in ash [–]
R: Removal efficiency [–]

$$E = A \times EF \times (1 - R) \quad (2)$$

E: Emissions [kg]
A: Energy consumption [J]
EF: Emission factor [kg J^{-1}]
R: Removal efficiency [–]

For road transport, emissions of SO_2, NO_x, CO, BC, and OC were estimated by the following equation:

$$E = A \times EF \times FE/(SG \times NCV) \quad (3)$$

E: Emissions [kg]
A: Energy consumption [J]
EF: Emission factor [kg m^{-1}]
FE: Fuel economy [m L^{-1}]
SG: Specific gravity [kg L^{-1}]
NCV: Net calorific value [J kg^{-1}]

We classified on-road vehicles into seven types (light-duty gasoline vehicles, heavy-duty gasoline vehicles, light-duty diesel vehicles, heavy-duty diesel vehicles, gasoline buses, diesel buses, and motorcycles). Motor gasoline and diesel oil consumption was distributed to each vehicle type by using traffic volume and fuel economy data, and then the emissions were estimated by using country-specific emission factors by vehicle type.

Table 2. Fuel consumption by region, sector, and fuel type between 1980 and 2003 (units: PJ).

Region		Power Plants			Industry			Transport		Domestic			Total
		Coal	Oil	Others	Coal	Oil	Others	Oil	Others	Coal	Biofuel	Others	
1980	China	2410	963	105	5498	1605	875	640	402	3017	4751	595	20860
	Japan	210	2525	1102	525	3869	1160	2108	0	23	122	1813	13456
	Other East Asia	279	514	1	835	992	178	391	0	531	335	288	4343
	Southeast Asia	55	539	14	74	698	345	637	3	22	3016	459	5861
	India	902	120	18	565	525	906	472	229	323	5920	284	10263
	Other South Asia	0	17	86	40	50	288	138	0	1	1459	123	2203
	Total	3856	4679	1325	7537	7738	3752	4385	634	3917	15602	3563	56986
1985	China	3547	741	122	6815	1652	1218	823	476	4138	5244	619	25394
	Japan	569	1524	1482	577	3619	1065	2145	0	50	9	1881	12921
	Other East Asia	526	246	39	1054	1057	200	483	0	674	356	375	5011
	Southeast Asia	133	502	148	139	755	639	803	3	13	3244	429	6807
	India	1529	140	49	851	704	1078	676	186	411	6530	374	12528
	Other South Asia	1	56	113	51	71	401	194	0	1	1608	176	2671
	Total	6305	3208	1954	9486	7858	4601	5124	666	5286	16991	3854	65334
1990	China	6046	659	193	8836	2518	1439	1145	430	4655	5788	908	32618
	Japan	807	2035	1798	626	3611	1218	2823	0	2	9	2352	15281
	Other East Asia	601	421	196	1042	1618	262	876	0	536	354	707	6614
	Southeast Asia	312	719	263	179	1106	1374	1263	1	12	3547	609	9385
	India	2481	150	145	1141	865	1321	996	102	464	7051	514	15229
	Other South Asia	1	100	222	80	87	517	257	0	0	1782	223	3269
	Total	10248	4086	2815	11905	9804	6130	7360	532	5670	18532	5313	82395
1995	China	10012	714	215	11313	3228	1829	1813	276	4099	6456	1478	41433
	Japan	1194	1685	2061	574	4137	1309	3307	0	1	6	2653	16927
	Other East Asia	990	702	381	868	2740	390	1448	0	204	366	1289	9377
	Southeast Asia	395	879	901	380	1558	2095	2067	1	28	3579	820	12701
	India	3929	166	284	1053	1219	1551	1440	5	486	7364	667	18163
	Other South Asia	7	192	264	83	137	541	371	0	0	1917	263	3775
	Total	16528	4337	4106	14270	13018	7715	10446	283	4817	19688	7170	102377
2000	China	12679	604	457	10828	4447	1991	2726	236	3055	5289	2207	44520
	Japan	1702	1045	2481	502	4759	1398	3473	0	10	4	2820	18194
	Other East Asia	1898	544	645	908	3538	572	1637	0	167	381	1313	11603
	Southeast Asia	801	728	1406	554	1793	2559	2557	1	37	3787	1088	15310
	India	5201	325	422	874	2382	1741	1273	0	355	7866	948	21387
	Other South Asia	4	320	354	84	151	674	469	4	0	2093	321	4475
	Total	22284	3566	5766	13751	17070	8936	12135	241	3625	19420	8697	115490
2003	China	18584	714	440	13040	5436	2689	3347	239	3102	5401	2651	55644
	Japan	2132	992	2596	613	4806	1481	3389	0	10	3	2757	18780
	Other East Asia	2464	440	983	963	4236	552	1798	5	162	329	1316	13248
	Southeast Asia	1145	587	1869	698	2035	2824	2919	5	45	3978	1127	17232
	India	5655	310	567	987	2470	1758	1313	0	388	8239	1088	22776
	Other South Asia	3	174	556	142	138	778	495	15	0	2221	356	4879
	Total	29984	3217	7011	16443	19121	10083	13262	264	3707	20172	9296	132559

Additionally, REAS includes SO_2 emissions from non-ferrous metals and sulfuric acid production and CO emissions from iron and steel production. These non-combustion emissions were estimated by industrial activity data and process emission factors. NMVOC emissions for 1995 and 2000 were not estimated independently in the present version; they were obtained from Klimont et al. (2002) and Streets et al. (2003).

The emissions from aviation and international shipping in 2000 were estimated from the gridded data for 1995 in EDGAR 3.2 (http://www.mnp.nl/edgar/model/edgarv32/), the rates of change in energy consumption (country value for aviation and Asian total value for international shipping) from 1995 to 2000 in the International Energy Agency (IEA) Energy Balances (2004), and BC and OC emission factors (Cass et al., 1982).

Regional- or country-based emission data, excluding LPSs data, were broken down into grid data with a $0.5° \times 0.5°$ resolution by using three kinds of allocation factor: (1) road networks, provided by Streets et al. (2003), for road transport sources; (2) rural populations, provided by Streets et al. (2003), for biofuel combustion in the domestic sector and all fuel combustion in the agricultural sector; and (3) total populations, extracted from the Land Scan Global Population database developed by Oak Ridge National Laboratory (ORNL, 2001), for other area sources. We assumed that the spatial distributions of these allocation factors did not vary in the period 1980–2020. In China, power plants with capacities over 100 MW are treated as LPSs. Information on the locations and fuel consumption of LPSs in China was provided from some institutes related to China State Grid Company. For other countries LPSs information was obtained from RAINS-Asia. In this study, the numbers of LPSs in China and other countries were taken to be 436 and 87, respectively.

2.2 Activity data

Table 2 shows fuel consumption by region, sector, and fuel type between 1980 and 2003. Fuel consumption data from IEA Energy Balances (IEA, 2004) were used for most of the countries, except for the period 1996–2003 in China for reasons described below. For countries whose fuel consumption data were not included in the IEA data, those from RAINS-Asia (IIASA, 2001) and the UN Energy Statistics Yearbook (United Nations, 1983–2004) were used. The IEA fuel consumption data for China are distributed to each province by using the China Energy Statistical Yearbook (CESY; National Bureau of Statistics, 1997–2004). For India, the total fuel consumption in the IEA data are subdivided into the fuel consumption for each Indian region by using the RAINS-Asia data.

In constructing the REAS, particular concern was paid to the coal consumption trend in China during 1996–2000, which, according to CESY and IEA statistics, was decreasing. These data were verified from GOME satellite observational data for tropospheric NO_2 column density in the North China Plain (Akimoto et al., 2006). The NO_2 column increase from 1996–2002 averaged for the two reports (Irie et al., 2005; Richter et al., 2005) was about 50%, whereas the NO_x emission increases based on the province-by-province data in the China Energy Statistics Yearbook (PBP-CESY) and the IEA data were 25% and 15%, respectively. The country-total data from CESY were even lower than the PBP-CESY and IEA data. The discrepancy in increasing trends between the satellite data and the PBP-CESY emission inventory could be within the uncertainty level, with the reservation that the increase in total fuel consumption in PBP-CESY may still be underestimated, particularly since 1999. After performing these verifications we adopted the fossil fuel consumption data of PBP-CESY for 1996–2003. Recently, statistical data on coal consumption were modified to higher values in the China Statistical Yearbook (National Bureau of Statistics, 2006), and this fact may support our conclusion.

Biofuel consumption was obtained from other data sources. For China, the provincial consumption of biofuel for 1995 or 2000 was obtained from Yan et al. (2006) and RAINS-Asia. For other countries, regional consumption data for 1990 or 1995 in RAINS-Asia were used. Data for the period 1980–2000 were extrapolated from these data of regional biofuel consumption for 1990 or 1995 or 2000 by using international statistics for fuelwood (FAO, 2000) and primary solid biomass (IEA, 2004). For non-combustion sources, an industrial activity data set (production of non-ferrous metals, sulfuric acid, iron, and steel) was derived from international statistics (e.g., USGS Minerals Yearbook, 2006; UN Statistics Yearbook, 1983–2004).

2.3 Emission factors

Emission factors were determined for each of the sectors, fuels, and countries for 1995 and 2000. Table 3 shows the mean emission factors for fuel combustion in 2000. Emission factors by economic sector, fuel type, combustion facility, country, and region were compiled from a wide range of literature, such as Kato et al. (1991), Kato and Akimoto (1992), AP-42 (US EPA, 1999), the IPCC Guideline (1997), the EMEP/CORINAIR Emission Inventory Guidebook (EEA, 2000), and Streets et al. (2003). Emission factors for other years in the period 1980–2003 were then estimated by using the emission control levels in each country. Because the historical data for emission factors were unavailable, it was assumed that the emission factors (except for those from some stationary sources in some developed countries and from the automobile sources in many countries) did not vary throughout the period. For Japan, the time variations of country-specific emissions factors in the period 1980–2003 were determined from a large number of domestic research reports (e.g. Kannari et al., 2007).

The sulfur contents of coal for power plants and industry and those of some types of oil (motor gasoline, kerosene, heavy fuel oil, and diesel oil) in China for pre-1980, 1990, 1995, and 2000 were determined from the information of Kato et al. (1991), Streets et al. (2000), and the China Coal Industry Yearbook 2002 (State Administration for Coal Safety, 2003). Because SO_2 emissions in China depended strongly on the sulfur content of coal, province-by-province data for power plants and other sectors were used in this estimation. The average sulfur content of coal in China was 1.35% pre-1985, 1.27% in 1990, 1.12% in 1995, and 1.08% in 2000. A simple interpolation was used to generate values for each year during the period 1985–2000. For India, we prepared state-by-state data on the sulfur content of coal on the basis of the data reported by Reddy et al. (2001a). For other countries, the RAINS-Asia and Kato et al. (1991) databases on sulfur content in fuel were used. On the basis of Streets et al. (2000) and others, adjustments were made to account for the reduction in sulfur content by national regulation in Japan, Taiwan, South Korea, Hong Kong, Singapore, and Thailand during the period 1990–2000. It was assumed that sulfur retention values in ash were 5% to 30% (depending on country, sector, and coal type) for coal and 0% for other fuels.

SO_2 emission factors for oil (excluding motor gasoline, kerosene, heavy fuel oil, and diesel oil), and gas were provided mainly from Kato et al. (1991), AP-42, the IPCC Guideline, and the EMEP/CORINAIR Guidebook and were provided from Garg et al. (2001) for biofuel. After 1990, the efficiencies of removal of SO_2 by desulfurization were defined for power plants, industry, and oil refineries on the basis of Wang et al. (2000) in the case of China and RAINS-Asia for other countries. Because post-2000 data were unavailable, it was assumed that these parameters remained constant

Table 3. Mean emission factors for fuel combustion in 2000.

	Region	Power Plants			Industry			Transport		Domestic			Total
		Coal	Oil	Others	Coal	Oil	Others	Oil	Others	Coal	Biofuel	Others	
SO_2 (g/GJ)	China	833.6	590.5	73.4	934.2	148.7	217.1	80.5	711.3	760.3	51.4	93.2	569.5
	Japan	26.2	61.1	17.4	250.1	35.9	71.8	20.0	–	317.2	0.0	30.1	38.8
	Other	504.2	674.4	8.6	536.5	310.3	41.8	145.1	0.0	376.4	47.9	124.2	152.4
NOx (g/GJ)	China	298.8	279.2	161.2	241.8	79.8	78.6	1017.1	241.2	95.0	82.9	110.8	246.3
	Japan	66.8	88.8	42.9	201.6	43.5	40.4	267.4	–	250.3	0.0	87.4	102.0
	Other	267.0	303.1	189.8	240.7	81.2	79.7	921.1	79.7	122.9	81.4	74.1	157.3
CO (g/GJ)	China	143.8	59.4	967.0	4366.4	54.3	23.4	6970.1	143.3	5706.1	7636.7	220.2	3196.9
	Japan	61.2	32.8	28.0	163.8	25.5	21.9	498.5	–	176.1	0.0	124.0	134.4
	Other	154.3	83.0	319.1	3934.3	44.3	2296.7	3612.1	12.7	5851.6	7467.2	102.7	2157.1
BC (g/GJ)	China	1.0	8.1	1.0	7.5	3.1	0.0	13.4	5.0	152.4	88.0	3.6	24.5
	Japan	0.1	8.4	0.1	0.7	1.7	0.0	13.9	–	152.4	0.0	2.6	4.1
	Other	1.2	8.1	0.4	4.8	3.2	3.2	29.2	0.0	147.0	83.8	2.4	20.3
OC (g/GJ)	China	0.2	6.1	0.5	1.6	2.3	0.0	11.6	0.9	123.3	399.1	4.1	57.6
	Japan	0.0	6.2	0.4	0.2	1.2	0.0	4.9	–	123.6	0.0	4.5	2.4
	Other	0.3	6.1	0.3	1.2	2.4	15.7	24.0	0.0	119.3	418.6	4.8	83.2

after 2000.

