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Projections of SO_2, NO_x and carbonaceous aerosols emissions in Asia

By Z. KLIMONT[1,*], J. COFALA[1], J. XING[2], W. WEI[2], C. ZHANG[2], S. WANG[2], J. KEJUN[3], P. BHANDARI[4], R. MATHUR[4], P. PUROHIT[1], P. RAFAJ[1], A. CHAMBERS[1], M. AMANN[1] and J. HAO[2], [1]*International Institute for Applied Systems Analysis, A-2361 Laxenburg, Austria;* [2]*Tsinghua University, Beijing 100084, China;* [3]*Energy Research Institute, B-1503, Jia. No.11, Beijing 100038, China;* [4]*The Energy and Resources Institute, Darbari Seth Block, Habitat Place, Lodi Road, New Delhi 110003, India*

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ABSTRACT

Estimates of Asian emissions of air pollutants and carbonaceous aerosols and their mid-term projections have been changing significantly in the last years. The remote sensing community has shown that increase in NO_x in Central East Asia is much stronger than any of the emission inventories or projections indicated so far. A number of studies reviewing older estimates appeared. Here, we review the key contributions and compare them to the most recent results of the GAINS model application for Asia and to the SRES projections used in the IPPC work. The recent projections indicate that the growth of emissions of SO_2 in Asia should slow down significantly towards 2010 or even stabilize at the current level. For NO_x, however, further growth is projected although it will be most likely slower that in the last decade, owing to introduction of measures in transport. Emissions of carbonaceous aerosols (black carbon and organic carbon) are expected to decline after 2010, largely due to reduced use of biofuels in residential sector and efficiency improvements. The estimates of these emissions are burdened with significantly larger uncertainties than SO_2 and NO_x; even for the year 2000 the differences in estimates between studies are up to a factor of 2.

1. Introduction

Asian emissions of air pollutants have been growing at an unprecedented rate over the last decade. This is directly linked to the continuing strong economic growth (averaging to about 10% a^{-1} in the last decade) in China and India. In spite of the environmental legislation introduced in several countries, specifically targeting transport sector in urban areas as well as power plant sector, the emissions continue to grow and the Asian contribution to the global emissions of SO_2 and NO_x increased from about 30 and 20% in the beginning of the 1990s to 50 and 35% in 2005, respectively (Cofala et al., 2007). The pace of change from mid 1990s until now has been hotly debated in several papers, especially for China where the decline in coal consumption reported in statistics in the end of the last century does not correspond to the continuing economic growth (Streets and Aunan, 2005; Akimoto et al., 2006).

The work of the remote sensing community has indicated a much faster growth of NO_x emissions in the Central and East Asia in the last decade (Richter et al., 2005) than previously shown in emission inventory work and models (He et al., 2007; Zhang et al., 2007). Similarly high growth has been estimated recently for emissions of SO_2 in Asia (Richter et al., 2007).

Early inventories and projections suffered from poor data availability, were too optimistic about the pace of introduction and efficiency of environmental legislation, and underestimated the economic growth experienced in the last decade in China and India. In the last few years a number of authors reassessed their previous emission estimates for Asia for several pollutants (e.g. Streets et al., 2006; Ohara et al., 2007; Zhang et al., 2007). The new assessment of past developments led to a revision of several projections. This paper discusses the recent mid-term scenarios of SO_2, NO_x, black carbon (BC) and primary particulate organic carbon (OC) emissions in Asia developed with the Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model and compares them to the key peer reviewed projections of air pollutants as well as to the SO_2 and NO_x SRES scenarios for Asia (Nakicenovic et al., 2000) used also in the Fourth Assessment Report of the IPPC (IPCC, 2007).

Presented here GAINS model findings are a further evolution of results shown for Asia by Klimont et al. (2001), Cofala et al. (2004) and in the global study by Cofala et al. (2007). They take

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[*] Corresponding author.
e-mail: klimont@iiasa.ac.at

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into account new information on activity data and local emission factors developed by the authors or updated based on the most recent studies, for example, Zhang et al. (2007), as well as new national economic projections for China and India. Finally, the model has been improved to better represent some important emission sources. Examples include: brick production, where regional statistics and several brick making technologies are distinguished, residential combustion, where more detailed types of biomass (fuel wood, agricultural residue and dung) and stoves (heating and cooking stoves) are considered. Also data on open burning of agricultural residue has improved due to inclusion of regional statistics. All data used in the model for larger countries are on the subnational level, compatible with the approach used previously in the RAINS-Asia model (IIASA, 2001; Cofala et al., 2004). For example, calculations for China distinguish 32 regions and for India 23 regions. Further details on the methodology and data used are discussed in the next section.

2. Method and data

Our emission estimates for Asia have been developed with the GAINS model (http://gains.iiasa.ac.at). The GAINS model (previously RAINS) has been originally developed for Europe (Schöpp et al., 1999) with specific modules for calculating air pollutant emissions, environmental impacts, and control costs. The relevant documentation for the pollutants included in this paper, that is, for SO_2 (Cofala and Syri, 1998a), NO_x (Cofala and Syri, 1998b) and carbonaceous aerosols (Kupiainen and Klimont, 2004, 2007) can be downloaded from the model site. Development of a comparable model for Asia followed; first for SO_2 and later for NO_x and the latest version of RAINS-Asia model is still available (IIASA, 2001). The model was peer reviewed in 2004 (CEC, 2004) and shortly afterwards the development of GAINS has started (Klaassen et al., 2004). GAINS extends to include greenhouse gasses and allows for the analysis of the synergies in air pollution and climate policies but the principles of emission calculation remain similar to the RAINS model. For a given country *i*, year *y* and pollutant *n* considered in this paper, this is shown in the equation below

$$E_{i,n,y} = \sum_{j,k,l} A_{i,j,k,l,y} \sum_{m} [ef_{i,j,k,l,n}(1 - \eta_{i,k,m,n})X_{i,j,k,l,m,y}], \quad (1)$$

where, *j* represents the province (administrative region); *k* represents the economic sector or combustion technology type (e.g. stoves in residential sector, cement production, open biomass burning); *l* represents the fuel type (if relevant for a specific *k*); *m* represents the abatement technology type; *E* is the national annual emissions; *A* is the activity level (e.g. fuel consumption, production of cement, amount of biomass burned on-field); *ef* is the uncontrolled emission factor; η is the reduction efficiency of the abatement technology and *X* is the penetration of the abatement measure *m* expressed as a percentage of total activity *A*, for example, fuel consumption in a given sector *k*, such that $\Sigma X = 1$.

2.1. Emission factors

Emission factors in GAINS-Asia are an updated and extended version of data collected for the RAINS-Asia model. Updates take into account recent literature reporting measurements of Asian sources, findings of local projects where authors of this paper have been involved, and local information on parameters needed to calculate emission factors, for example, sulphur or ash content of fuels. Methodologies differ in detail for considered compounds.

The uncontrolled emission factors (*ef*) for SO_2 are calculated using country-region (*i,j*), sector (*k*) and fuel (*l*) specific parameters (Cofala and Syri, 1998a)

$$ef_{i,j,k,l} = 2\frac{sc_{i,j,k,l}}{hv_{i,j,k,l}}(1 - sr_{i,j,k,l}), \quad (2)$$

where, *sc* is the sulphur content (per weight) of the fuel; *hv* is the heat value of the fuel and *sr* is the fraction of sulphur retained in ash. The parameters used in this equation have been collected from national sources and vary between provinces/states in a given country resulting in province/state specific values of *ef*. Emission factors derived in eq. (2) represent uncontrolled situation. The actual emission rate will depend on the type and implementation rate of abatement measure, which in GAINS include for SO_2 low sulphur fuel, in-furnace control (limestone injection) and flue gas desulphurization (FGD). The assumptions on the current and future penetration of measures, determining the implied emission factor, are discussed in the next section.

