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The contribution of megacities to regional sulfur pollution in Asia

Sarath K. Guttikunda[a], Gregory R. Carmichael[a,*], Giuseppe Calori[b], Christina Eck[c], Jung-Hun Woo[d]

[a] *Department of Chemical and Biochemical Engineering, The University of Iowa, Iowa City, IA 52242, USA*
[b] *ARIANET s.r.l, Viale Elvezia, 42, 20052 Monza MI, Italy*
[c] *Department of Chemical Engineering, The University of Missouri, Rolla, MO 65402, USA*
[d] *Center for Global and Regional Environmental Research, The University of Iowa, Iowa City, IA 52242, USA*

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Abstract

Asia is undergoing rapid urbanization resulting in increasing air pollution threats in its cities. The contribution of megacities to sulfur emissions and pollution in Asia is studied over a 25-year period (1975–2000) using a multi-layer Lagrangian puff transport model. Asian megacities cover $<2\%$ of the land area but emit $\sim 16\%$ of the total anthropogenic sulfur emissions of Asia. It is shown that urban sulfur emissions contribute over 30% to the regional pollution levels in large parts of Asia. The average contribution of megacities over the western Pacific increased from $<5\%$ in 1975 to $>10\%$ in 2000. Two future emission scenarios are evaluated for 2020—"business as usual (BAU)" and "maximum feasible controls (MAXF)" to establish the range of reductions possible for these cities. The MAXF scenario would result in 2020 S-emissions that are $\sim 80\%$ lower than those in 2000, at an estimated control cost of US $87 billion per year (1995 US$) for all of Asia. An urban scale analysis of sulfur pollution for four megacities—Shanghai, and Chongqing in China; Seoul in South Korea; and Mumbai (formerly Bombay) in India is presented. If pollution levels were allowed to increase under BAU, over 30 million people in these cities alone would be exposed to levels in excess of the WHO guidelines.

Keywords: Sulfur pollution; Urban pollution; Population exposure

1. Introduction

The urban environment is where an increasing share of the world's population resides, where most commercial energy is consumed, and where the impacts of pollution are felt the most. Rapid economic growth in urban Asia has attracted millions of rural residents to metropolitan environments. Asia presently has ~ 1 billion ($\sim 35\%$ of total population) urban dwellers, projected to grow at an average of 4% per year to ~ 3 billion ($\sim 55\%$ of total population) by 2025 (WDI, 2000). Presently, in Asia there are 30 grid cells (at $1^\circ \times 1^\circ$ resolution, LandScan, 2000) with population more than 10 million and at least 169 grid cells with population over 5 million; and the number is rapidly increasing (see Fig. 1). These cities are distributed throughout Asia, including Mumbai, New Delhi, Calcutta, Dhaka, and Karachi in the Indian Subcontinent; Singapore, Kuala Lumpur, Jakarta, and Bangkok in the Southeast Asia; and Beijing, Shanghai, Chongqing, Guangzhou, Tokyo, Seoul and Pusan in East Asia. Changing standards of living in the urban centers have fueled increasing energy demand often associated with unchecked emissions from automobiles, domestic heating, and small-scale

*Corresponding author.
E-mail address: gcarmich@engineering.uiowa.edu (G.R. Carmichael).