NO_x emission factors, excluding those from automobile sources, were derived from Kato et al. (1991), AP-42, the IPCC Guideline, and the EMEP/CORINAIR Guidebook. Additionally, Streets et al. (1998), and Zhang et al. (2000) were used. Because NO_x emissions in the developed countries of Asia depended on emission controls after the 1980s, these effects were reflected in the emission factors and removal efficiencies for Japan, Taiwan, South Korea, Hong Kong, and Singapore (where national regulations are applied to major stationary sources, especially in the case of power plants and industry sectors), based on information in RAINS-Asia. For other countries, uncontrolled emission factors were used throughout the period 1980–2003.

Excluding emissions from automobile sources, the BC and OC emission factors for 1995 and 2000 were provided by Streets et al. (2001b, 2003). These emission factors were classified into those for developed countries (Japan, South Korea, Taiwan, Hong Kong, and Singapore) and other countries known to have no emission controls. For the other countries it was assumed that the emission factors, which were considered to be uncontrolled, did not vary throughout the period 1980–2003. On the other hand, the emission factors for developed countries were changed in the period 1980–2003: (1) before 1985, emission factors were uncontrolled; (2) between 1985 and 1995 emission factors were interpolated from the 1985 and 1995 values; (3) between 1995 and 2000 emission factors were interpolated from the 1995 and 2000 values; and (4) after 2000 emission factors for 2000 were used.

CO emission factors, excluding those from automobile sources, were derived from Kato et al. (1991), AP-42, the IPCC Guideline, and the EMEP/CORINAIR Guidebook. Additionally, Veldt and Berdowski (1995), Zhang et al. (2000), and Streets et al. (2003) were used for biofuel emissions. Recently, Streets et al. (2006) updated the a priori Chinese CO emission inventory (Streets et al., 2003) by making some improvements in the emission factors for industrial sectors. These estimates for Chinese CO emissions in 2001 were 31% higher than the former estimates for 2000 (Streets et al., 2003) and agreed with some of the results obtained by inverse and forward modeling. This increase was caused mainly by some improvements in the emission factors from coal combustion. Therefore, we based our emission factors for coal combustion in power plants, by industry, and by the residential sector on the data of Streets et al. (2006). However, for residential coal combustion we selected an emission factor (150 kg/t), which was the close to the average of the value for hand-feed stokers (124 kg/t) by Streets et al. (2006) and the maximum value for coal stoves (170 kg/t) by Zhang et al. (1999). These are comparatively rough assumptions and need to be improved in future. These emission factors were considered invariant throughout the period 1980–2003 in all developing countries.

Automobile emissions in the period 1980–2003 were calculated by using country-specific emission factors under country-specific emission controls. For Japan, year-by-year emissions factors for the period 1980–2003 were developed from a large number of domestic research reports. For other countries the emission factors were determined by the following method. We were able to collect the NO_x emission factors for around 1995 in several modeled countries (China, South Korea, Taiwan, Thailand, Philippines, Indonesia, and India). Other countries were assigned the emission factors of those modeled countries that they resembled. For CO, BC, and OC the emission factors for 2000 were obtained from Streets et al. (2003). These emission factors were used as the values for the base year of 1995 or 2000. For other years we calculated the emissions by using the emission factor for the base year and country-specific information (Minato, 2002; Nissan Automobile Corporation, 2005) on emission controls and car age profiles.

Process emission factors were gathered from Kato et al. (1991) and Kato and Akimoto (1992) for SO_2emissions and from Streets et al. (2003) for CO emissions. They were invariable throughout the period 1980–2003. Finally, NMVOC emissions for the period 1980–2003 were calculated by an extrapolation of NMVOC emissions for 1995 and 2000 by using an appropriate indicator per sector. Emissions from fuel combustion sources were scaled in time by using fuel consumption data. National production or fuel (gas and oil) consumption was used to scale non-combustion emissions related to fuel use. For other sectors the Gross Domestic Product (GDP) was used as a scaling factor (provinces of China: China Statistical Yearbook; other countries: World Bank, 2006).

2.4 Projection of future emissions

Future projection of Asian emissions was performed on the basis of emission scenarios and emissions for 2000. Three emission scenarios for China have been developed for the years 2010 and 2020 by Zhou et al. (2003). The socioeconomic indices, such as population, urbanization, and GDP, are almost the same under these scenarios. The population in 2020 (1.45–1.49 billion) is about equal to that of the IPCC B2 scenario (1.45 billion) (Nakicenovic and Swart, 2000). The GDP growth rate from 2000 to 2020 (7.3% y^{-1} before 2010 and 6.7% y^{-1} after 2010) is close to that of the A2 scenario of IPCC (7% y^{-1}) (Nakicenovic and Swart, 2000).

The first scenario was termed the Policy Failed Case scenario, or PFC. This is a pessimistic scenario with high emission rates caused by continuation of the current energy structure, increased energy consumption, and the slow deployment of new energy technologies and new emission control technologies. The second scenario was termed the Reference scenario, or REF. This was a sustainable scenario with moderate emission rates caused by the suppression of energy consumption through energy conservation, a change to clean energy, and the moderate deployment of new energy technologies and new emission control technologies. We considered that this represented our “best guess” as to what emissions in Asia will be in 2010 and 2020. The third scenario was termed the Policy Succeed Case scenario, or PSC. This was the optimistic case, with low emission rates owing to the implementation of strong energy and environmental policies and the fast deployment of new energy technologies and new emission control technologies. Each concept – PSC, REF, and PFC – resembled that of the B1 scenario, the B2 scenario, and the A2 scenario of IPCC (Nakicenovic and Swart, 2000), respectively.

In the research project of the China Energy Research Institute and National Lawrence Berkley Laboratory (Zhou et al., 2003), fuel consumptions under the PSC, REF, and PFC scenarios were provided from forecasts by a simulation model, the Long-range Energy Alternatives Planning system (LEAP; available at http://forum.seib.org/leap), developed by the Stockholm Environment Institute. Chinese fuel consumption for the years 2010 and 2020 are presented in Fig. 3. Total fuel consumption in China in 2010 was 1.22 (PSC), 1.30 (REF), and 1.35 (PFC) times that in 2000. There is expected to be a further marked increase by 2020. There should be increases in fuel consumption of 39% (PSC), 63% (REF), and 77% (PFC), between 2000 and 2020. In particular, the differences in coal consumption by power plants between the three scenarios are important to note. For other countries, fuel consumption in 2010 and 2020 was calculated on the basis of Reference Scenario Projections in the “World Energy Outlook” (IEA, 2002).

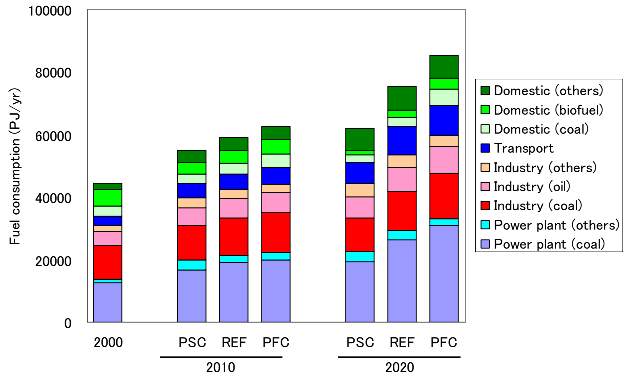

Fig. 3. Chinese fuel consumption in 2000, 2010, and 2020 under the three REAS scenarios.

Changes in emission factors were considered only in terms of the following: (1) the efficiencies of removal of SO_2 by the power plants and industry sector under the three scenarios in China (Wang et al., 2002). For other countries, removal efficiencies by power plants were set on the basis of RAINS-Asia and on the assumption that these would be 99% in 2030; (2) the emission factors of NO_x for power plants under the three scenarios in China. It was assumed that those in 2020 would be the same as the Japanese values for the year 2000 under the PSC scenario, as the Chinese 2000 values under the PFC scenario, and as the average values of those for PSC and PFC scenarios under the REF scenario. For other countries, efficiencies of removal by power plants were set on the assumption that the 2030 values would reach the new technology level in RAINS-Asia; and (3) for the road transport sector, country-specific information on emission controls (Nissan Automobile Corporation, 2005).

Non-combustion emissions in 2010 and 2020 were estimated by using 2000 emissions and the increment rate of GDP under each scenario, except in the case where data on the industrial production of iron, cement, and some metals were available for the three scenarios in China. NMVOC

Table 4. Summary of national emissions in 2000[a].

Country	SO_2	NO_x	BC	OC	CO	NMVOC
China	27555	11186	1093	2563	137011	14730
Japan	926	1959	75	44	2661	1880
S. Korea	986	1559	33	57	4627	1134
N. Korea	297	221	42	117	5363	200
Mongolia	88	41	4	13	395	23
Taiwan	266	648	10	10	2299	502
Macau	4	5	0	0	24	–
Brunei	3	20	0	1	43	43
Cambodia	30	48	9	45	802	113
Indonesia	1073	1653	189	889	20890	5310
Laos	9	18	3	16	372	61
Malaysia	219	388	13	30	2878	986
Myanmar	83	93	35	178	3413	517
Philippines	712	473	23	78	5500	969
Singapore	287	157	15	61	1045	81
Thailand	998	591	34	98	10892	2124
Vietnam	235	330	92	437	8679	886
Bangladesh	106	169	67	266	5410	483
Bhutan	5	8	2	9	205	21
India	6140	4730	795	3268	79382	8638
Nepal	26	41	27	136	2404	206
Pakistan	1095	640	112	445	9016	1135
Sri Lanka	97	120	17	61	1557	196
Afghanistan	7	12	9	50	547	–
Maldives	1	2	0	0	6	–
Aviation[b]	6	199	3	1	92	–
Shipping[c]	1525	2005	26	10	21	–
All Asia	42778	27316	2728	8883	305533	40238

[a] Data are in kt y^{-1}.
[b] Fossil fuel use for international aviation.
[c] Fossil fuel use for international shipping.

emissions were estimated by extrapolation of NMVOC emissions for 2000 by using national or regional values of fuel consumption for fuel combustion and non-combustion sources related to fuel use, and of GDP for other emission sources.

3 Results and discussion

3.1 Asian and national emissions in 2000

Table 4 summarizes national emissions in 2000 and Table 5 shows regional emissions in 2000 by emitting sector and fuel type.

3.1.1 SO_2

Total Asian emissions of SO_2 was 42.8 Mt in 2000; China at 27.6 Mt (65%) and India at 6.1 Mt (14 %) were the high-emission countries. In terms of sectoral and fuel-type contribution, emissions from coal combustion were dominant (70%); in particular, those from power plants and industry were major sources with 35% and 28%, respectively, of total emissions. In China, the country with the highest emission rates, the contribution of coal combustion to total emissions was as high as 84%. In India, the country with the second-highest emission rate, emissions from coal-burning power plants accounted for around half (47%), whereas the contribution of emissions from coal combustion to the total emissions (58%) was smaller than that of China (84 %).

Table 6 shows the emissions for 2000 from different inventories, excluding emissions from international aviation and shipping and from open biomass burning. We compared the values in the Asian inventories REAS and TRACE-P (Streets et al., 2003) and the global inventories IIASA (http://www.iiasa.ac.at/rains/global_emiss/global_emiss1.html) and EDGAR 32FT2000 (http://www.mnp.nl/edgar/model/v32ft2000edgar/). For Asian emission of SO_2, the REAS value (41.2 Mt) was the same as the IIASA one (41.2 Mt), whereas the TRACE-P value (32.9 Mt) was

Table 5. Regional emissions in 2000 by emitting sector and fuel type[a].

	Power Plants			Industry				Transport		Domestic			Aviation[b]	Shipping[c]	Total
	Coal	Oil	Others	Coal	Oil	Others	Process	Oil	Others	Coal	Biofuel	Others			
China															
SO_2	10569	357	34	10464	719	432	1794	219	168	2323	272	206			27555
NO_x	3788	169	74	2839	357	156		2773	57	290	439	245			11186
BC	13	5	0	85	14	0		37	1	465	465	8			1093
OC	3	4	0	17	10	0		32	0	377	2111	9			2563
CO	1824	36	442	47633	241	47	9442	19003	34	17431	40391	486			137010
India															
SO_2	2865	216	3	490	1339	63	241	199	0	165	348	212			6140
NO_x	1543	185	81	249	228	161	0	1564	0	45	618	56			4730
BC	8	2	0	7	8	11	0	78	0	62	616	2			795
OC	2	2	0	1	6	56	0	62	0	50	3083	6			3268
CO	936	71	262	4088	160	6978	1461	7093	0	2253	56058	22			79382
All Asia															
SO_2	14598	1713	101	12102	3750	803	2631	1150	168	2536	948	747	6	1525	42778
NO_x	6012	842	717	3695	1217	690		9169	57	361	1588	763	199	2005	27316
BC	22	29	2	99	48	18		258	1	549	1649	24	3	26	2728
OC	6	22	2	21	35	87		191	0	445	8025	39	1	10	8883
CO	3147	229	1414	57478	713	18747	13680	42176	34	20710	145879	1213	92	21	305533

[a] Data are in kt y^{-1}.
[b] Fossil fuel use for international aviation.
[c] Fossil fuel use for international shipping.

20% lower and that of EDGAR (56.0 Mt) was 36% higher than that of REAS. The distributions of emissions among sectors in REAS and IIASA were similar (data not shown).