For stationary sources of NO_x, uncontrolled emission factors rely on reported measurements on specific installations. Each type of stationary combustion sources needs to meet emission standard, which may be achieved through implementation of primary (combustion modification, including low NO_x burner) or secondary (catalytic or non-catalytic reduction) measures. In particular, our current assessment includes (in aggregated form) recent findings for China by Zhang et al. (2007). For other countries and industrial combustion our values are similar to those summarized by Streets et al. (2003) and Garg et al. (2001) who reviewed a number of local measurements, and those used by Cofala et al. (2007).

The uncontrolled emission factors in transport are determined based on studies where local conditions, fuel and vehicle type, and driving patterns representative of the pre-2000 vehicle fleet are considered (Fu et al., 2001; Garg et al., 2001; Streets et al., 2003). In order to include the impacts of legislation on transport sector emissions, GAINS distinguishes EURO stages (a package of measures including fuel standards, engine modification and end-of-pipe measures) as abatement technologies.

Emissions factors for BC and OC in the GAINS framework are assessed together with the estimates of total particulate matter (PM) emissions to assure overall consistency (Klimont et al., 2002; Kupiainen and Klimont, 2004). For solid fossil fuels the PM emission factors consider the local fuel quality parameters like ash content, heat value and ash retention in boiler resulting in province/state specific values. Although, the BC and OC emission rates are 'decoupled' from the fossil fuel quality parameters and consequently are independent from the estimates of PM10, PM2.5, etc., the consistency is safeguarded by comparing the BC and OC rates with estimates of fine particles. Such verification is also performed for biomass and other fuels as well as for process sources.

Originally developed characteristics for BC and OC in GAINS are applicable in general for the developed countries (Kupiainen and Klimont, 2007). The database was extended further for global application (Cofala et al., 2007) drawing largely on Bond et al. (2004) who reviewed several measurements performed in the developing countries with special emphasis on Asia. Further, we have reviewed newer sources of information for Asia, that is, available after Bond et al. (2004) study (Parashar et al., 2005; Venkataraman et al., 2005; Cao et al., 2006; Kannari et al., 2007; Ohara et al., 2007) and introduced minor adjustments.

All emission factors, underlying parameter data, and other assumptions can be viewed in the on-line version of the GAINS-Asia model (http://gains.iiasa.ac.at) while a more detailed description of several specific aspects for Asia is also available in the methodology document (Amann et al., 2008a).

2.2. *Scenario assumptions*

We report results of several projects carried out with the support of the European Commission. The GAINS projection originates from the GAINS-Asia model scenarios (Amann et al., 2008b). They were developed in the period 2006–2008 in collaboration between the research groups at International Institute for Applied Systems Analysis (IIASA) in Laxenburg (Austria), Tsinghua University and Energy Research Institute (ERI) in Beijing (China) and The Energy and Resources Institute (TERI) in New Delhi (India). The Atmospheric Composition Change, The European Network of Excellence (ACCENT) projections originate from the studies of global emissions (Cofala et al., 2006, 2007).

The recent GAINS-Asia scenarios include not only update of activity data for the years 2000–2005 but also a number of potential future developments in the energy sector, including penetration of alternative technologies and renewable energy, creating basis for the 'alternative' scenario to the 'baseline' development. These new projections originate from the most recent national studies; for India developed by The Energy and Resources Institute (TERI, 2006) and for China by the Energy Research Institute based on the latest 11-yr plan and described in the recently completed GAINS-Asia report (Amann et al., 2008b). Furthermore, we have developed two projections simulating varying level of the implementation of air pollution legislation. These define upper (baseline) and lower (very optimistic assumptions about implementation of legislation) bounds for the presented GAINS projection (see the range in Figs. 3–6). This is justified not only by the uncertainty in the real life reduction efficiencies of the control technologies but even more so due to the uncertainty in the actual enforcement (Xu et al., 2009), size distribution and lifetime of installations which will play a significant role in how quickly the expected reduction can be achieved. More detailed discussion of respective assumptions and their effects is presented in Section 3.1 (see Tables 1–3).

All databases developed in the GAINS-Asia study include provincial/state level data, that is, detailed sectoral, fuel and technological information considering, to an extent possible, the local factors. The databases and results can be accessed from the GAINS-Asia model website (registration required): http://gains.iiasa.ac.at/. Sectoral fuel consumption in the GAINS-Asia baseline is provided in the Appendix S1 in Supporting Information to this paper while base year and future evolution of emission factors for key categories is discussed in Section 3.1 and shown in Tables 2 and 3.

The global ACCENT projections up to 2030 were developed between 2005 and 2006 making use of the available at the time national information on emission legislation and on projections of activity data; for Asia data from the RAINS-Asia implementation (Cofala et al., 2004) were used. Where national activity data was not available we applied the trends of future economic and energy developments of the IPCC SRES B2 MESSAGE scenario (Nakicenovic et al., 2000; Riahi and Roehl, 2000) to the activity levels reported in international statistics for the year 2000 (IEA, 2002; UN, 2003). Within ACCENT we developed two sets of scenarios. The first set (ACCENT_v1) includes estimates for SO_2, NO_x, CO and CH_4. Detailed information on the assumptions, data sources, and regional results have been documented in Cofala et al. (2006). The second set (ACCENT_v2) includes, for Asia, updates of the air pollution control legislation (ADB, 2005) and year 2000 activity data that were available by the end of 2006. This projection includes also emission estimates for carbonaceous aerosols and has been documented in Cofala et al. (2007). For both ACCENT studies, the activity data and estimated emissions, aggregated by SRES, regions can be also downloaded from the dedicated websites; for details see the original papers.

2.2.1. Comparison with SRES scenarios. In order to compare our recent projections to SRES we selected four marker scenarios representative of the four SRES families (Nakicenovic et al., 2000). For A1, the results of the AIM model were used; for A2, the ASF model, for B1, the IMAGE model and for B2, the MESSAGE model. Fig. 1 shows scenario assumptions on the evolution of key macroeconomic parameters related to the year 2000 and the total primary energy supply for the year 2000 and 2030.

Table 1. Penetration of selected control measures assumed in GAINS baseline scenario for key sectors in China, India and Japan,% of fuel use

Sector	Technology[a]	2000			2005			2010			2020			2030		
		Data shown[b] in the following order: China / India / Japan[c]														
Power plants (old – coal)	FGD (SO_2)[d]	1		95	8		95	28		95	43		95	64		95
	CM (NO_x)	36		20	46		10	66			77			89		
	SCR (NO_x)			80			90			100			100			100
Power plants (new – coal)	FGD (SO_2)[d]	3		100	11		100	56		100	73		100	84		100
	LNB (NO_x)	100	100	20	100	100	10	100	100		100	100		100	100	
	SCR (NO_x)			80			90			100			100			100
Heavy Duty Trucks – diesel	EURO I		10	60	34	11	15	25	9	4			.5			
	EURO II			30	22	8	30	25	15	10	5	8	1			.2
	EURO III			10		1	54	25	8	28	14	81	2.5		81	.3
	EURO IV						1	8	1	20	11	11	2		18	.2
	EURO V									38	70		27	100		
	EURO VI												67			99.3
Cars – diesel	EURO I	5	10	30	40	9	10	28	8	2			.2			
	EURO II			50	10	8	17	25	21	5	5	16	.4			
	EURO III			20			50	25	3	18	14	84	1.6		100	.2
	EURO IV						23	8		65	81		17.8	100		.4
	EURO V									10			30			.4
	EURO VI												50			99
Cars – gasoline	EURO I	7	10		36	9		28	8							
	EURO II			99.8	21	8	44	24	21	18	6	16	2			
	EURO III						22	24	3	15	17	84	1		100	.3
	EURO IV						34	8		57	78		21	100		.4
	EURO V									10			76			99.3

[a] FGD, flue gas desulphurization; CM, combustion modification, including low NO_x burner and other primary measures; SCR, selective catalytic reduction; EURO, European emission limits for mobile sources.