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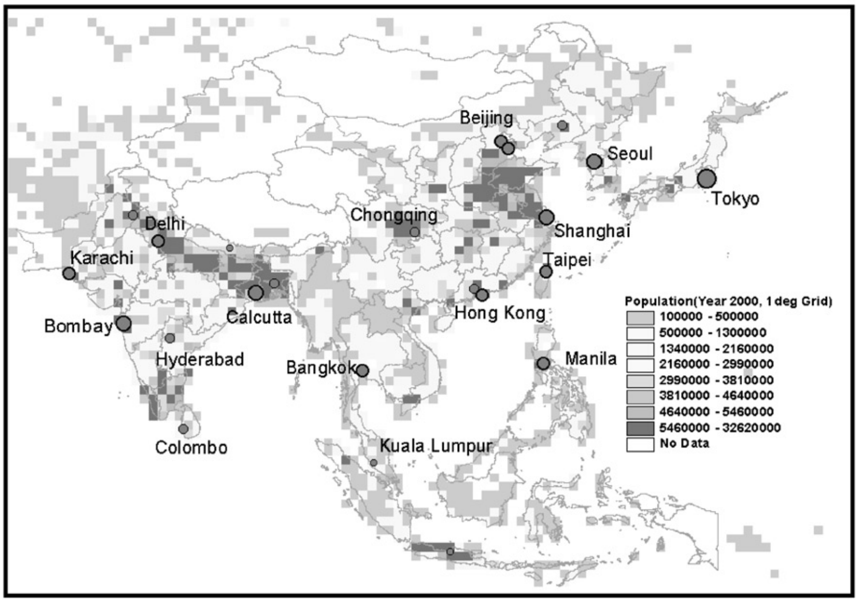
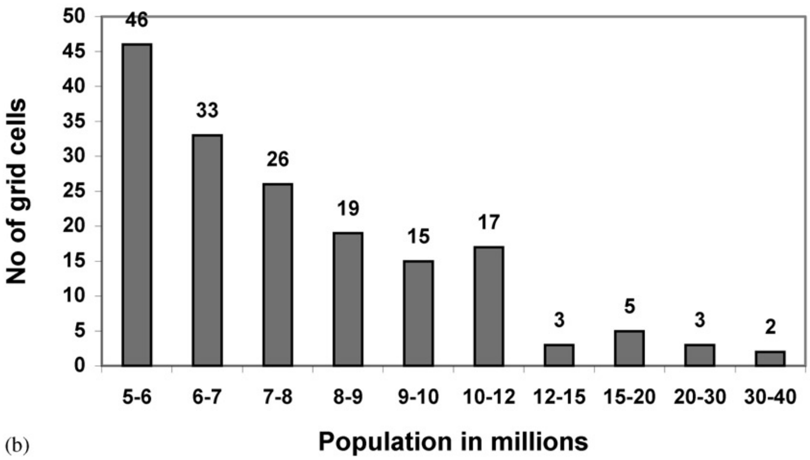


(a)



(b)

Fig. 1. (a) Asian population at $1^\circ \times 1^\circ$ resolution; (b) statistics of Asian population at $1^\circ \times 1^\circ$ resolution (LandScan, 2000).

industries. Coal being the cheapest and most widely accessible, is still the primary source of energy in Asia and contributes significantly to sulfur and particulate pollution levels that often exceed the WHO air quality guidelines (World Bank, 1997). Every year, Asian urban centers, prone to air pollution, incur hundreds of millions of dollars in health and economic damages (OECD, 2000).

Presently, the urban air pollution problems in Asia are continuing to increase and air pollutants originating from urban regions are recognized as increasing sources of regional- and global-scale pollution (Streets et al., 1999a). Besides stationary combustion sources such as thermal power plants and industrial estates, air pollution from mobile sources has also become a major contributor to increasing human health effects in the urban environments of Asia (Krupnick and Harrington 2000). The fact that the megacities and urban centers in Asia cover $<2\%$ of the landcover and still produce 10–20% of regional trace gas emissions signifies their importance. In the last two decades, Asian cities have experienced an increased demand for fossil fuels, viz., coal, and petroleum products in the industrial, domestic and transport sectors, which in turn has led to increased levels of sulfur pollution due to the high sulfur content in locally available energy resources. However, increased pollution awareness campaigns, stringent pollution control regulations, use of low sulfur fuel, implementation of desulfurization techniques, and periodic monitoring have resulted in a significant reduction in sulfur and other trace gas emissions in many cities. Nevertheless, sulfur pollution levels remain significantly above compliance levels throughout large parts of Asia (Calori et al., 2001; Klimont et al., 2001; Reddy and Venkataraman, 2002, Streets et al., 2000b, Yang et al., 2001).