Table 7 compares the Chinese emissions from 1995 to 2003 according to REAS and other inventories, including the values estimated by the State Environmental Protection Administration, China (SEPA, 2003). For SO_2 emissions in 2000, the REAS value (27.6 Mt) was almost the same as the IIASA one (27.7 Mt) but higher than those of SEPA (20.0 Mt) and TRACE-P (20.3 Mt). The main reason is the differences in fuel consumption values used in each inventory: total fuel consumption used in TRACE-P (Streets et al., 2003) was 36201 PJ (coal consumption 18189 PJ), whereas that used in REAS was 44520 PJ (coal consumption 26797 PJ) – 1.23 times the total fuel consumption and 1.47 times the coal in TRACE-P. These differences reflect the fact that coal consumption for 2000 in PBP-CESY, which was used in REAS, was 1.5 times that in CESY (Akimoto et al., 2006). On the other hand, EDGAR estimated emissions in China in 2000 to be 34.2 Mt – much higher than the values used in other inventories.

Table 8 compares the Indian emissions for 1995 and 2000 as estimated by REAS and other inventories. For SO_2 emissions in 2000 in India, REAS estimated 6.1 Mt, which is very close to the value reported by IIASA (5.9 Mt). However the TRACE-P value (5.5 Mt) was slightly lower and that of EDGAR (7.8 Mt) much higher than the REAS and IIASA values; these results are similar to those for the Chinese emissions.

It should be noted that the SO_2 emissions in EDGAR were larger than those in other emission inventories, with the exception of emissions from other South Asia (Table 6). For example, EDGAR estimated emissions from China in 2000 as 34.2 Mt, compared with about 20–28 Mt in other inventories. Because EDGAR was the inventory most widely used for global modeling, the marked discrepancy in Asia needs to be resolved (Akimoto and Ohara, 2004).

3.1.2 NO_x

Total emissions of NO_x in Asia were 27.3 Mt in 2000 (Table 4); China at 11.2 Mt (65%) and India at 4.7 Mt (17%) were high-emission countries, as was the case for SO_2 emissions. Japan (7%), South Korea (6%), and Indonesia (6%) also made relatively large contributions. In terms of sectoral and fuel-type contributions (Table 5), transport oil use was the largest (34%), followed by coal use in power plants (22%) and industrial coal use (14%). For contributions by fuel type alone, oil use (41%) was slightly greater than coal use (37%), unlike the case with SO_2 emissions, where coal use was the dominant contributor. In China, the country with the largest emissions, coal-burning power plants were the largest emitters (34%), followed by industrial coal use and transport oil use (both at 25%). In India, the contributions of coal-burning power plants and transport oil use were dominant (both at 33%). Additionally, domestic biofuel use was a large contributor (13%) – larger than in China (4%).

Comparison of the Asian total emissions for 2000 (Table 6), as estimated by REAS and other inventories revealed that the REAS value (25.1 Mt) was almost the same as the

Table 6. Comparison of estimates of Asian emissions in 2000[a].

Inventory projects	REAS	TRACE-P[b]	EDGAR 3.2[c]	IIASA[d]
		SO_2		
China	27555	20303	34197	27711
Japan	926	800	2210	871
Other East Asia	1642	1513	6511	1581
Southeast Asia	3649	3150	4127	3411
India	6140	5462	7846	5919
Other South Asia	1336	1634	1130	1658
All Asia	41248	32862	56021	41152
		NO_x		
China	11186	10531	13728	11722
Japan	1959	2188	2725	2504
Other East Asia	2473	2137	3006	2260
Southeast Asia	3770	3058	3913	3944
India	4730	4047	6285	4563
Other South Asia	992	713	1444	800
All Asia	25112	22674	31102	25792
		BC		
China	1093	936		
Japan	75	52		
Other East Asia	89	52		
Southeast Asia	413	321		
India	795	517		
Other South Asia	234	142		
All Asia	2699	2020		
		OC		
China	2563	2657		
Japan	44	62		
Other East Asia	197	133		
Southeast Asia	1833	1370		
India	3268	2190		
Other South Asia	967	626		
All Asia	8872	7038		
		CO		
China	137011	141700	86518	75442
Japan	2661	6576	10718	5324
Other East Asia	12708	8454	10789	6002
Southeast Asia	54514	34045	42616	39800
India	79382	51081	58631	46753
Other South Asia	19145	11165	22231	12232
All Asia	305420	253021	231503	185554

[a] Data are in kt y^{-1}, excluding emissions from fossil fuel use for international aviation, international shipping, and open biomass burning.
[b] Streets et al. (2003) and http://www.cgrer.uiowa.edu/EMISSION_DATA/index_16.htm. CO emissions in China is the result of Streets et al. (2006).
[c] http://www.mnp.nl/edgar/model/v32ft2000edgar/
[d] http://www.iiasa.ac.at/rains/global_emiss/global_emiss1.html. Excluding Afghanistan.

IIASA one (25.8 Mt), whereas the TRACE-P value (22.7 Mt) was 10% lower, and that of EDGAR (31.1 Mt) 24% higher, than the REAS value. For Chinese NO_x emissions (Table 7), the REAS value for 2000 (11.2 Mt) was almost the same as the IIASA one (11.7 Mt), whereas the TRACE-P value (10.5 Mt) was lower, and that of EDGAR (13.7 Mt) substantially higher, than the REAS and IIASA values. For Indian NO_x emissions (Table 8), the REAS (4.7 Mt) and IIASA (4.6 Mt) values were very close, whereas the TRACE-P value (4.0 Mt) was slightly lower, and the EDGAR (6.3 Mt) value higher, than the REAS and IIASA values.

Table 7. Comparison of estimates of Chinese emissions, 1995–2003[a].

Study	1995	1996	1997	1998	1999	2000	2001	2002	2003
SO_2									
SEPA	23700	23000	22400	21100	18575	19951	19478	19266	21587
Xue et al. (1998)	23700								
RAINS-ASIA	23800								
Klimont et al. (2001)	20900								
Streets and Waldhoff (2000)[b]	24724								
Streets et al. (2000)	25852	26359	25110						
TRACE-P; Streets et al. (2003)						20300			
IIASA	24818					27711			
EDGAR 3.2	34548					34197			
REAS; this study	27141	28395	27755	27638	26987	27555	29292	31932	36627
NOx									
Hao et al. (2002)	11298	12035	11666	11184					
Xue et al. (1998)	10700								
Klimont et al. (2001)	9700								
Streets and Waldhoff (2000)[b]	11295								
Streets et al. (2001a)	11192		12537						
TRACE-P; Streets et al. (2003)						10531			
IIASA	9907					11722			
EDGAR 3.2	12361					13728			
REAS; this study	9305	9943	10003	10463	10740	11186	11765	12688	14488
BC									
Cao et al. (2006)						1396			
Streets et al. (2001b)	1267								
TRACE-P; Streets et al. (2003)						936			
Bond et al. (2004)		1365							
REAS; this study	1394	1331	1250	1213	1149	1093	1100	1113	1137
OC									
Cao et al. (2006)						3815			
TRACE-P; Streets et al. (2003)						2657			
Bond et al. (2004)		2111							
REAS; this study	3189	3072	2919	2811	2685	2563	2580	2599	2624
CO									
Streets and Waldhoff (2000)[b]	10900								
TRACE-P; Streets et al. (2003)						100000			
Streets et al. (2006)							141700		
IIASA	73446					75442			
EDGAR 3.2	88000					86518			
REAS; this study	149386	148927	144974	143301	139187	137011	140642	146298	158267

[a] Data are kt y^{-1}, excluding emissions from open biomass burning.
[b] Data including emissions from open biomass burning.

Thus, the differences among emission inventories (REAS, IIASA, TRACE-P, and EDGAR) were similar for SO_2 and NO_x emissions in Asia, China, and India: the values estimated by REAS were close to those of IIASA, whereas TRACE-P values were smaller, and EDGAR ones larger, than those of REAS and IIASA.

3.1.3 BC

Total emissions of BC in Asia were 2.73 Mt in 2000 (Table 4), and emissions from China (1.09 Mt; 40%) and India (0.80 Mt; 29%) were dominant, as were the SO_2 and NO_x emissions. Domestic consumption of biofuel and coal was the dominant contributor of BC emissions (80%–60%

Table 8. Comparison of estimates of Indian emissions, 1995 and 2000[a].

Study	SO_2		NOx		BC		OC		CO	
	1995	2000	1995	2000	1995	2000	1995	2000	1995	2000
Garg et al. (2001)	4640		3460							
Reddy & Venkataraman (2002a,b)[b]	4330				307		692			
RAINS-ASIA	5000									
Streets et al. (2001a)	5610		4500							
TRACE-P; Streets et al. (2003)		5462		4047		517		2190		51081
Parashar et al. (2005)[c]					830		2270			
Bond et al. (2004)[d]					483		1362			
IIASA	5171	5919	3470	4563					52850	46753
EDGAR 3.2	6484	7846	5347	6285					55099	58631
REAS; this study	5238	6140	4377	4730	791	795	3093	3268	74942	79382

[a] Data are $kt\,y^{-1}$, excluding emissions from open biomass burning.
[b] Base year is 1996–1998.
[c] Base year is 1995 (biofuels) and 1993-1994 (fossil fuels).
[d] Base year is 1996.

for biofuel and 20% for coal)(Table 5). For China, domestic combustion contributed 85% (43% each for biofuel and coal), and this percentage of coal use was twice the Asian average. In India, domestic biofuel use is a huge contributor at 77% – larger than the Asian total (60%) or the Chinese value (43%).

The Asian total BC emissions estimated by REAS (2.73 Mt) were 34% higher than those of TRACE-P (2.02 Mt) (Table 6). However, more recent estimates of emissions for 1996 that were developed for global carbonaceous particle inventories by the same group (Bond et al., 2004; Streets et al., 2004) were 2.65 Mt (central value), which corresponds to 2.88 Mt for 1996 in REAS. The Chinese BC emissions in 2000 (Table 7) as estimated by REAS (1.09 Mt) were lower than those of Cao et al. (2006) (1.40 Mt) but slightly higher than those of TRACE-P (0.94 Mt). For Chinese emissions in 1996 (Table 7), the REAS value of 1.33 Mt agreed with that of 1.37 Mt estimated by Bond et al. (2004). The Indian BC emissions for 2000 (Table 8) as estimated by REAS (0.80 Mt) were the same as those of Dickerson et al. (2002), which were based on the INDOEX (Indian Ocean Experiment) observations, but higher than those of TRACE-P (0.52 Mt). For Indian emissions in about 1995 (Table 8), the REAS value of 0.79 Mt is close to the 0.83 Mt (central value; range 0.31–1.94 Mt) estimated by Parashar et al. (2005), but higher than the values of 0.31 Mt by Reddy and Venkataraman (2002b) and 0.48 Mt (central value; range 0.31–1.04 Mt) by Bond et al. (2004). It should be noted that the estimated BC emissions are highly variable because of the large uncertainties in the emission factors.

3.1.4 OC

Total emissions of OC in Asia was 8.88 Mt in 2000 (Table 4). India at 3.27 Mt (37%) was the largest emitter, followed by China at 2.56 Mt (29%): the Indian emissions were larger than the Chinese one, unlike the case for SO_2, NO_x, and BC. Domestic consumption was the dominant contributor of OC emissions (95%), especially for biofuel use (90%). In India, domestic biofuel use contributed a large proportion of the OC emissions (94%). For Chinese emissions, domestic combustion contributed 97% (82% for biofuel and 15% for coal).

Asian total OC emissions as estimated by REAS (8.87 Mt) were 26% higher than those estimated by TRACE-P (7.04 Mt) (Table 6), owing to differences in coal consumption in the domestic sector (for which the REAS value was 1.5 times the TRACE-P one). In addition, more recent estimates of emissions for 1996 (Bond et al., 2004; Streets et al., 2004) were 2.80–9.18 Mt (central value; 4.81 Mt); the upper value corresponded to the value for 1996 estimated by REAS (9.05 Mt; data not shown). The emission factors for residential biofuel and coal combustion used by Bond et al. (2004) were lower than those in REAS and TRACE-P.