[b] The '%' implementation refers to fuel consumption in the sector rather than generating capacity or number of vehicles. It is also assumed in the model that technologies introduced achieve the design reduction efficiency. Therefore, the values presented here might be lower than suggested by some reports owing to poor operation or malfunction period considered in the model. Furthermore, these values are not always representative for all regions in a given country as some areas have more or less stringent legislation, for example, some cities introduced more stringent standards for transport sources or industry, and therefore shall be seen as country averages.

[c] Empty space indicates no control is assumed.

[d] Sulphur content of coal varies strongly from region to region and introduction of low sulphur coal plays an important role in abating SO_2 emissions in specific areas. Assumptions not presented here but can be viewed in the GAINS model for each province.

ACCENT and more recent GAINS projections show similarity to B1 and B2 scenarios with respect to population and GDP growth assumptions. In fact, with exception of the SRES A2 scenario, all discussed scenarios assume for 2030 a population of 4.15–4.3 billion in Asia (about 30% increase compared to the year 2000); in A2 nearly 4.8 billion. Large span of GDP growth in SRES scenarios (Fig. 1, left-hand side) show primarily the big difference between assumptions in the global (A1) and regional (A2) scenarios where the first one shows the highest growth rates. ACCENT, GAINS, B1 and B2 show comparable development resulting in total 2030 Asian GDP (excluding Japan) of about 16–20 trillion US$, that is, a GDP/capita of about US$ 5000. These scenarios assume nearly doubling of GDP every 10 yr. The difference in GDP between ACCENT and GAINS is due to the updated projections for India and China in the GAINS scenario. These projections represent the latest national long-term planning studies (TERI, 2006; Amann et al., 2008b).

Energy use (Fig. 1, right-hand side) increases by a factor 2–3 within the considered time horizon with ACCENT scenario at the lower end and recent GAINS assuming the highest increase. While SRES scenarios show diverse structure of fuel consumption in 2030, ACCENT and GAINS differ significantly only for coal that makes most of the difference between the two and obviously will have implications on emissions of air pollutants and greenhouse gases. The energy projections underlying the latter scenarios originate from national sources but are few years apart, GAINS being the newer. GAINS scenario has one of the highest economic growths from the considered scenarios,

Table 2. Impact of air quality legislation. Change in implied emission factors for China in GAINS baseline scenario (mg MJ^{-1})

Sector	Fuel	2000	2005	2010	2020	2030
Sulphur dioxide (SO_2)						
Power plants (old)	Coal	898	806	677	513	328
	Oil	272	272	272	272	272
Power plants (new)	Coal	894	783	440	282	190
	Oil	272	272	272	272	272
Industrial boilers	Coal	634	474	469	466	457
	Oil	272	272	272	272	272
Residential combustion	Coal	602	602	602	602	602
	Biomass	68	68	68	68	68
Road transport	Heavy Duty Trucks – diesel	27	26	9	9	9
	Cars – diesel	31	28	9	9	9
Nitrogen oxides (NO_x)						
Power plants (old)	Coal	246	231	201	184	166
	Oil	241	241	241	241	241
	Gas	96	96	96	96	96
Power plants (new)	Coal	150	150	150	150	150
	Oil	120	120	120	120	120
	Gas	50	50	50	50	50
Industrial boilers	Coal	250	250	250	250	250
	Oil	142	142	142	142	142
	Gas	65	65	65	65	65
Residential combustion	Coal	100	100	100	100	100
	Biomass	72	72	72	72	72
Road transport	Heavy Duty Trucks – diesel	642	539	456	200	139
	Cars – diesel	323	322	315	248	240
	Cars – gasoline	819	417	210	41	34
Black carbon (BC)						
Residential combustion	Coal	14	15	18	18	18
	Biomass	86	80	80	67	46
Road transport	Heavy Duty Trucks – diesel	34	25	16	2	1
	Cars – diesel	74	56	37	14	13
	Cars – gasoline	6	6	5	3	3
Organic carbon (OC)						
Residential combustion	Coal	18	20	24	24	25
	Biomass	251	219	218	181	126
Road transport	Heavy Duty Trucks – diesel	21	14	8	1	1
	Cars – diesel	28	16	9	3	3
	Cars – gasoline	19	13	8	2	2

obviously extrapolating from the success of Asian economies in the last decade. It has been assumed that such growth has to be supported strongly by locally available fuels and so coal plays a much more important role than in the past scenarios. At the same time the projections for transport are higher and increase in nuclear power is comparable with the assumptions made in most of the SRES scenarios. Consistently all scenarios show large increase in transport demand; oil consumption is growing by a factor of 3 or more compared to the base year. Although gas consumption increases significantly in all scenarios, the national projections (used in ACCENT and GAINS) result in about half of the SRES demand in 2030.

The very high coal use projected in GAINS scenario seems off the mark; however, the current coal consumption in China alone, about 55 EJ in 2007 (BP, 2008), exceeds already the SRES B2 value for 2030. Adding consumption in other Asian countries makes 2007 value higher than that projected in SRES B1 and nearly as high as previous national projections used in ACCENT

Table 3. Impact of air quality legislation. Change in implied emission factors for India in GAINS baseline scenario (mg MJ^{-1})

Sector	Fuel	2000	2005	2010	2020	2030
Sulphur dioxide (SO_2)						
Power plants (old)	Coal	503	506	501	529	511
	Oil	1282	1237	1333	1322	1295
Power plants (new)	Coal	474	483	485	477	470
	Oil	773	960	1151	1471	1560
Industrial boilers	Coal	457	456	455	455	455
	Oil	1814	1814	1814	1814	1814
Residential combustion	Coal	431	431	431	431	431
	Biomass	23	23	23	23	23
Road transport	Heavy Duty Trucks – diesel	121	43	24	11	12
	Cars – diesel	118	39	25	9	9
Nitrogen oxides (NO_x)						
Power plants (old)	Coal	298	298	298	298	298
	Oil	160	160	160	160	160
	Gas	150	150	150	150	150
Power plants (new)	Coal	149	148	148	149	149
	Oil	100	86	79	89	92
	Gas	50	50	50	50	50
Industrial boilers	Coal	230	230	230	230	230
	Oil	170	170	170	170	170
	Gas	70	67	64	59	53
Residential combustion	Coal	80	80	80	80	80
	Biomass	50	50	50	50	50
Road transport	Heavy Duty Trucks – diesel	1261	1238	1178	825	799
	Cars – diesel	350	350	349	339	335
	Cars – gasoline	788	735	612	67	61
Black carbon (BC)						
Residential combustion	Coal	130	130	130	129	129
	Biomass	85	84	84	84	83
Road transport	Heavy Duty Trucks – diesel	33	31	26	6	6
	Cars – diesel	72	69	60	18	17
	Cars – gasoline	6	6	6	3	3
Organic carbon (OC)						
Residential combustion	Coal	200	200	197	187	168
	Biomass	231	229	225	218	211
Road transport	Heavy Duty Trucks – diesel	20	19	16	3	3
	Cars – diesel	26	25	21	4	3
	Cars – gasoline	19	18	16	3	2

for 2030. Comparably fast growth of Chinese coal consumptions until 2030 has been also projected in the recent EIA energy outlook (EIA, 2008). Furthermore, while in 2000 Chinese coal use represented nearly 70% of the total coal consumption in Asia, the energy policy in India (TERI, 2006) foresees a significant increase of coal use, mainly in the power sector. This causes a rise of total national consumption from about 7 EJ in 2000 to over 45 EJ in 2030. Even if that latter value might be on the high side (over six-fold increase compared with 2000), the IEA (2007) projection shows also strong coal increase to nearly 22 EJ for India in 2030. In relative terms, coal plays a key role as energy supply source in Asia in the GAINS scenario, contributing about 50% to total energy demand in 2020 and 2030. In the presented marker SRES scenarios energy consumption grows between 2020 and 2030 by 25–33%, while in GAINS that growth is 34%, which is mainly due to a faster increase of