The Chinese OC emissions in 2000 (Table 7) as estimated by REAS (2.56 Mt) were close to those of TRACE-P (2.66 Mt) but much lower than those of Cao et al. (2006) (3.82 Mt), whose industrial emission value (1.12 Mt) was much higher than those of REAS and TRACE-P (both 0.03 Mt), as was the case with BC emissions. For 1996, the REAS emission value of 3.07 Mt was higher than the 2.11 Mt estimated by Bond et al. (2004). There were large differences in the OC/BC ratio between inventories for China – 1.55 for Bond et al. (2004), 2.24 for REAS, 2.73 for Cao

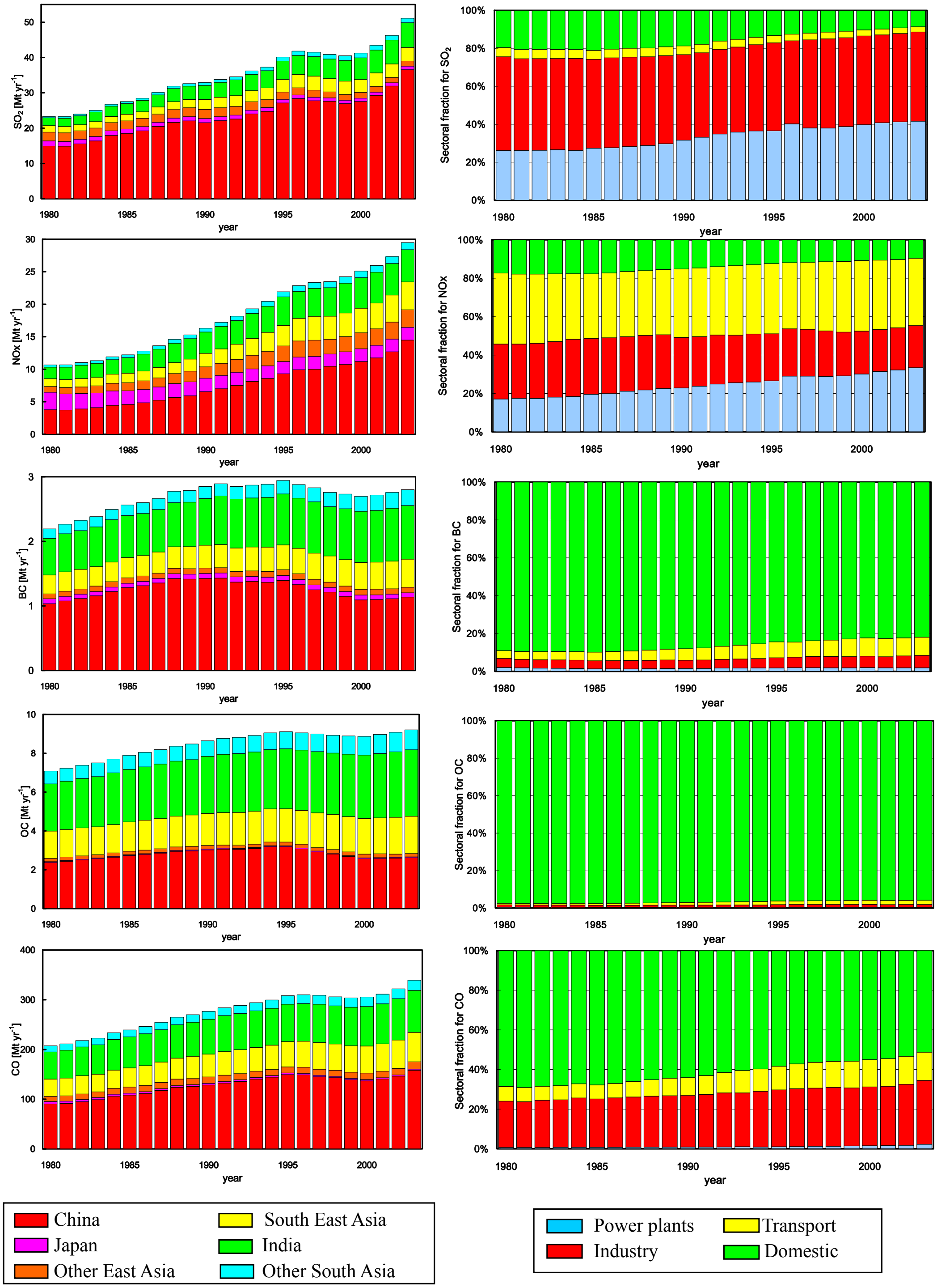

Fig. 4. Temporal evolution of emissions for SO_2, NO_x, BC, OC, and CO and their sectoral distributions between 1980 and 2003.

et al. (2006), and 2.84 for TRACE-P – indicating that the emission factors for carbonaceous aerosols were highly uncertain. The discrepancy in the OC/BC ratio between REAS and TRACE-P was because there were large differences in the contribution of each fuel type in the domestic sector but only small differences in the emission factors in this sector. That is, fuel consumption in the domestic sector for REAS was 10.6 EJ (coal 3.1 EJ, biofuel 5.3 EJ, others 2.2 EJ) and that for TRACE-P was 10.6 EJ (coal 2.4 EJ, biofuel 7.2 EJ, others 1.0 EJ). Thus, total consumption was the same, but

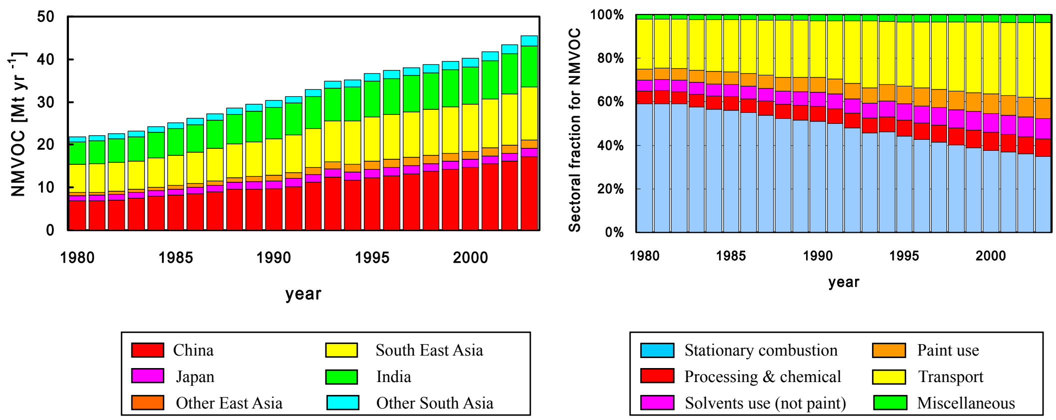

Fig. 5. Temporal evolution of NMVOC emissions and their sectoral distributions between 1980 and 2003.

each apportionment was quite different: for coal, the REAS value was larger than the TRACE-P one, whereas for biofuel the REAS value was smaller than the TRACE-P one. For BC, the averaged emission factor for coal combustion was twice that for biofuel, whereas for OC that for biofuel was 3.5 times that for coal (see Table 3). Therefore, the value of BC emissions in REAS was higher than that in TRACE-P, whereas the value of OC emissions in REAS was lower than that in TRACE-P, and the resulting OC/BC ratio for REAS was lower than that in TRACE-P.

The Indian OC emissions in 2000 as estimated by REAS (3.27 Mt) (Table 8) were higher than that of TRACE-P (2.19 Mt). This discrepancy was due to differences in biofuel consumption in the domestic sector: the REAS value was 20% larger than the TRACE-P one. For Indian emissions in about 1995, the REAS emission value of 3.09 Mt was close to the upper value (range, 1.19–3.34 Mt) estimated by Parashar et al. (2005) but much higher than the 0.69 Mt of Reddy and Venkataraman (2002b) and the 1.36 Mt (central value; range 0.80–2.47 Mt) of Bond et al. (2004). This higher REAS value was a result of the high emission factor for biofuel in the residential sector; the value used in REAS ($5\,\mathrm{g\,kg^{-1}}$) was close to the upper limit in Table 2 of Parashar et al. (2005).

3.1.5 CO

Total emissions of CO in Asia were 306 Mt in 2000 (Table 4); China was the dominant country with 137 Mt (45%), followed by India with 79 Mt (26%). In terms of sectoral and fuel-type contribution (Table 5), domestic biofuel use was the largest (48%), followed by industrial burned coal (19%), transport oil use (14%), and domestic coal use (7%). Thus, CO emission sources, unlike those of other species, were distributed over many kinds of sector and/or fuel type. Contributors to Chinese CO emissions were industrial burned coal (35%), biofuel and coal in the domestic sector (29% and 13%), and transport oil use (14%): the contribution of burned coal was higher than the average for Asia. In India, domestic biofuel use was the largest contributor (71%), followed by industrial biofuel use and transport oil use (each 9%).

The Asian CO emissions for 2000 as estimated by REAS (306 Mt) (Table 6) were higher than the values by TRACE-P (253 Mt), EDGAR (232 Mt), and IIASA (186 Mt) because of the application of higher emission factors for coal combustion in REAS. For Chinese CO emissions in 2000 (Table 7), the REAS value (137 Mt) was similar to that of Streets et al. (2006) (142 Mt). However, there were large differences in sectoral emissions between REAS and Streets et al. (2006): emissions from the power plants, industry, transport, and domestic sectors were, respectively 2, 57, 19, and 58 Mt by REAS and 2, 54, 38, and 48 Mt by Streets et al. (2006). Thus, the REAS value was higher in the domestic sector and lower in the transport sector than that of Streets et al. (2006). The Chinese CO emissions in REAS were consistent with the values for fossil fuel and biofuel combustion sources (145–168 Mt) estimated by top-down approaches such as inverse modeling (Palmer et al., 2003; Yumimoto and Uno, 2006) and forward modeling (Allen et al., 2004).

3.2 Historical emissions between 1980 and 2003

By using the activity data and emission factors described in Sects. 2.2 and 2.3, emissions of SO_2, NO_x, BC, OC, and CO, as well as NMVOC, were calculated for the period 1980–2003. Annual variations in regional emissions and the sectoral distributions of total emissions between 1980 and 2003 are shown in Fig. 4 for SO_2, NO_x, BC, OC, and CO, and in Fig. 5 for NMVOC. Table 9 shows the Asian and Chinese emissions at 5-year intervals in the period 1980–2003. Asian total emissions for every species increased by 1.3 times (for BC) to 2.8 times (for NO_x) from 1980–2003. Asian emissions for SO_2 and NO_x, whose major sources are combustion facilities of fossil fuel, rapidly increased from 1980. NMVOC emissions also rapidly increased because of such factors as the growth of automobile use and solvent and paint

Table 9. Asian and Chinese emissions, 1980–2003[a].

		1980	1985		1990		1995		2000		2003	
Asia [b]	SO_2	23338	27681	*(1.19)*	33040	*(1.42)*	40377	*(1.73)*	41488	*(1.78)*	51020	*(2.19)*
	NOx	10676	12243	*(1.15)*	16316	*(1.53)*	21936	*(2.05)*	25112	*(2.35)*	29486	*(2.76)*
	BC	2194	2563	*(1.17)*	2850	*(1.30)*	2944	*(1.34)*	2699	*(1.23)*	2802	*(1.28)*
	OC	7083	7895	*(1.11)*	8644	*(1.22)*	9109	*(1.29)*	8872	*(1.25)*	9205	*(1.30)*
	CO	207388	239353	*(1.15)*	276734	*(1.33)*	308093	*(1.49)*	305420	*(1.47)*	339399	*(1.64)*
	NMVOC	21850	25144	*(1.15)*	30335	*(1.39)*	36671	*(1.68)*	40238	*(1.84)*	45470	*(2.08)*
China	SO_2	14944	18524	*(1.24)*	21564	*(1.44)*	27141	*(1.82)*	27555	*(1.84)*	36627	*(2.45)*
	NOx	3774	4603	*(1.22)*	6550	*(1.74)*	9305	*(2.47)*	11186	*(2.96)*	14488	*(3.84)*
	BC	1034	1283	*(1.24)*	1425	*(1.38)*	1394	*(1.35)*	1093	*(1.06)*	1137	*(1.10)*
	OC	2370	2730	*(1.15)*	3020	*(1.27)*	3189	*(1.35)*	2563	*(1.08)*	2624	*(1.11)*
	CO	90311	108228	*(1.20)*	128354	*(1.42)*	149386	*(1.65)*	137011	*(1.52)*	158267	*(1.75)*
	NMVOC	6826	8185	*(1.20)*	9701	*(1.42)*	12212	*(1.79)*	14730	*(2.16)*	17183	*(2.52)*

[a] Data are kt y^{-1}. Numbers in parentheses are ratios to the 1980 values.
[b] Excluding emissions from international aviation and international shipping.

use. The trend in carbonaceous particles (BC and OC) emissions, whose major sources are biofuel combustion in the residential sector, showed small increases or fluctuations. The trend in CO emission showed the blended features of emissions for SO_2 (or NO_x) and carbonaceous particles. A detailed explanation of these features is presented in the following sections.

3.2.1 SO_2

Total emissions of SO_2 in Asia increased from 1980 to 1996, but subsequently decreased till 1999, reflecting a decrease in fuel consumption due to the Asian economic crisis; after 2000 SO_2 emissions increased at a phenomenal rate. Those emissions increased by 2.2 times in the period 1980–2003, and, notably, by 3.2 times in India and 2.5 times in China. Examination of sectoral contributions in Asia revealed that the contribution of power plants increased from 28% in 1980 to 46% in 2003. That of industry varied only slightly from 46% in 1980 to 42% in 2003, and that of the domestic sector greatly decreased from 21% in 1980 to 9% in 2003.

We examined the time series of Chinese SO_2 emissions in REAS, along with previous estimates (Fig. 6). Before 2000, the REAS variation corresponded to that of IIASA. The variation in SEPA (2003) was similar to that in REAS during 1986–1994, but about 7 Mt y^{-1} lower. In contrast, there were large differences between SEPA and REAS in the decreasing trend of SO_2 emissions during 1995 and 2000, reflecting the differences in coal consumption in each inventory (Akimoto et al., 2006).

3.2.2 NO_x

Total emissions of NO_x in Asia (Table 9 and Fig. 4) showed a monotonic increase between 1980–2003 with no dips, in contrast to the pattern of SO_2 emissions. The emissions increased by 2.8 times from 1980–2003, with values of 10.7 Mt in 1980 and 29.5 Mt in 2003. In particular, Chinese NO_x emissions increased dramatically by 3.8 times from 1980 to 2003 – an annual-average growth rate of 6%, with the highest growth after 2000 (by 1.3 times over only 3 years). Recently, these NO_x trends in the period 1996–2003 over China were validated by comparison with column NO_2 data from the GOME (Global Ozone Monitoring Experiment) satellite by Akimoto et al. (2006) and Uno et al. (2006). These trends in Chinese NO_x emissions in REAS were consistent with those in other inventories, including IIASA, TRACE-P, and Hao et al. (2002) (Fig. 6).

Examination of sectoral contributions to Asian NO_x emissions revealed that emissions from the power plants, industry, transport, and domestic sectors contributed 17%, 29%, 37%, and 17%, respectively, in 1980 and 33%, 22%, 35%, and 10%, respectively, in 2003: thus, the contribution of power plants almost doubled between 1980 and 2003 .