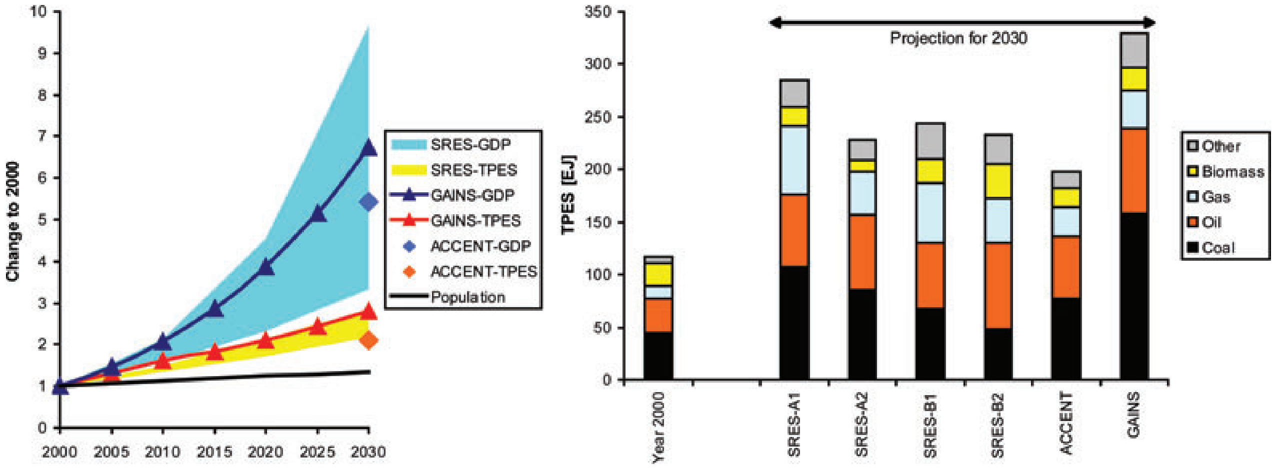

Fig. 1. Assumptions on the growth of population, GDP (market exchange rates) and total primary energy supply (TPES) in Asia (left-hand side) and TPES in 2030 by fuel (right-hand side) for the presented projections.

energy use in India. Sectoral fuel use assumed in the GAINS-Asia baseline is available in the Appendix S1 in the Supporting Information.

3. Results and discussion

Recent remote sensing results (Richter et al., 2005, 2007) show a high increase in pollution levels over Asian continent in the last years, especially in East Asia. These increases are often larger than those estimated in emission inventories and models (Ma et al., 2006; He et al., 2007; Zhang et al., 2007). We have developed new estimates of past emissions reviewing data on activities and especially on the effectiveness of the air pollution legislation in industry and power plant sector. For China, these revised GAINS time series show for all presented pollutants (SO_2, NO_x, BC and OC) higher emissions in 2005 than in previous GAINS work, for example, ACCENT scenarios (Cofala et al., 2006, 2007). Since China dominates Asian emissions, the strong growth in the last years is clearly visible in the total emissions in Asia (Figs. 2–6). A fast growth between mid 1990s and 2005 in NO_x and SO_2 emissions (Figs. 2–4) is comparable with the remote sensing results.

A discussion of main features and trends of GAINS scenarios is provided below and further compared to other recently published work and SRES scenarios.

3.1. GAINS baseline scenario

We have developed several scenarios that vary in assumptions on the penetration of emission control measures. The baseline results presented in Fig. 2 assume that the new legislation in industry and power plant sector is not as effective as originally anticipated, especially with respect to real life efficiency of end of pipe abatement installed on existing and new plants, for example, flue gas FGD. This is based on incidental evidence collected during the GAINS-Asia study showing that the installed equipment was not always operating or used in less than optimal ways. This assumption has been recently confirmed by Xu et al. (2009). On the other hand, IEA Clean Coal Centre database (IEA, 2008) shows that significant proportion of power generation capacity in China is being equipped with FGD and other control measures like low NO_x burners and electrostatic precipitators, including plants commissioned well before the year 2000. Also Xu et al. (2009) document a significant increase in installed SO_2 scrubber capacity in China, especially after 2005. As of 2006, the installed scrubber capacity in China is larger than in the US and it grows faster than the coal power capacity (Xu et al., 2009). Such assumptions are included in the baseline scenario (Table 1) resulting after 2005 in decline of implied (sector average) emission factors for several key emission sources (Table 2). Consequently, the growth in emissions of SO_2 and NO_x slows down after 2005 (Table 4, Fig. 2) in spite of significant further increase in capacity (see Appendix S1 in Supporting Information).

The development is different in India where current legislation does not prescribe installation of FGD units (Table 1) and thus a steep increase of SO_2 emissions (Fig. 2, Table 5) follows the trend in coal use (see discussion in Section 2.2 and Appendix S1 in Supporting Information). Fast growth of Indian emissions results in reduced share of Chinese emissions in total Asian SO_2 from 70% in 2005 to 40% by 2030 (see also Appendix S2 in Supporting Information). Overall Asian emissions of SO_2 in this scenario nearly double between 2000 and 2020, reaching about 60 Tg SO_2. About half of that increase occurred till 2005. Similarly high growth in the last years has been also indicated by others (Ohara et al., 2007; Richter et al., 2007; Ramanathan and Carmichael, 2008). Further growth beyond 2020 is driven by doubling of coal use in India between 2020 and 2030 in poorly controlled power plants (TERI, 2006). If a more moderate growth in coal use would materialize (IEA,

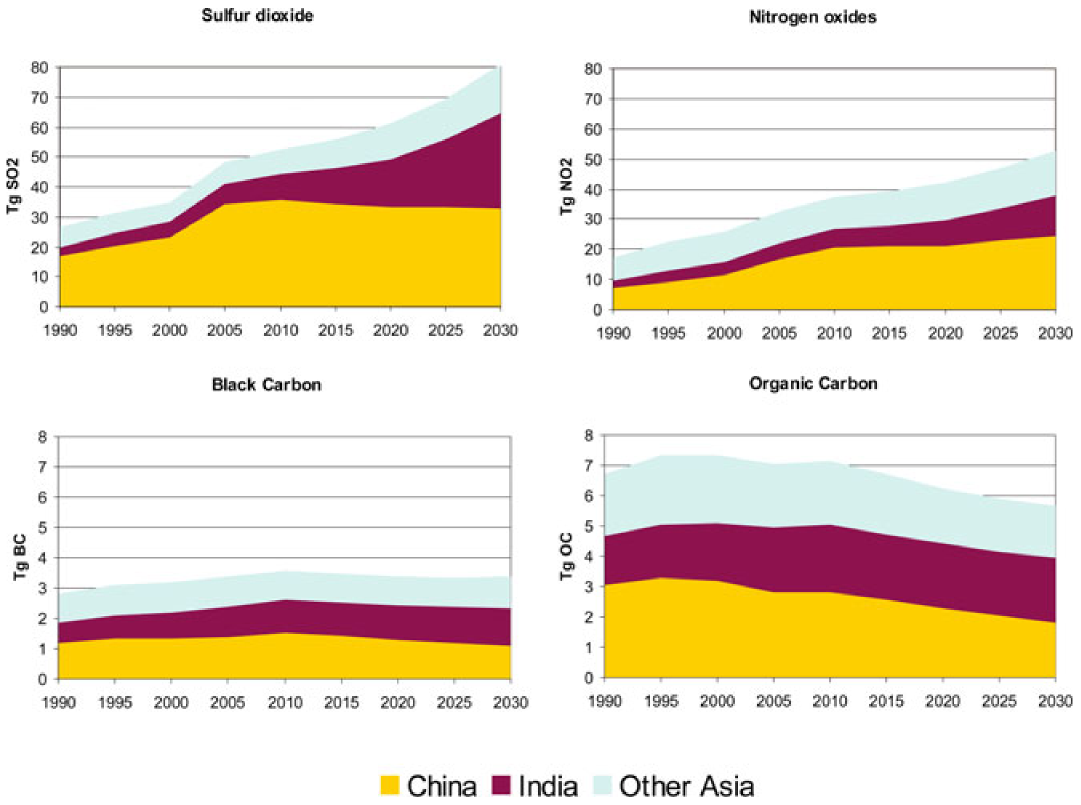

Fig. 2. Emissions of air pollutants in Asia in the GAINS baseline scenario and contribution of China and India.

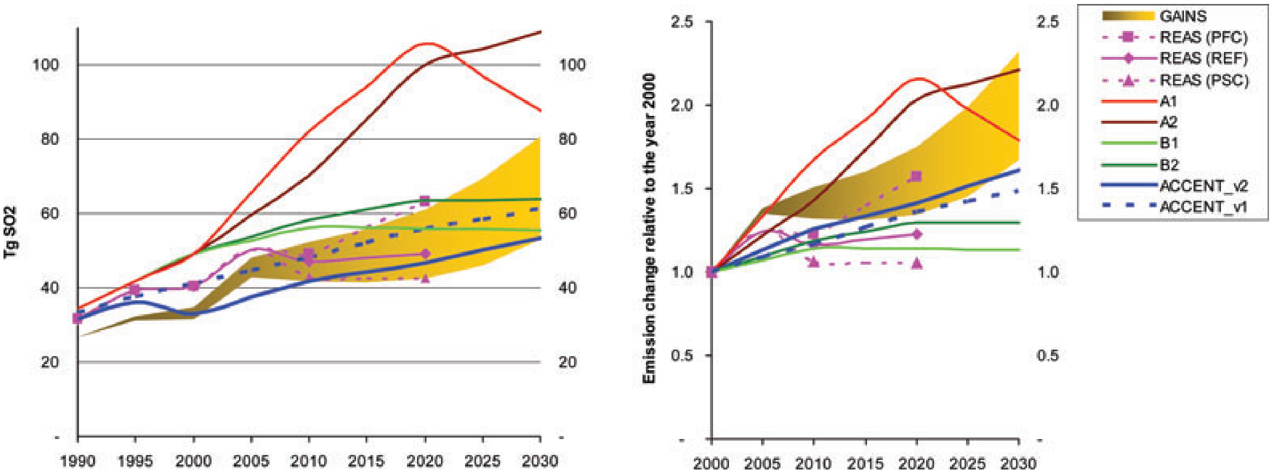

Fig. 3. Comparison of SO_2 emission estimates for Asia (left-hand side) and their growth rates from the year 2000 (right-hand side).

2007), the total emissions of SO_2 in Asia would remain at the 2020 level.

The fast growth in Indian SO_2 emissions beyond 2005 is not in agreement[1] with earlier work on Indian projections (Garg et al., 2003), where under the reference scenario, SO_2 emissions would not exceed 10 Tg SO_2 while current GAINS scenario projects 16 Tg in 2020 and 32 Tg in 2030. Obviously, energy projection is different; GAINS scenario assumes for 2030 a three-fold increase in per capita energy consumption from 2000 while Garg et al. (2003) assumes a growth factor of 2.4. This alone however cannot explain this large

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[1] The GAINS estimates for 2000 and 2005 agree very well with Garg et al. (2003).

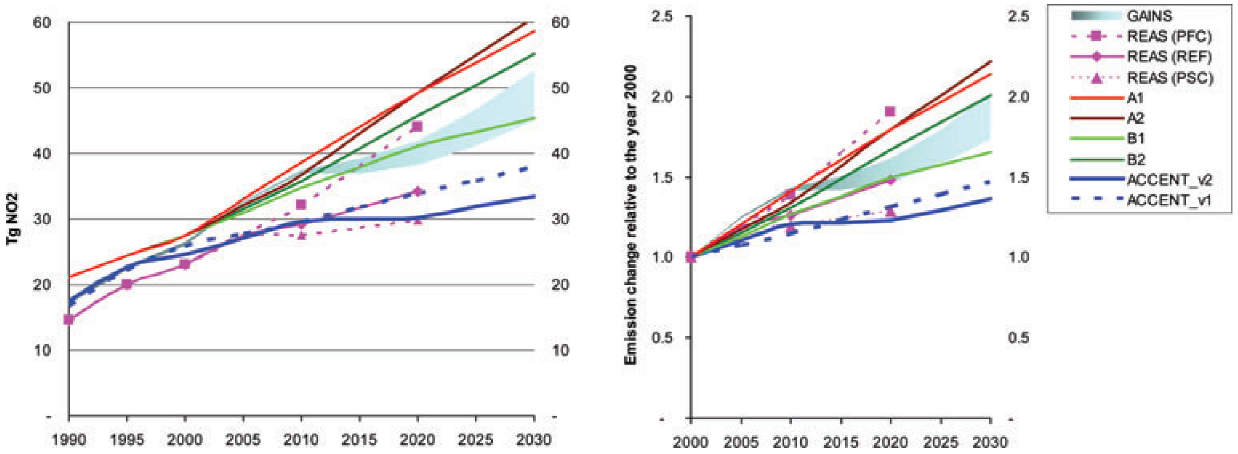

Fig. 4. Comparison of NO_x emission estimates for Asia (left-hand side) and their growth rates from the year 2000 (right-hand side).