3.2.3 BC

Total BC emissions in Asia increased by 1.3 times over the period 1980–2003 (Table 9 and Fig. 4). However, the complexity of the temporal variation in this period was relatively large: emissions increased from 1980 to 1991, but subsequently were almost constant or slightly decreased till 2000; after 2000 they increased again. These complicated variations are reflected by those of the Chinese emissions. In China, the trend in total BC emissions is controlled by the balance between a decreasing rate of emissions from coal and biofuel combustion in the domestic sector and an increasing rate of emissions from coal-burning sources in the industrial sector and diesel vehicles. Examination of sectoral contributions showed that the contribution of the domestic sector decreased from 89% in 1980 to 82% in 2003 owing to the trend toward upgrading fuel quality from biofuels and coals

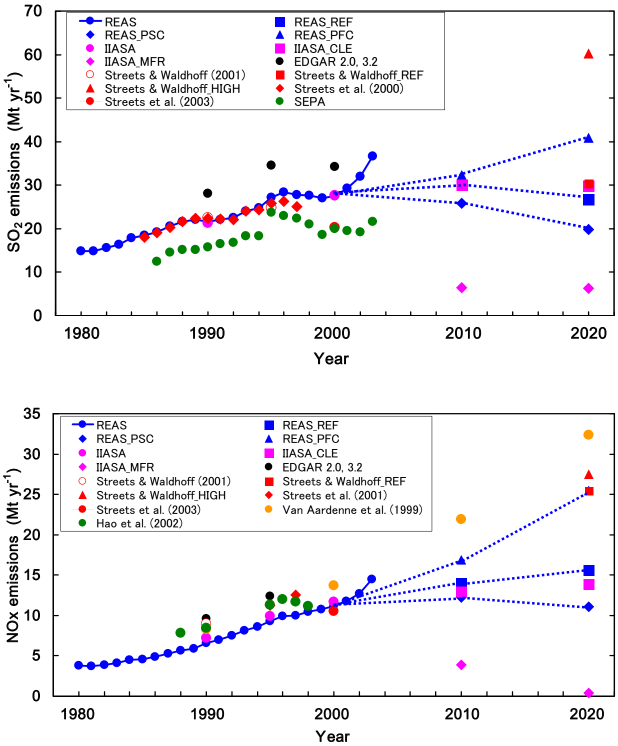

Fig. 6. Time series of SO_2 and NO_x emissions in China.

(as mentioned below), whereas that of transport sector increased from 4% in 1980 to 10% in 2003 because of the increase in the use of diesel vehicles.

The increase in BC emissions from 1980 to 2000 in South Asia, including India, was highest (1.5 times; data not shown), but that in China was comparatively small (1.1 times). Accordingly, there was a large difference between India and China in the changes in spatial distribution of BC emissions (see Fig. 8 in Sect. 3.4). In China, coal and biofuel combustion in the domestic sector is the dominant contributor to BC emissions (see Table 5). Total fuel consumption in the domestic sector increased from 8.4 EJ in 1980 to 10.6 EJ in 2000, whereas the contributions of coal and biofuel to total fuels decreased. As a result, total consumption (7.9 EJ) of coal and biofuel in 2000 was almost the same as that in 1980 (7.8 EJ; see Table 2). This caused a small increase in BC emissions in China. On the other hand, in India, only biofuel combustion in the domestic sector was the dominant contributor to BC emissions (see Table 5). Biofuel consumption in the domestic sector in India increased from 5.9 EJ in 1980 to 7.9 EJ in 2000, and its contribution in the period 1980–2000 was maintained at around 90% (91% for 1980 and 86% for 2000; see Table 2). Consequently, Indian BC emissions continued to increase throughout the period, unlike Chinese BC emissions.

3.2.4 OC

Total OC emissions in Asia increased by 1.3 times in the period 1980–2003 (Table 9 and Fig. 4), and the temporal variations were very similar to those of BC. Biofuel combustion in the domestic sector was the dominant contributor to OC emissions in both China and India (see Table 5). Biofuel consumption in China increased until 1995, and then slightly decreased or was uniform, whereas that in India continued to increase. As a result, although the value of OC emissions in India was almost the same as that in China before 1995, the former was higher than the latter after 1996. Consequently, the contrast between India and China in the changes in spatial distributions of OC emissions was similar to, but clearer than, that for BC (see Fig. 8 in Sect. 3.4).

The OC/BC ratio in emissions varies widely throughout Asia, depending on the biofuel share of total fuels in the domestic sector. For example, the averaged OC/BC ratio in the period 1980–2003 was almost 2.3 (2.29 in 1980 and 2.31 in 2003) in China, but it was higher at almost 4.2 (4.29 for 1980 and 4.12 for 2003) in India because of the higher share of biofuel. Additionally, a clear contrast in the regional OC/BC ratio was also found within China: the ratio in southern areas of China was higher than that in northern areas, reflecting the higher share of coal and lower share of biofuel in northern areas. It should be noted that these spatial and temporal variations in OC/BC ratio play an important role in the radiative effects of these aerosols over Asia.

3.2.5 CO

Total emissions for CO in Asia increased by 1.6 times in the period 1980–2003 (Table 9 and Fig. 4). The variation was similar to that of SO_2 and was reflected by that of Chinese CO emissions, whose value was the largest in Asia, whereas CO emissions in India, which had the second-highest emission rate in Asia, continued to increase throughout the period. For China, CO emissions increased by 1.8 times from 1980 to 2003, but they decreased from 1995–2000 owing to a reduction in consumption of coal and biofuel in the domestic sector in this period. Examination of sectoral contributions to Asian CO emissions revealed that the contribution of industry increased from 23% in 1980 to 32% in 2003, and that of transport increased from 7% in 1980 to 14% in 2003. That of the domestic sector decreased from 69% in 1980 to 51% in 2003.

3.2.6 NMVOC

Total emissions of NMVOC in Asia showed a monotonic increase over the years 1980–2003 with no dip (Table 9 and Fig. 5), and the fundamental features of variation were similar to those for NO_x. Asian emissions increased by 2.1 times during the same period, especially in China, which had an increase of 2.5 times. Stationary combustion, processing and handling of fossil fuels and chemical industry ("Processing & chemical" in Fig. 5), solvent use (excluding paint), paint use, transport, and miscellaneous contributed 59%, 6%, 5%, 5%, 23%, and 2%, respectively, to the total Asian NMVOC emissions in 1980, and 35%, 8%, 9%, 9%, 35%, and 4%, respectively, in 2003: thus, examination of sectoral contributions showed a decrease for stationary combustion, a small increase for processing and handling of fossil fuels and chemical industry, and an increase for solvent and paint use and transport.

3.3 Projection of future emissions

Here, we briefly summarize the projected emissions of SO_2, NO_x, BC, OC, CO, and NMVOC in 2010 and 2020 (Table 10 and Fig. 7).

3.3.1 SO_2

Chinese SO_2 emissions in the REF scenario showed a 9% increase (to 30.0 Mt) for 2010 and a 3% decrease (to 26.8 Mt) for 2020 compared with 2000 (27.6 Mt). Although SO_2 emissions in China were significantly reduced from 2000 levels in the PSC scenario (by 6% in 2010 and 28% in 2020), the PFC scenario showed an increase of 17% in 2010 and 48% in 2020 over the 2000 level.

Consequently, Asian total SO_2 emissions are strongly influenced by the emission scenario in China. The future total Asian emissions for SO_2 under the REF scenario for China were projected to increase by 16% (to 47.9 Mt) in 2010 and 22% (to 50.2 Mt) in 2020 over the 2000 level (41.2 Mt). Asian 2020 emissions under the PSC scenario for China were estimated to be 43.3 Mt, showing only a small increase (by 5%) compared with the 2000 level, whereas the PFC scenario for China showed a rapid increase in Asian 2020 emissions: by 55% compared with the 2000 level.

SO_2 emissions in East Asia excluding China (sum of values for Japan and other East Asia in Table 10) were projected to increase by 41% from 2000 (2.6 Mt) to 2020 (3.6 Mt). In Southeast Asia, SO_2 emissions would double between 2000 (3.6 Mt) and 2020 (7.1 Mt). Indian and other South Asian SO_2 emissions in 2020 were estimated to be 10.2 Mt and 2.5 Mt, respectively, showing a rapid growth in emissions (by 66% in India and 91% in other South Asia) compared with the 2000 level.

3.3.2 NO_x

In China, future NO_x emissions under the REF scenario were projected to increase by 25% (to 14.0 Mt) in 2010 and by 40% (15.6 Mt) in 2020, compared with 2000 emissions (11.2 Mt). There was a marked difference between NO_x projections under the PSC and PFC scenarios. Under the PSC scenario, 2020 NO_x emissions were projected to be 11.1 Mt, but the PFC projection was more than twice as large at 25.5 Mt. Although the 2020 PSC scenario showed a slight reduction in emissions (1%) compared with the 2000 level, the 2020 PFC scenario projected a marked increase of 128% over the 2000 level.

Asian total emissions for NO_x under the REF scenario for China were projected to increase by 24% (to 31.1 Mt) in 2010 and 44% (36.1 Mt) for 2020 over 2000 values (25.1 Mt). Asian 2020 emissions under the PSC scenario for China were estimated to be 31.6 Mt, a modest increase (by 26%) compared with the 2000 level, whereas the PFC scenario for China showed a rapid increase in Asian 2020 emissions (to 46.0 Mt), by 83% compared with the 2000 level.

NO_x emissions in East Asia excluding China were projected to increase by 24% from 2000 (4.4 Mt) to 2020 (5.5 Mt). In Southeast Asia, NO_x emissions would increase by 53% from 3.8 Mt in 2000 to 5.8 Mt in 2020. Indian and other South Asian NO_x emissions in 2020 were estimated at 7.1 Mt and 2.2 Mt, respectively – a rapid growth in emissions (by 49% in India and 122% in other South Asia) compared with 2000 levels.

3.3.3 BC

Under the REF scenario, 2010 BC emissions in China (1.11 Mt) would be almost equal to those in 2000 (1.09 Mt) and would then decrease by 17% (to 0.91 Mt) by 2020, owing to the reduction in coal and biofuel consumption in the domestic sector. Under the PSC scenario, Chinese BC emissions would be markedly reduced from 2000 levels (by 11% in 2010 and 40% in 2020). On the other hand, the PFC scenario showed an increase of 19% (in 2010) and 29% (in 2020) compared with the 2000 level because the increase in coal combustion will exceed the decrease in biofuel combustion in the domestic sector.

The future trend in Asian total BC emissions depends on the emission scenario in China. Under the REF scenario for China, future BC emissions in all of Asia would increase from the 2000 level (2.70 Mt) by 16% (to 2.84 Mt) in 2010, and would then decline to about the 2000 level (2.73 Mt) in 2020. Asian 2020 emissions under the PSC scenario for China were estimated to be 2.48 Mt, a decrease (by 8%) compared with the 2000 level, whereas the PFC scenario for China gave an increase in Asian 2020 emissions of 20% over the 2000 level.

BC emissions in East Asia excluding China were projected to decline by 12% from 2000 (0.16 Mt) to 2020 (0.14 Mt) owing to the rapid reduction in Japan. In Southeast Asia, BC emissions would increase from 2000–2020, with 0.41 Mt in 2000 and 0.46 Mt in 2020. In India and other South Asia, 2020 BC emissions were estimated to be 0.89 Mt and 0.34 Mt, respectively – a modest increase in emissions (12% in India and 45% in other South Asia) compared with 2000 levels.

Table 10. Summary of regional emissions in 2010 and 2020[a].

Scenario	2000	2010REF	2010PSC	2010PFC	2020REF	2020PSC	2020PFC
				SO_2			
China	27555	29972	25864	32289	26804	19902	40863
Japan	926	913	-	-	914	-	-
Other East Asia	1642	2094	-	-	2698	-	-
Southeast Asia	3649	5170	-	-	7062	-	-
India	6140	7935	-	-	10192	-	-
Other South Asia	1336	1849	-	-	2546	-	-
All Asia	41248	47933	43825	50250	50216	43313	64275
				NO_x			
China	11186	13990	12253	16912	15619	11049	25469
Japan	1959	1837	-	-	1837	-	-
Other East Asia	2473	3069	-	-	3651	-	-
Southeast Asia	3770	4800	-	-	5763	-	-
India	4730	5900	-	-	7052	-	-
Other South Asia	992	1496	-	-	2201	-	-
All Asia	25112	31093	29355	34014	36124	31553	45973
				BC			
China	1093	1107	975	1306	911	659	1415
Japan	75	43	-	-	36	-	-
Other East Asia	89	95	-	-	105	-	-
Southeast Asia	413	447	-	-	456	-	-
India	795	862	-	-	886	-	-
Other South Asia	234	287	-	-	339	-	-
All Asia	2699	2841	2709	3041	2733	2481	3237
				OC			
China	2563	2187	1967	2549	1378	920	2214
Japan	44	35	-	-	33	-	-
Other East Asia	197	208	-	-	218	-	-
Southeast Asia	1833	1933	-	-	1897	-	-
India	3268	3540	-	-	3633	-	-
Other South Asia	967	1152	-	-	1289	-	-
All Asia	8872	9055	8834	9416	8448	7991	9285
				CO			
China	137011	144540	131417	174131	131031	103630	212032
Japan	2661	1900	-	-	1846	-	-
Other East Asia	12708	15312	-	-	18829	-	-
Southeast Asia	54514	61762	-	-	68443	-	-
India	79382	88708	-	-	95733	-	-
Other South Asia	19145	23065	-	-	27227	-	-
All Asia	305420	335286	322163	364878	343109	315708	424110
				NMVOC			
China	14730	22424	20757	23611	35098	28971	38599
Japan	1880	2153	-	-	2462	-	-
Other East Asia	1859	2724	-	-	3789	-	-
Southeast Asia	11091	14675	-	-	19104	-	-
India	8638	11485	-	-	15744	-	-
Other South Asia	2040	2835	-	-	3914	-	-
All Asia	40238	56297	54630	57483	80112	73985	83613

[a] Data are in kt y^{-1}.