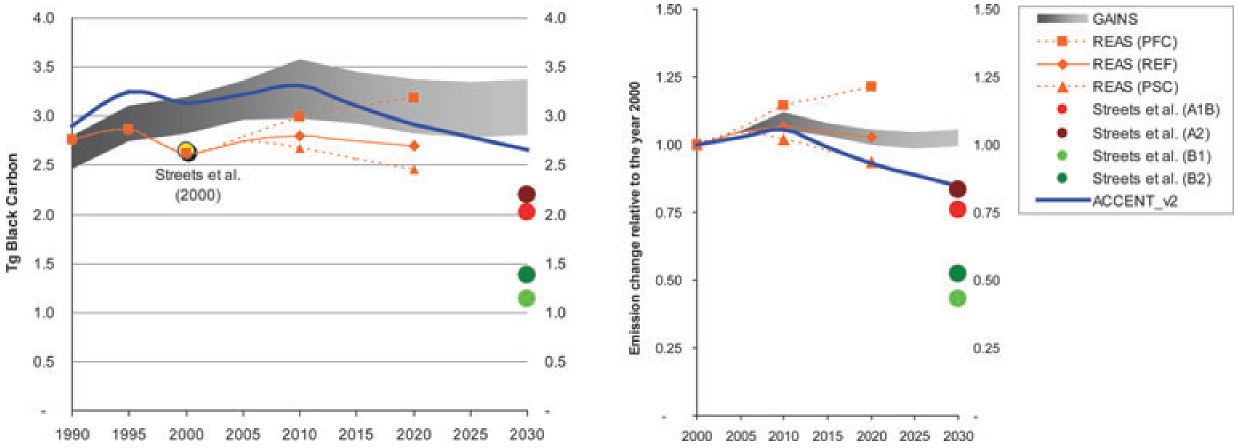

Fig. 5. Comparison of BC emission estimates for Asia (left-hand side) and their growth rates from the year 2000 (right).

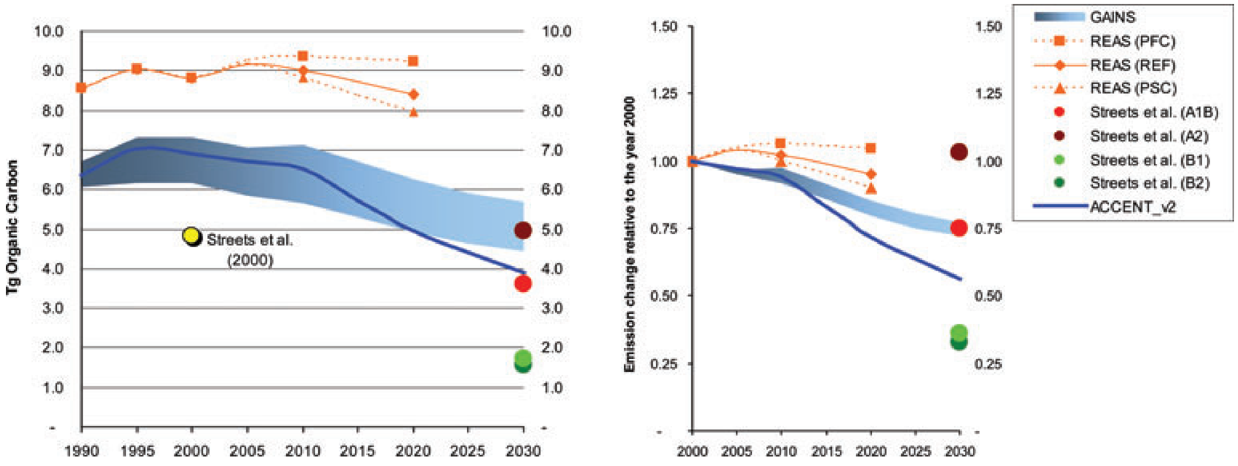

Fig. 6. Comparison of OC emission estimates for Asia (left) and their growth rates from the year 2000 (right-hand side).

discrepancy. He assumes that significant reductions of emissions will occur from expected improvements in energy efficiency, fuel quality and eventually from introduction of FGD. GAINS also considers impacts of these factors but our scenario is less optimistic about emissions reduction achieved. As for the FGD, we assume no pick-up of this option in the baseline because the current emission limit values do not require FGD (Table 1). We found no statistical evidence that this technology is being introduced on any significant scale; by 2007, there was only one power plant equipped with FGD in India (IEA, 2008). In effect, there is a stark difference in evolution of implied emission factors for power sector in China (Table 2) and India (Table 3). Owing to much lower sulphur content of coal used in India and very low penetration of end-of-pipe measures in China, the implied emission factor in 2000 is lower in India. However, already in 2010 the Chinese emission rate is lower for new power plants and by 2020 also for the old power plants, coinciding with significant increase in FGD penetration (Table 1). For comparison, also implementation of measures in Japan is demonstrated in Table 1.

While for SO_2 the contribution of transport is rather small, it plays much more important role in emissions of NO_x, although not as large as in Europe or the US. In China, transport contribution remains at about 20% of total emissions in spite of a very fast growth in demand (see Appendix S1 and S2 in Supporting Information). In India the share is much larger, changing from about 44% in 2005 to 31% in 2030 and total transport emissions in India nearly double in the period 2005–2030, from about 1.8 to 4.3 Tg NO_x, equalling Chinese emissions from this sector. In the same period transport emissions in China do not change much, growing only slightly from 4.1 Tg in 2005 to 4.3 Tg NO_x in 2030 (Tables 4 and 5 and Appendix S2 in Supporting Information). The different trend is justified by much more stringent legislation in China where after 2010 a requirements of EURO 5 are coming into force for new vehicles while at the same time India continues to require EURO 3 (CAI-Asia, 2008; Table 1). For comparison, Table 1 also includes Japan where one of the strictest road transport legislations in the World is implemented. Owing to different pace of implementation of legislation in road transport in China and India there is a significant difference in how implied emission factors for this sector change over time (Tables 2 and 3). For some categories there are notable differences in uncontrolled (initial) emission factors between China and India. This is due to local factors taken into account by national experts as well as different composition of the sectors shown in Tables 2 and 3, that is, shares of large and small vehicles in a specific category shown in these tables vary between regions affecting the final value of emission factor.

The steady growth in total NO_x emissions in Asia (Figs. 2 and 4), no stabilization within discussed time horizon, is still fuelled primarily by fast increase in energy use in industrial combustion, rather than transport. This is due to only moderate controls assumed in this sector in China and India, that is, no legislation requiring selective catalytic reduction (SCR) exists and primary measures (low NO_x burners, LNB) are installed mostly on new plants (Table 1). This is too little to stabilize or reduce emissions; this scenario estimates doubling of total Asian NO_x emissions by 2030 compared to the level of the year 2000, that is, growing from 26 to 53 Tg NO_x.

Emissions of carbonaceous aerosols (BC and OC) are expected to peak between 2005 and 2010 and then steadily decline. The changes projected for China are the main driver for this trend and they are linked to the developments in residential combustion sector, which is by far the most important contributor to the total emissions, especially biofuel use. In 2005, about 50% of BC and 65–70% of OC emissions (anthropogenic, i.e. excluding forest and savannah fires) are estimated to originate from combustion of biofuels (agricultural residue, fuel wood and dung-cake) for cooking and heating in 2005 (Tables 4 and 5), which is comparable to other estimates (Bond et al., 2004; Streets et al., 2004; Cofala et al., 2007). This share is expected to decline towards 2030. The extent of decline varies between regions and is strongly linked to the assumptions about future biofuel consumption with the highest reduction in China where it drops by nearly 20% by 2030 compared to 2005 (see Appendix S1 in Supporting Information). In India it remains at about the same level; the growing demand for energy in the domestic sector is met by rapidly increasing consumption of gaseous fuels and by centralized heat and power, sources, which emit far less particles. As can be seen from Tables 2 and 3, only a small change in average emission factors occur over time. The reduction towards the end of the period can be attributed to the changing fuel use structure in the residential sector. This scenario assumes, especially for China, that relatively more coal is used in stokers rather than stoves and similarly for biomass, share of fuel use in larger boilers increases. One potential option to reduce emissions would be accelerated replacement of poor combustion devices with more efficient and cleaner stoves but in this baseline scenario we refrain from such incentives and the turnover of these installations is very slow contributing little to improvement of the average emission rate.

3.2. Comparison with other studies

3.2.1. Sulphur dioxide. Historical estimates of SO_2 (1990–2005) show a similar pattern in all studies (Fig. 3), although the absolute values vary greatly, especially for 2000 and 2005. Furthermore, the drop of emissions in 2000 is not visible in SRES scenarios since they were developed before the data for the year 2000 was available. At the same time, it is rather surprising that SRES A1 and A2 reproduce the observed stronger growth after 2000 (Fig. 3, right-hand side). Both of the last features make the 2000 and 2005 estimates in SRES significantly higher than the latest inventories.

There is still a significant difference in assessments for the year 2000 which is primarily due to estimates for China where discussion continues on how large, or how 'real', the decline in coal use between 1995 and 2000 was (Streets and Aunan, 2005; Akimoto et al., 2006; Ohara et al., 2007) and what emission factors should be used. In fact, the difference in coal consumption in 2000 between the studies is not as large as the discrepancy in emission estimates, that is, ACCENT_v1 (Cofala et al., 2006) and REAS inventories (Ohara et al., 2007) assume coal consumption of 34–37 EJ in Asia while all the other studies about

38–44 EJ. For example, GAINS and SRES values are very similar but there is over 30% difference in emission level (Fig. 3). It is the distribution between sectors and implied emission factor assumptions (determined by sulphur content and the penetration of control measures) that matter more. Similarly, for 2005[2] the assumptions on the abatement play a key role. However, the very fast growth in coal consumption has not been captured to the same extent in the discussed assessments especially that, with exception of REAS and GAINS, no other study had access to statistical data for 2005. Therefore, ACCENT projections show only moderate growth as well as SRES B1 and B2, where only very little coal increase is assumed.

Nearly all of the compared scenarios show similarity in the assumption that growth in SO_2 emissions will slow down after 2005, leading even to stabilization of emissions in some projections. Relative to the year 2000, the growth rates for the REAS and SRES A2, B1, B2 bear strong similarities (Fig. 3, right-hand side). Indeed, Ohara et al. (2007) assumed that his Policy Failed Case (PFC), Reference (REF) and Policy Succeed Case (PSC) resemble the storylines presented by A2, B2 and B1, respectively. The absolute numbers tell a different story since SRES does not include the developments of the last decade and seemingly underestimates the impact of control technologies, resulting in much higher emissions than REAS. By 2020, only the B1 is within the range of REAS estimates and this is comparable to the PFC scenario, while A2 projected nearly twice the emissions of the PFC. GAINS and ACCENT scenarios show a very similar range to REAS, between 40 and 60 Tg SO_2 in 2020 (Fig. 3, left-hand side). While the upper values in GAINS represent the GAINS baseline (see Section 3.1), the lower bound represents a scenario where successful enforcement of air pollution policy has been assumed as well as larger improvements in energy efficiency (similar storyline to REAS PSC).

3.2.2. Nitrogen oxides. In contrary to SO_2, for NO_x the agreement of the past estimates is reasonably good, withstanding also comparisons to regional inventories (e.g. Garg et al., 2006) for India. Although all scenarios show a steady growth driven by strong increase in traffic volumes and only limited end-of-pipe controls on stationary combustion sources, there is a larger variation in the projections (Fig. 4). The highest SRES projections estimate over 60 Tg NO_x in 2030; more than doubling of the 2000 emissions. GAINS baseline has the strongest growth from 2000 to 2010 but then the impact of the tighter legislation in transport leads to a slowdown (Fig. 4, right-hand side) resulting in 2030 emissions of 53 Tg. The lower range of GAINS shows the effect of the alternative energy scenario where higher efficiency improvements and lower coal use is assumed. The SRES B1 scenario and GAINS follow a very similar trajectory throughout the period (Fig. 4, left-hand side) although the energy consumption in GAINS is significantly higher, up to 20%, pointing again to the importance of air pollution legislation. Very strong growth in GAINS scenario after 2020 is driven mainly by increase in Indian emissions. It is the expected doubling of coal consumption in power plants and industry between 2020 and 2030, assuming only moderate emission controls, that contributes most, rather than the growing transport demand.

The lowest growth rates and lowest absolute emission levels are calculated in the ACCENT and REAS (REF and PSC) scenarios. In both cases the estimate for the period 2000–2005 is lower than in other scenarios and the projected growth is much more moderate, driven by lower fuel consumption and optimistic assumptions on the penetration and performance of control policies. Taking into account the most recent statistical information and lack of more stringent legislation on stationary sources, we believe that the ACCENT and REAS, especially PSC case, underestimate the future development of NO_x emissions in Asia.

3.2.3. Carbonaceous aerosols. Use of coal and biofuels (fuel wood, crop residues and dung-cake) for cooking and heating in the residential sector are the major sources of carbonaceous aerosols emissions in Asia. The estimates of emissions are burdened with high uncertainties (Bond et al., 2004), typically higher than those of SO_2 and NO_x, owing primarily to uncertainties in domestic fuel use, especially biofuels, and their emission factors (Bond et al., 2004; Parashar et al., 2005; Streets and Aunan, 2005; Venkataraman et al., 2005). Comparing the residential biofuel consumption data for India and China from various studies (Streets and Aunan, 2005; Venkataraman et al., 2005; Ohara et al., 2007) and GAINS we see significant differences for the past years, typically ranging within about ±25%. We use this variation to define high and low BC and OC estimates in GAINS; compare Figs. 5 and 6 where upper GAINS line represents the baseline energy use (see Section 3.1) and the lower line includes 20–25% lower biofuel consumption.

Figure 6 illustrates large differences in historical estimates for the OC; variation of nearly a factor 2 for the year 2000. In fact, the differences would be larger if all published estimates would be included. Specifically for India, a number of studies (Reddy and Venkataraman, 2002a,b; Venkataraman et al., 2005) estimated significantly lower emissions of OC (as well as BC) than Bond et al. (2004).[3] High estimates of OC in REAS inventory are comparable to the upper value calculated for Asia by Bond et al. (2004). REAS uses significantly higher consumption of biofuels and coal in the domestic sector in several countries, for example, for India their OC estimate is more than twice as high as Bond et al. (2004). For BC the differences for historical years are smaller (Fig. 5).

The relative growth of carbonaceous emissions (Figs. 5 and 6, right-hand side) shows a similar trend pattern for all projections, indicating a steady decline after 2010. Exception is the REAS PFC scenario. All other cases vary in extent of the drop in emissions, however, consistently show faster reduction for

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[2] For REAS, only estimates for 2003 were available.

[3] Streets et al. (2004) uses Bond et al. (2004) results for historical years.