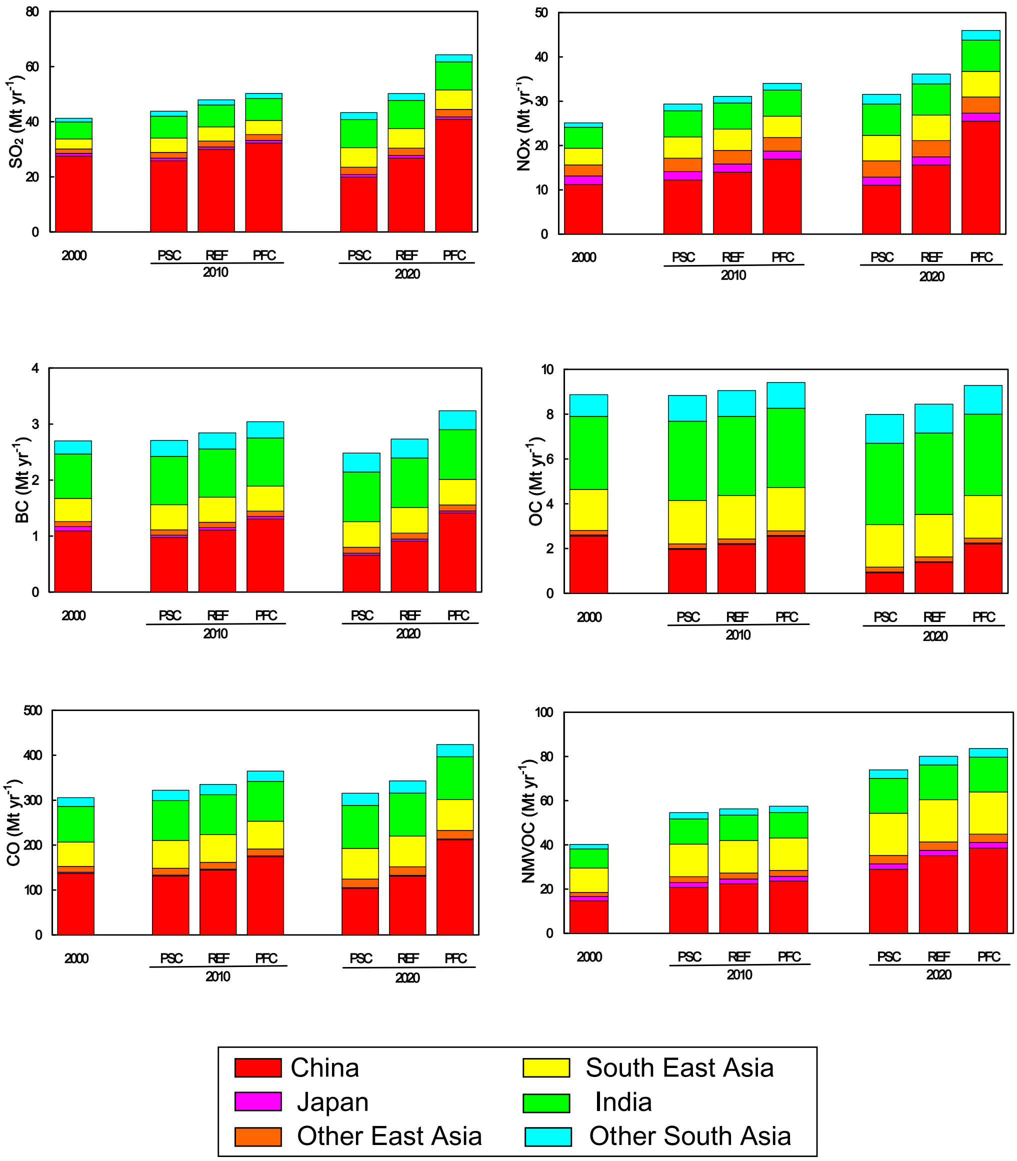

Fig. 7. Comparison of Asian emissions in 2000, 2010, and 2020.

3.3.4 OC

Chinese OC emissions in both 2010 and 2020 would decrease under any scenario compared with the 2000 level, owing to the decrease in biofuel consumption in the domestic sector. OC emissions in 2020 under the PSC, REF, and PFC scenarios were markedly reduced by 64% (to 0.92 Mt), 46% (to 1.38 Mt), and 14% (to 2.21 Mt), respectively, compared with the 2000 level (2.56 Mt).

Total Asian 2020 OC emissions under the PSC, REF, and PFC scenarios in China were estimated to be 7.99 Mt, 8.45 Mt, and 9.29 Mt – a 10% decrease, 5% decrease, and 5% increase, respectively, compared with 2000 emissions (8.87 Mt).

OC emissions in 2020 in East Asia excluding China were estimated to be 0.25 Mt – almost equal to the 2000 emissions (0.24 Mt). In Southeast Asia, India, and other South Asia, 2020 OC emissions showed increases (4%, 11%, and 33%, respectively) compared with 2000 levels.

The OC/BC ratio in China was projected to decrease from 2.3 in 2000 to 1.5 in the 2020 REF because of a marked reduction in OC but a modest reduction in BC. On the other hand, the Indian OC/BC ratio in 2020 was projected to be the same as that in 2000 (almost 4.1). Consequently, the difference in the OC/BC ratio between China and India would increase in future.

3.3.5 CO

Under the REF scenario, CO emissions in China were projected to increase from 137 Mt in 2000 to 145 Mt in 2010, and then to decrease to 131 Mt in 2020 (a 5% increase in 2010 and a 4% decrease in 2020 compared with the 2000 level). Although Chinese CO emissions under the PSC scenario were projected to decrease by 4% in 2010 and 28% in 2020 compared with 2000 emissions, the PFC scenario showed an increase in emissions (27% in 2010 and 55% in 2020) over 2000 levels.

The future changes in Asian CO emissions were projected to be similar to those for SO_2 emissions. Under the REF scenario for China, total Asian emissions were estimated to increase by 10% (to 335 Mt) and 12% (to 343 Mt) in 2010 and 2020, respectively, compared with the 2000 level (305 Mt). Under the PSC scenario for China, total Asian CO emissions were projected to increase by 5% (to 322 Mt) and 3% (to 316 Mt) in 2010 and 2020, respectively. Under the PFC scenario for China, total Asian CO emissions would increase by 19% (to 365 Mt) and 39% (to 424 Mt) in 2010 and 2020, respectively.

CO emissions in East Asia excluding China were estimated to increase by 35% from 15 Mt in 2000 to 21 Mt in 2020. In Southeast Asia, 2020 CO emissions (68 Mt) should increase by 26% from 55 Mt in 2000. CO emissions in India (and other South Asia) were projected to increase by 21% (42%) from 79 Mt (19 Mt) in 2000 to 96 Mt (27 Mt) in 2020.

3.3.6 NMVOC

Under the REF scenario, 2020 NMVOC emissions in China (35.2 Mt) would rapidly increase by 139% from 2000 (14.7 Mt). Under the PSC and PFC scenarios, the 2020 NMVOC emissions in China would increase markedly by 97% and 163%, respectively, compared with the 2000 level. Thus, Chinese NMVOC emissions were expected to rapidly at least double under any scenario, because the development of control technologies for anthropogenic NMVOC emissions would be behind those for other species. It should be noted that there were comparatively small differences between the values under the three kinds of scenarios. This shows that our assumptions of control technologies under each scenario (especially under the PSC scenario) may have been too conservative.

Under the REF scenario, total Asian NMVOC emissions were estimated to increase by 40% (to 56.3 Mt) and 100% (to 80.1 Mt) in 2010 and 2020, respectively, from 2000 (40.2 Mt). Under the PSC scenario, Asian NMVOC emissions were projected to increase by 36% (to 54.6 Mt) and 84% (74.0 Mt) in 2010 and 2020, respectively. Under the PFC scenario, Asian NMVOC emissions would increase by 43% (to 57.5 Mt) and 108% (to 83.6 Mt) in 2010 and 2020, respectively.

NMVOC emissions in East Asia except China were estimated to increase by 67% from 3.7 Mt in 2000 to 6.3 Mt in 2020. NMVOC emissions in 2020 in Southeast Asia, India, and other South Asia were projected to be 72%, 82%, and 92%, respectively, higher than those in 2000.

3.3.7 Comparison with other inventories

Projected emissions depend strongly on the emission scenarios. In this section, the future emissions obtained by this study are compared with previous emission estimates for Asian countries: Van Aardenne et al. (1999), Streets and Waldhoff (2000), Streets et al. (2001b), Klimond et al. (2002), and Cofala et al. (2006).

Streets and Waldhoff (2000) projected SO_2, NO_x, and CO emissions in China for 2020 by using two scenarios ([REF] and [HIGH]) and the emissions for 1990 and 1995. Their [REF] scenario was a "best guess" scenario, which means their best estimates of changes in emission factors and rates of deployment of emission control technologies and of new energy and process technologies, and their [HIGH] scenario was the most plausible upper estimates of emissions. SO_2 emissions in China were projected to increase from 24.7 Mt in 1995 to 30.4 Mt in the 2020 [REF] scenario, provided that emission controls are implemented on major power plants; if this does not happen, emissions could increase to as much as 60.2 Mt under the 2020 [HIGH] scenario. The value of SO_2 emissions under the 2020 [REF] scenario was close to the value in the 2020 REF scenario of REAS (26.8 Mt), whereas the 2020 [HIGH] scenario projected markedly higher emissions than those in the 2020 PFC scenario of REAS (40.9 Mt). Chinese NO_x emissions were projected to increase from 11.3 Mt in 1995 to 25.4 Mt ([REF]) and 29.7 Mt ([HIGH]) in 2020. This value in the 2020 [REF] scenario is almost the same as the value in the 2020 PFC scenario of REAS (25.5 Mt; see Table 10). Chinese CO emissions were projected to decline from 115 Mt in 1995 to 96.8 Mt in the 2020 [REF] scenario because of more efficient combustion techniques, especially in the transportation sector; if these measures are not realized, CO emissions could increase to 130 Mt in the 2020 [HIGH] scenario. However, it should be noted that the Chinese CO emissions estimated by Streets and Waldhoff (2000) were extensively revised by Streets et al. (2006).

Recently, IIASA (Cofala et al., 2006; data available at: http://www.iiasa.ac.at/rains/global_emiss/global_emiss.html) developed emission scenarios by using the global version of the RAINS model (Amann et al., 1999) to project global atmospheric and climate change. They presented a set of global emission projections for SO_2, NO_x, CO, and CH_4 during the period 1990–2030, and their emissions for 1990 and 2000 have been described in Sects. 3.1 and 3.2. For the future evolution of emission factors, two scenarios were proposed. One scenario was the "current legislation" ([CLE] scenario), which was characterized by the impacts of the emission control measures imposed by present legislation. An additional scenario was the "maximum technically feasible reduction" ([MFR] scenario), which included the levels of emission control offered by the full application of all the technical emission control measures that are presently available. We compared the changes between 2000 and 2020 for Asian SO_2 and NO_x emissions under the [CLE] scenario, which is more plausible than the [MFR] scenario, with those under the REAS scenarios. The change in Chinese SO_2 emissions from 2000 to 2020 was projected to be an 8% increase under the [CLE] scenario and a 23% decrease, 3% decrease, and 48% increase under the PSC, REF, and PFC scenarios, respectively, of REAS. Thus, the SO_2 emissions change in China under the [CLE] scenario was only slightly higher than those under the REF scenario. This feature of SO_2 emissions is similar to that of the Indian emissions ([CLE]: 109% increase, REF: 66% increase) and the Asian total emissions ([CLE]: 36% increase, REF: 22% increase). The change in Chinese NO_x emissions between 2000 and 2020 was estimated to be an 18% increase under the [CLE] scenario, and a 1% decrease, 40% increase, and 128% increase under the PSC, REF, and PFC scenarios, respectively, of REAS. Therefore, the future change in Chinese NO_x emissions under the [CLE] scenario would be higher than that under the PSC scenario but lower than that under the REF scenario. On the other hand, in India, the future change in NO_x emissions under [CLE] (67% increase) would be higher than that under the REF scenario (49% increase), as with SO_2 emissions. Asian total NO_x emissions were projected to increase by 31% under the [CLE] scenario and by 26%, 44%, and 83% under the PSC, REF, and PFC scenarios, respectively.

Van Aardenne et al. (1999) estimated NO_x emissions for Asia in the period 1990–2020 by using the RAINS-Asia methodology. For the projection of future emissions, an energy scenario based on a no-further-control ([NFC]) assumption was used. They reported that the NO_x emissions in China and in all Asian countries would grow rapidly (by 290% and 350%, respectively) during the period 1990–2020. The [NFC] scenario projected the same growth of Chinese NO_x emissions as the PFC scenario (290%) in the REAS inventory, but showed a doubling of growth in total Asian emissions under PFC (180%).

Streets et al. (2001b) predicted that Chinese BC emissions would be reduced by 8% from 1.28 Mt in 1995 to 1.17 Mt in 2020 (emissions from open burning were excluded) because of the reduction in emissions from coal and biofuel combustion in the domestic sector. Our projections of Chinese BC emissions in 2020 were 0.66 Mt (PSC), 0.91 Mt (REF), and 1.42 Mt (PFC) – changes from 1995 representing a 53% decrease, 35% decrease, and 2% increase, respectively. Thus, the growth rate from 1995 to 2020 reported by Streets et al. (2001b) was close to that under the PFC scenario.