Table 4. Emission of air pollutants for key sectors in China in GAINS baseline scenario (Gg a^{-1})

Sector	Fuel	2000	2005	2010	2020	2030
Sulphur dioxide (SO_2), Gg SO_2 a^{-1}						
Power plants (old)	Coal	10828	8267	5901	3230	1493
	Oil	8	8	7	5	4
Power plants (new)	Coal	2023	11116	9334	7394	8357
	Oil	1	1	3	2	1
Industrial boilers	Coal	3878	5203	7431	8625	8967
	Oil	292	413	533	746	908
Residential combustion	Coal	1394	1496	1597	1880	2226
	Biomass	587	562	559	488	464
Road transport	Heavy Duty Trucks – diesel	27	36	15	24	30
	Cars – diesel	6	10	4	15	26
Other sources		4130	7251	10167	10878	10463
Total		23176	34364	35550	33286	32939
Nitrogen oxides (NO_x), Gg NO_2 a^{-1}						
Power plants (old)	Coal	2967	2368	1751	1161	757
	Oil	7	7	6	5	3
	Gas	2	8	7	5	3
Power plants (new)	Coal	340	2131	3184	3939	6602
	Oil	1	1	1	1	0
	Gas	5	13	25	53	110
Industrial boilers	Coal	1529	2745	3961	4627	4907
	Oil	153	216	278	390	474
	Gas	42	63	84	121	149
Residential combustion	Coal	232	248	265	312	373
	Biomass	620	594	590	516	491
Road transport	Heavy Duty Trucks – diesel	638	735	779	553	488
	Cars – diesel	66	119	164	422	715
	Cars – gasoline	609	527	360	138	156
Other sources		4445	7152	9058	9072	9187
Total		11653	16926	20515	21315	24417
Black carbon (BC), Gg C a^{-1}						
Residential combustion	Coal	33	37	47	55	67
	Biomass	742	659	652	477	314
Road transport	Heavy Duty Trucks – diesel	33	34	27	7	5
	Cars – diesel	15	21	19	24	40
	Cars – gasoline	4	7	8	11	14
Other sources		516	608	762	722	666
Total		1345	1366	1516	1295	1107
Organic carbon (OC), Gg C a^{-1}						
Residential combustion	Coal	43	50	65	76	92
	Biomass	2165	1808	1784	1300	856
Road transport	Heavy Duty Trucks – diesel	21	20	14	3	2
	Cars – diesel	6	6	5	5	8
	Cars – gasoline	14	17	14	8	10
Other sources		957	912	942	896	863
Total		3205	2812	2824	2288	1830

Table 5. Emission of air pollutants for key sectors in India in GAINS baseline scenario (Gg a^{-1})

Sector	Fuel	2000	2005	2010	2020	2030
Sulphur dioxide (SO_2), Gg SO_2 a^{-1}						
Power plants (old)	Coal	1918	1805	1782	827	539
	Oil	149	117	98	71	52
Power plants (new)	Coal	592	1266	2026	5786	12700
	Oil	46	183	240	683	1268
Industrial boilers	Coal	68	65	93	150	258
	Oil	354	427	592	1375	2435
Residential	Coal	150	149	145	146	147
	Biomass	126	148	159	156	153
Road transport	Heavy Duty Trucks – diesel	72	29	18	10	12
	Cars - diesel	54	29	22	11	14
Other sources		1599	2195	3422	6756	13942
Total		5128	6413	8597	15969	31520
Nitrogen oxides (NO_x), Gg NO_2 a^{-1}						
Power plants (old)	Coal	1139	1064	1062	466	314
	Oil	19	15	12	9	6
	Gas	25	24	21	29	22
Power plants (new)	Coal	186	389	619	1806	4026
	Oil	6	16	16	41	75
	Gas	10	16	66	229	236
Industrial boilers	Coal	34	33	47	76	130
	Oil	33	40	55	129	228
	Gas	14	16	10	11	11
Residential	Coal	28	28	27	27	27
	Biomass	271	319	343	336	329
Road transport	Heavy Duty Trucks - diesel	753	820	845	734	852
	Cars – diesel	159	254	303	416	526
	Cars – gasoline	141	134	140	21	25
Other sources		1317	1898	2566	4191	6829
Total		4135	5065	6134	8520	13638
Black carbon (BC), Gg C a^{-1}						
Residential combustion	Coal	45	45	44	44	44
	Biomass	459	538	576	564	550
Road transport	Heavy Duty Trucks – diesel	19	20	19	6	6
	Cars – diesel	33	50	52	22	27
	Cars – gasoline	1	1	1	1	1
Other sources		284	375	412	513	599
Total		842	1029	1104	1149	1227
Organic carbon (OC), Gg C a^{-1}						
Residential combustion	Coal	70	69	67	63	58
	Biomass	1252	1460	1543	1467	1390
Road transport	Heavy Duty Trucks – diesel	12	12	12	3	3
	Cars – diesel	12	18	18	4	5
	Cars – gasoline	3	3	4	1	1
Other sources		538	569	565	600	658
Total		1887	2132	2208	2139	2115

OC than for BC. The lowest presented projections (Streets et al., 2004) show a strong decline, compared to the year 2000. SRES projections of energy consumption used by Streets et al. (2004), assume virtually elimination of residential coal use in China by 2030 and significant reduction of use of biofuels in Asia, especially in B1 and B2 scenarios. Since residential combustion is a key source of carbonaceous aerosols in Asia, the 2030 emissions of BC and OC are estimated to drop in B1 and B2 by more than 50% compared to the levels of 2000 (Figs. 5 and 6). No comparable assumptions on a very strong reduction of solid fuels use in the domestic sector in Asia were made in REAS, ACCENT or GAINS leading to significantly higher estimates in 2030. In GAINS baseline, the biofuel use in residential sector in India and most other countries remains fairly constant over time, while in China it declines by nearly 20% compared to the 2000. At the same time, residential use of coal continues to grow (see Appendix S1 in Supporting Information). For OC emissions, ACCENT and GAINS projections are similar to the A1 and A2 (Streets et al., 2004) while REAS is much higher although shows a similar trend (Fig. 6, left-hand side). For BC, the 2030 estimates of REAS, ACCENT and GAINS are very similar but still higher than A1 and A2 (Fig. 5, left-hand side). Generally, REAS and GAINS show similar ranges of BC emissions towards the end of the forecasting period while ACCENT and especially SRES B1 and B2 are significantly lower for BC as well as OC.

4. Conclusions

The past (1990–2005) emissions of SO_2, NO_x, BC and OC in Asia have been reassessed in the last years following the findings of the remote sensing community indicating a very high growth of air pollution in East Asia in the last decade. New inventories and modelling studies confirm these findings for NO_x and SO_2 although they estimate slightly smaller increases. No comparably high growth in emissions of BC and OC has been estimated. There are still significant uncertainties in estimates for the historical years, especially for the emissions of carbonaceous aerosols where data on biofuel use and emission factors from residential combustion need improvement.

For the future, the recent studies show comparable trends in emissions of SO_2 (moderate growth to stabilization after 2010, especially in China), NO_x (continuing growth, slowed down slightly by already decided legislation), and BC and OC (steady decline after 2010).

Future SO_2 and NO_x emission levels in Asia estimated in this study for 2020 and 2030 are lower than in the previously shown and widely used IPCC SRES marker A1, A2 and B2 scenarios while B1 is within the GAINS range of estimates. Although the GAINS scenarios have significantly higher coal consumption than SRES futures, the assumptions about the future penetration of control technologies, especially in the power plant and transport sectors, include more stringent standards resulting in lower pollutant releases than previously anticipated. Similar trends as in GAINS have been estimated in the REAS project. It seems that the impact of legislation has been underestimated in the SRES work. Similar conclusions for sulphur emissions were presented recently (Van Vuuren and O'Neil, 2006) and the authors concluded further that other factors being equal, the lower sulphur emissions would imply increase in the expected temperature change associated with respective SRES scenarios.

IPCC SRES did not include BC and OC estimates but their importance for climate change has been highlighted in several studies. Asia is a major contributor to the global BC and OC budget and the key sources of these aerosols (domestic combustion) need to be better understood since the uncertainties of the emission estimates remain large and are carried forward in the projections, limiting also our ability to assess future reduction potentials.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Fuel consumption in China, India, and other Asia in the GAINS baseline scenario
Appendix S2. Sectoral emissions of SO_2, NO_x, BC and OC for China, India and other Asia in the GAINS baseline scenario.