Klimont et al. (2002) reported emission inventories for NMVOC in China for the years 1990–2020. They estimated that emissions could grow by 40% to 18.2 Mt in 2020 from 13.1 Mt in 1995. On the other hand, our estimates showed a marked increase of 140% (PSC) to 220% (PFC) over the 1995 levels. The differences in emissions in the transport sector between the two inventories are important to note. Whereas transport emissions in 2020 were markedly increased over 1995 levels under the REAS scenario (e.g., by 350% under the REF scenario), Klimont et al. (2002) showed the same level as for the 1995 emissions. This may have been caused by differences in the future fuel consumption and/or emission controls for automobiles between the two inventories.

We compared the future emission trends in China according to several inventories (Fig. 6). The projected trends, of course, depend strongly on the emission scenarios provided by each researcher and reveal marked differences between projections, compared with the small differences between estimates for the years before 2000. For SO_2 emissions, the REF scenario of REAS provided a projection for 2020 emissions that was similar to the [CLE] scenario of IIASA and to the [REF] scenario of Streets et al. (2000). On the other hand, the [HIGH] scenario of Streets et al. (2000) showed a marked increase compared with other projections (including the three REAS scenarios), but this highest trend may be a "best guess" estimate, considering the rapid growth of emissions after 2000. For NO_x emissions, the scenario of Van Aardenne et al. (1999) gave an estimate at the top of the projection range, whereas the MFR scenario of IIASA projected a minimum value in the range. The REF scenario of REAS projected estimates in 2010 and 2020 similar to the [CLE] scenario of IIASA. Additionally, the PFC scenario of REAS estimated 2020 emissions that were similar to those of the [REF] and [HIGH] scenarios of Streets and Waldhoff (2000).

It should be noted from Fig. 6 that the dramatic growth after 2000 in SO_2 and NO_x emissions has overshot all of the projections. This means that every scenario, including ours, failed to project the recent growth in Chinese emissions. However, although the trend in Chinese NO_x emissions in the period 1996–2003 was validated by Akimoto et al. (2006) using the column NO_2 data from the GOME satellite, the recent growth in SO_2 emissions has not been validated by satellite data and may be overestimated because the implementation of emission controls after 2000 was not taken into account. Additionally, it may be necessary to make projections on the basis of the emission inventories for more recent years because of the rapid growth in economic activity and energy consumption and the development of regulations for emission control after 2000.

3.4 Gridded emissions

We examined the geographical distribution of six species (SO_2, NO_x, BC, OC, CO, and NMVOC) at $0.5^\circ \times 0.5^\circ$ resolution under 1980, 2000, and 2020 REF (Fig. 8). The growth of SO_2 emissions in China and India in the period 1980–2000 is clearly shown, whereas the spatial distribution in 2000 is similar to that in 2020 REF. The growth in NO_x emissions from 1980 to 2000 is more rapid than that of SO_2 and is especially located in the coastal areas of China and on the Hindustan Plain and central west coast of India, as is the case for SO_2. NO_x emissions would continue to grow until at least 2020 under the REF scenario. On the other hand, SO_2 and NO_x emissions in Japan and South Korea have resulted in only small changes in the 40 years.

It is important to note the difference in the temporal variation of the spatial distributions of BC and OC emissions between China and India: the Chinese emission patterns indicate a small change from 1980 to 2000 and then a decrease until 2020, whereas the Indian emissions continue to increase from 1980 to 2020. The main reason for this is that the trend in biofuel consumption for domestic use in China is quite different from that in India, as mentioned in Sects. 3.2 and 3.3. In China, domestic biofuel consumption did not vary with time before 2000 and was markedly reduced from 2000 levels under the 2020 REF scenario (by 42%). On the other hand, consumption in India increased by 1.3 times in the period 1980–2000, and the 2020 scenario showed an increase of nearly 10% over 2000 levels.

A large growth in NMVOC emissions – as much as the growth of NO_x emissions – was projected throughout Asia (Fig. 8). By 2020, under any of the REAS scenarios, it was projected that the growth rate of NMVOC emissions from 2000 would be higher than that of NO_x. The resulting Asian average NMVOC/NO_x ratio – a key indicator of photochemical reactivity – was 2.05 (in units of g/g) in both 1980 and 2000; it then increased to as much as 4.44 (g/g) by 2020 under the REF scenario, proceeding to an NO_x-limited regime. Ozone concentrations increase with increasing NO_x and are insensitive to NMVOC (Yamaji et al., 2007[1]).

4 Summary and conclusions

We developed a Regional Emission Inventory in Asia (REAS version 1.1) with $0.5° \times 0.5°$ resolution. It includes a historical and present inventory for 1980–2003 and projects emissions till 2020 for SO_2, NO_x, CO, NMVOC, BC, and OC from fuel combustion and industrial sources.

Total energy consumption in Asia more than doubled between 1980 and 2003, causing a rapid growth in Asian emissions, by 28% for BC, 30% for OC, 64% for CO, 108% for NMVOC, 119% for SO_2, and 176% for NO_x over this period. In particular, Chinese NO_x emissions showed a marked increase of 280% over 1980 levels, and NO_x emissions growth after 2000 has been extremely high, as has been that of SO_2 emissions. These increases in China are caused mainly by increases in coal combustion by power plants and the industrial sector. NMVOC emissions have also rapidly increased owing to the growth of automobile use and solvent and paint use. By contrast, EC, OC, and CO emissions in China decreased from 1996 to 2000 because of a reduction in the use of biofuels and coal in the domestic and industrial sectors. After 2000, Chinese emissions of these species began to increase. Thus the emission of air pollutants in Asian countries (especially China) showed large temporal variations in the period 1980–2003.

Future emissions in 2010–2020 are projected in Asian countries on the basis of the emission scenarios. For China, we developed three emission scenarios, PSC, REF, and PFC. Under the 2020 REF scenario, Asian total emissions for SO_2, NO_x, and NMVOC were projected to increase substantially by 22%, 44%, and 99%, respectively, over 2000 levels. With regard to other species, the 2020 REF scenario showed a modest increase in CO (12%), a lesser increase in BC (1%), and a slight decrease in OC (–5%) compared with 2000 levels. However, it should be noted that Asian total emissions are strongly influenced by the emission scenarios for China. Under the PFC scenario, the growth of emissions was expected to be greater, whereas the PSC scenario showed acceleration of the decrease, or deceleration of the increase, in emissions. For example, SO_2 emissions in China were projected to increase from 27.6 Mt in 2000 to 30.0 Mt in 2010, and to then decrease to 26.8 Mt in 2020 under the REF scenario; SO_2 emissions in China were markedly reduced from 2000 levels under the PSC scenario (by 6% in 2010 and 28% in 2020) and the PFC scenario showed an increase of 17% in 2010 and 48% in 2020 over the 2000 level. Future total Asian emissions of SO_2 under the REF scenario were projected to increase by 16% (to 47.9 Mt) in 2010 and 22% (50.2 Mt) in 2020 from 2000 (41.2 Mt). Asian 2020 emissions for SO_2 were estimated to be 43.3 Mt under the PSC scenario – only a small increase (by 5%) compared with the 2000 level – whereas the PFC scenario showed a rapid 5% increase in Asian 2020 emissions over the 2000 level. As with SO_2, under the 2020 PFC scenario Asian total emissions for all another species were projected to increase, by 83% for NO_x, 20% for BC, 5% for OC, 3% for CO, and 108% for NMVOC, over 2000 levels, whereas the 2020 PSC scenario showed modest changes of 26% for NO_x, –8% for BC, –10% for OC, and 3% for CO, but an extreme change of 84% for NMVOC, compared with 2000 emissions. The fact that there are large variations depending on the emission scenario suggests that a series of emission controls needs to be implemented in Asian countries – especially in China and India – to prevent deterioration of the air quality in Asia.

Further research on the emission characterization of small and/or old-fashioned sources and on the recent progress of emission control in each country, together with the use of a top-down approach that combines field and satellite measurements and forward/inverse modeling with emission inventory

[1] Yamaji, K., Ohara, T., Uno, I., Kurokawa, J., and Akimoto, H.: Future prediction of surface ozone over East Asia using the Models-3 Community Multi-scale Air Quality Modeling System (CMAQ) and the Regional Emission Inventory in Asia (REAS), J. Geophys. Res., submitted, 2007.

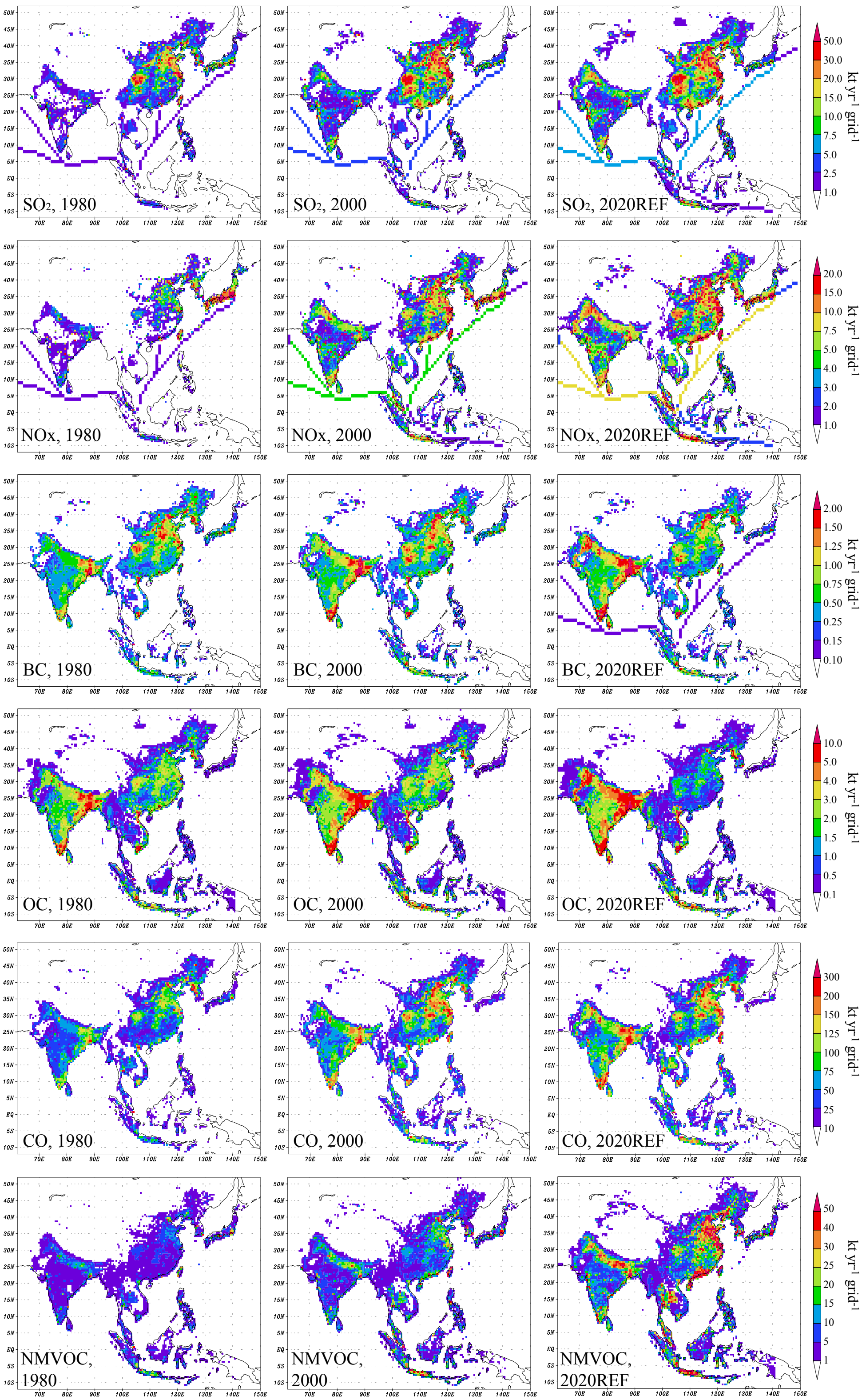

Fig. 8. Spatial distributions of emissions of SO_2, NO_x, BC, OC, CO, and NMVOC at 0.5°×0.5° resolution in 1980, 2000, and 2020 under the REF scenario.

development, will be required to reduce the uncertainty in the estimation of emissions.

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References

Akimoto, H. and Narita, H.: Distribution of SO_2, NO_x, and CO_2 emissions from fuel combustion and industrial activities in Asia with $1^\circ\times1^\circ$ resolution, Atmos. Environ., 28, 213–225, 1994.

Akimoto, H.: Global air quality and pollution, Science, 302, 1716–1719, 2003.

Akimoto, H. and Ohara, T.: Asian Inventories, in: Emissions of Atmospheric Trace Compounds, edited by: Granier, C., Artaxo, P., Reeves, C. E., Kluwer Academic Publishers, Dordrecht/Boston/London, 47–53, 2004.

Akimoto, H., Ohara, T., Kurokawa, J., and Horii, N.: Verification of energy consumption in China during 1996–2003 by satellite observation, Atmos. Environ., 40, 7663–7667, 2006.

Allen, D., Pickering, K., and Fox-Rabinovitz, M.: Evaluation of pollutant outflow and CO sources during TRACE-P using model-calculated, aircraft-based, and Measurements of Pollution in the Troposphere (MOPITT)-derived CO concentrations, J. Geophys. Res., 109, D15S03, doi:10.1029/2003JD004250, 2004.

Amann, M., Bertok, I., Cofala, J., Gyarfas, F., Heyes, C., Klimont, Z., Makowski, M., Schoopp, W., and Syri, S.: Cost-effective control of acidification and ground-level ozone, Seventh Interim Report, International Institute for Applied Systems Analysis, Laxenburg, Austria, 1999.

Bond, T. C., Streets, D. G., Yarber, K. F., Nelson, S. M., Woo, J.-H., and Klimont, Z.: A technology-based global inventory of black and organic carbon emissions from combustion, J. Geophys. Res., 109, D14203, doi:10.1029/2003JD003697, 2004.

Cao, G., Zhang, X., and Zheng, F.: Inventory of black carbon and organic carbon emissions from China, Atmos. Environ., 40, 6516–6527, 2006.

Cass, G. R., Boone, P. M., and Macias, E. S.: Emissions and air quality relationships for atmospheric carbon particles in Los Angeles, in: Particulate carbon – atmospheric life cycle, edited by: Wolff, G. T. and Klimisch, R. L., Plenum, New York, 207–240, 1982.

Cofala, J., Amann, M., and Mechler, R.: Scenarios of world anthropogenic emissions of air pollutants and methane up to 2030, Interim Report IR-06-023, available at: http://www.iiasa.ac.at/rains/global_emiss/global_emiss.html, 2006.

Dickerson, R. R., Andreae, M. O., Campos, T., Mayol-Bracero, O. L., Neusuess, C., and Streets, D. G.: Analysis of black carbon and carbon monoxide observed over the Indian Ocean: implications for emissions and photochemistry, J. Geophys. Res., 107, 8017, doi:10.1029/2001JD000501, 2002.

Downing, R. J., Ramankutty, R., and Shah, J. J.: Rains-Asia: An assessment model for acid deposition in Asia, The World Bank, Washington, D.C., 1997.

EEA (European Environment Agency): EMEP/CORINAIR Emission Inventory Guidebook, Copenhagen, available at: http://reports.eea.europa.eu/EMEPCORINAIR3/en/page002.html/, 2000.

FAO (Food and Agriculture Organization): FAO Statistical Database, United Nations Food and Agriculture Organization, Rome, available at: http://www.fao.org, 2000.

Garg, A., Shukla, P. R., Bhattacharya, S., and Dadhwal, V. K.: Subregion (district) and sector level SO_2 and NO_x emissions for India: assessment of inventories and mitigation flexibility, Atmos. Environ., 35, 703–713, 2001.

Hao, J., Tian, H., and Lu, Y.: Emission inventories of NO_x from commercial energy consumption in China, 1995–1998, Environ. Sci. Technol., 36, 552–560, 2002.

IEA (International Energy Agency): World energy outlook, IEA, Paris, 2002.

IEA (International Energy Agency): Energy statistics of OECD countries and energy statistics of non-OECD countries, IEA, Paris, 2004.

IIASA (International Institute for Applied Systems Analysis): RAINS-ASIA CD-ROM Version 7.52, Laxenburg, Austria, 2001.

IPCC (Intergovernmental Panel on Climate Change): Revised 1996 IPCC guidelines for national greenhouse gas inventories, edited by: Houghton, J. T., Meira Filho, L. G., Lim, B., Treanton, K., et al., IPCC WGI Technical Support Unit, Bracknell, UK, 1997.

Irie, H., Sudo, K., Akimoto, H., Richter, A., Burrows, J. P., Wagner, T., Wenig, M., Beirle, S., Kondo, Y., Sinyakov, V. P., and Goutail, F.: Evaluation of long-term tropospheric NO_2 data obtained by GOME over East Asia in 1996–2002, Geophys. Res. Lett., 32, L11810, doi:10.1029/2005GL022770, 2005.

Minato, K.: Improving urban air quality in Asia, JARI (Japan Automobile Research Institute) Research Journal, 24, 477–481 [in Japanese], 2002.

Kannari, K., Tonooka, Y., Baba, T., and Murano, K.: Development of multiple-species 1 km×1 km resolution hourly basis emissions inventory for Japan, Atmos. Environ., 41, 3428–3439, 2007.

Kato, N., Ogawa, Y., Koike, T., Sakamoto, T., and Sakamoto, S.: Analysis of the structure of energy consumption and the dynamics of emissions of atmospheric species related to the global environmental change (SO_x, NO & CO) in Asia, NISTEP Report No. 21, National Institute of Science and Technology Policy, Japan, 1991.

Kato, N. and Akimoto, H.: Anthropogenic emissions of SO_2 and NO_x in Asia: emissions inventories, Atmos. Environ., 26, 2997–3017, 1992.

Klein Goldewijk, C. G. M. and Battjes, J. J.: A hundred year (1890–1990) database for integrated environmental assessments (HYDE, version 1.1), Report no. 422514002, National Institute of Public Health and the Environment (RIVM), Bilthoven, The Netherlands, 1997.

Klimont, Z., Cofala, J., Schopp, W., Amann, M., Streets, D. G., Ichikawa, Y., and Fujita, S.: Projection of SO_2, NO_x, NH_3 and VOC emissions in East Asia up to 2030, Water Air Soil Poll., 130, 193–198, 2001.

Klimont, Z., Streets, D. G., Gupta, S., Cofala, J., Fu, L., and Ichikawa, Y.: Anthropogenic emissions of non-methane volatile organic compounds in China, Atmos. Environ., 36, 1309–1322, 2002.

Nakicenovic, N. J. and Swart, R. (Eds.): IPCC special report on emissions scenarios, Cambridge University Press, Cambridge, United Kingdom and New York, NY, 2000.

National Bureau of Statistics: China energy statistical yearbook (1991–1996, 1997–1999, 2000–2002, 2004 editions), China Statistics Press, Beijing, 1997–2004.

National Bureau of Statistics: China statistical yearbook 2006, China Statistics Press, Beijing, 2006.

Nissan Automobile Corporation: Handbook of exhaust and fuel efficiency 2005, Atsugi, Japan [in Japanese], 2005.

Oak Ridge National Laboratory (ORNL): LandScan Global population 1998 Database, Oak Ridge National Laboratory, Oak Ridge, Tenn., 1999.

Palmer, P. I., Jacob, D. J., Jones, D. B. A., Heald, C. L., Yantosca, R. M., Logan, J. A., Sachse, G. W., and Streets, D. G.: Inverting for emissions of carbon monoxide from Asia using aircraft observations over the western Pacific, J. Geophys. Res., 108, 8828, doi:10.1029/2003JD003397, 2003.

Parashar, D. C., Gadi, R., Mandal, T. K., and Mitra, A. P.: Carbonaceous aerosol emissions from India, Atmos. Environ., 39, 7861–7871, 2005.

Reddy, M. S. and Venkataraman, C.: Inventory of aerosol and sulphur dioxide emissions from India: Part I – Fossil fuel combustion, Atmos. Environ., 36, 677–697, 2002a.

Reddy, M. S. and Venkataraman, C.: Inventory of aerosol and sulphur dioxide emissions from India. Part II – Biomass combustion, Atmos. Environ., 36, 699–712, 2002b.

Richter, A., Burrows, P., Nues, H., Granier, C., and Niemeijer, U.: Increase in tropospheric nitrogen dioxide over China observed from space, Nature, 437, 129–130, 2005.

State Administration for Coal Safety: China Coal Industry Yearbook 2002, Coal Industry Publishing House, 2003.

SEPA (State Environmental Protection Administration): Report on the state of the environment in China, State Environmental Protection Administration of China, Beijing, 2003.

Streets, D. G. and Waldhoff, S. T.: Biofuel use in Asia and acidifying emissions, Energy, 23, 1029–1042, 1998.

Streets, D. G. and Waldhoff, S. T.: Present and future emissions of air pollutants in China: SO_2, NO_x and CO, Atmos. Environ., 34, 363–374, 2000.

Streets, D. G., Tsai, N. Y., Akimoto, H., and Oka, K.: Sulfur dioxide emissions in Asia in the period 1985–1997, Atmos. Environ., 34, 4413–4424, 2000.

Streets, D. G., Tsai, N. Y., Akimoto, H., and Oka, K.: Trends in emissions of acidifying species in Asia, 1985–1997, Water Air Soil Poll., 130, 187–192, 2001a.

Streets, D. G., Gupta, S., Waldhoff, S. T., Wang, M. Q., Bond, T. C., and Bo, Y.: Black carbon emissions in China, Atmos. Environ., 35, 4281–4296, 2001b.

Streets, D. G., Bond, T. C., Carmichael, G. R., Fernandes, S. D., Fu, Q., He, D., Klimont, Z., Nelson, S. M., Tsai, N. Y., Wang, M. Q., Woo, J.-H., and Yarber, K. F.: An inventory of gaseous and primary aerosol emissions in Asia in the year 2000, J. Geophys. Res., 108, 8809, doi:10.1029/2002JD003093, 2003.

Streets, D. G., Bond, T. C., Lee, T., and Jang, C.: On the future of carbonaceous aerosol emissions, J. Geophys. Res., 109, D24212, doi:10.1029/2004JD004902, 2004.

Streets, D. G., Zhang, Q., Wang, L., He, K., Hao, J., Wu, Y., Tang, Y., and Carmichael, G. R.: Revisiting China's CO emissions after the Transport and Chemical Evolution over the Pacific (TRACE-P) mission: synthesis of inventories, atmospheric modeling, and observations, J. Geophys. Res., 111, D14306, doi:10.1029/2006JD007118, 2006.

UN (United Nations): Statistical yearbook (twenty-seventh to forty-eighth issues), United Nations, New York, NY, 1983–2004.

Uno, I., He, Y., Ohara, T., Yamaji, K., Kurokawa, J., Katayama, M., Wang, Z., Noguchi, K., Hayashida, S., Richter, A., and Burrows, J. P.: Systematic analysis of interannual and seasonal variations of model-simulated tropospheric NO_2 in Asia and comparison with GOME-satellite data, Atmos. Chem. Phys., 7, 1671–1681, 2007,
http://www.atmos-chem-phys.net/7/1671/2007/.

US EPA (United States Environmental Protection Agency): Compilation of air pollutant emission factors (AP-42) Volume 1: point and area sources, U.S. Environmental Protection Agency, Research Triangle Park, NC, 1999.

USGS (United States Geological Survey): USGS mineral yearbook volume III. – area reports: international, available at: http://minerals.usgs.gov/minerals/pubs/myb.html, 2006.

Van Aardenne, J. A., Carmichael, G. R., Levy, H., Streets, D., and Hordijk, L.: Anthropogenic NO_x emissions in Asia in the period 1990–2020, Atmos. Environ., 33, 633–646, 1999.

Van Aardenne, J. A., Dentener, F. J., Olivier, J. G. J., Klein Goldewijk, C. G. M., and Lelieveld, J.: A $1^\circ \times 1^\circ$ resolution data set of historical anthropogenic trace gas emissions for the period 1890–1990, Global Biogeochem. Cy., 15, 909–928, 2001.

Veldt, C. and Berdowski, J. J. M.: GEIA-note on the combustion of biomass fuels (emission factors for CO, CH_4 and NMVOC), TNO-report, TNO-MW-R 94/218, 1995.

Wang, J., Yang, J., Ma, Z., and Benkovic, S.: SO_2 Emission Trading Program-US Experience and China's Perspective, China Environmental Science Publishing Company, Beijing, 2000.

Wang, J., Yang, J., Benkovic, S., Schreifels, J., and Ma, Z.: SO_2 Emission Trading Program-A feasibility study for China, China Environmental Science Publishing Company, Beijing, 2002.

World Bank: World Development Indicators 2006, The world bank, Washington, D.C., 2006.

Xue, Z., Yang, Z., Zhao, X., Chai, F., and Wang, W.: Distribution of SO_2 and NO_x emissions in China, 1995, Proceedings of the 6th International Conference on Atmospheric Sciences and Applications to Air Quality, Beijing, China, 3–5 November, 1998.

Yamaji, K., Ohara, T., and Akimoto, H.: A country-specific, high-resolution emission inventory for methane from livestock in Asia in 2000, Atmos. Environ., 37, 4393–4406, 2003.

Yamaji, K., Ohara, T., and Akimoto, H.: Regional-specific emission inventory for NH_3, N_2O, and CH_4 via animal farming in South, Southeast, and East Asia, Atmos. Environ., 38, 7111–7121, 2004.

Yan, X., Cai, Z. C., Ohara, T., and Akimoto, H.: Methane emission from rice fields in mainland China: amount and seasonal and spatial distribution, J. Geophys. Res., 108, 4505, doi:10.1029/2002JD003182, 2003a.

Yan, X., Akimoto, H., and Ohara, T.: Estimation of nitrous oxide, nitric oxide, and ammonia emissions from croplands in East, Southeast, and South Asia, Global Change Biol., 9, 1080–1096, 2003b.

Yan, X., Ohara, T., and Akimoto, H.: Development of region-specific emission factors and estimation of methane emission from rice field in East, Southeast and south Asian countries, Global Change Biol., 9, 237–254, 2003c.

Yan, X., Ohara, T., and Akimoto, H.: Bottom-up estimate of biomass burning in mainland China, Atmos. Environ., 40, 5262–5273, 2006.

Yumimoto, K. and Uno, I.: Adjoint inverse modeling of CO emissions over Eastern Asia using four-dimensional variational data assimilation, Atmos. Environ., 40, 6836–6845, 2006.

Zhang, J., Smith, K. R., Uma, R., Ma, Y., Ye, S., Kishore, V. V. N., Lata, K., Khalil, M. A. K., Rasmussen, R. A., and Thorneloe, S. T.: Carbon monoxide from cookstoves in developing countries: 1. Emission factors, Chemosphere, 1, 353–366, 1999.

Zhang, J., Smith, K. R., Ma, Y., Ye, S., Jiang, F., Qi, W., Liu, P., Khalil, M. A. K., Rasmussen, R. A., and Thorneloe, S. A.: Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors, Atmos. Environ., 34, 4537–4549, 2000.

Zhou, D., Dai, Y., Yi, C., Guo, Y., and Zhu, Y.: China's sustainable energy scenarios in 2020, China Environmental Science Press, Beijing [in Chinese], 2003.