This study is a continuing effort in support of the integrated assessment modeling of air pollution in Asia, started as part of the RAINS-Asia (Regional Air pollution INtegration and Simulation—Asia) project (Foell et al., 1995; Shah et al., 2000). Here, we focus on the analysis of air pollution in and from Asian megacities. In this paper, we present estimates of the contribution of sulfur emissions from Asian megacities to the ambient sulfur levels over the last 25 years. Finally, we assess the vulnerability of urban population exposure and cost-effectiveness for two distinct energy consumption scenarios for year 2020.

2. Sulfur emissions in Asian urban centers

Emissions of SO_2 from Asia have been estimated for the period 1975–2000 as part of the RAINS-Asia project (Calori et al., 2001; Streets et al., 2000b). The RAINS-Asia data base contains energy consumption statistics, fuel mix characteristics, emission factors, and emission projection information through 2030 for sulfur and other trace gas species, including NO_x, NH_3, and VOC's (Amann, 2001; Klimont et al., 2001). Emission sources from industrial, domestic, and transportation sectors, elevated Large Point Sources (LPS's) (associated with power and industrial plants with generation capacity of more than 500 MW), and volcanoes are included. In addition to inland anthropogenic sources, sulfur emissions due to shipping activity in Asian waters are also included. Shipping activities in the major ports of Asia have been shown to contribute significantly to high sulfur deposition and concentration levels in Asia (Streets et al., 2000a).

Table 1 presents the population for year 2000 and total sulfur emissions from a $1^\circ \times 1^\circ$ grid cell covering the city limits of 25 megacities included in this study. Today these urban centers account for an average of $\sim 16\%$ of the total anthropogenic sulfur emissions in Asia. For 1990, grid cells containing Karachi, Mumbai, Bangkok, Singapore, Manila, Hong Kong, Beijing, Shanghai, Chongqing, Guangzhou, Wuhan, Taipei, Seoul and Tokyo each had emissions in excess of 100 kt SO_2 per year.

Important information on emission trends is contained in this table. Chinese cities have the highest sulfur emissions, but SO_2 emissions in many cities have declined in the 1990s. Efforts of national and municipal governments, with the cooperation of private industry, have lead to sulfur pollution control programs in East Asia which have resulted in: improvements in combustion processes; the substitution of coal based applications with low-sulfur fuel and natural gas; a change in fuel standards in the transportation sector leading to a reduction in the S-content of fuels used; and the installation of air pollution control facilities (Shah et al., 2000). In China, control measures focused on the largest cities have encompassed a wide range of environmental regulations and standards including pollution levies, discharge permits, and mandatory pollution controls to help contain sulfur pollution from existing sources (Pu et al., 2000). In Hong Kong, emissions have decreased due to the use of low sulfur fuel and the installation of flue gas desulfurization (FGD) systems in all new power plants (Hong Kong EPD, 1998). On the other hand, S-emissions in the cities of the Indian subcontinent have continued to grow rapidly ($\sim 8.6\%$ per year). The city of Karachi, Pakistan has the highest growth rate in sulfur emissions ($\sim 19\%$ per year). In Dhaka, Bangladesh, the primary reason for low sulfur emissions, in spite of population figures exceeding 20 million is due to the consumption of biofuels for large portion of its energy requirement (Streets and Waldhoff, 1999b; Guttikunda et al., 2001). Singapore, Kuala Lumpur, and Bangkok have growth rates comparable to cities in the Subcontinent ($\sim 10\%$) and Manila comparable to East Asia ($\sim 3\%$).

We also studied possible future emissions under two scenarios derived from RAINS-Asia Emission and Cost (EMCO) module for 2010 and 2020. Although in reality there are a large variety of options available to control emissions, we have selected the following scenarios to show the range of reductions possible from urban centers: (1) the "Business As Usual" (BAU) scenario assumes current emission and fuel standards for all the countries and projections for 2020 show an increase in sulfur emissions of 2–3 times above 1990-levels; and (2) the "Maximum Feasible SO_2 Emission Control" (MAXF) scenario, in which emission sources in the urban centers are dramatically reduced due to the implementation of FGD and in-furnace control (limestone injection) for industrial boilers, high efficiency FGD (regenerative processes) for power plants, and low sulfur diesel oil for transportation sector. Table 1 presents sulfur emissions for 2010 and 2020 under the BAU and MAXF scenarios. Under the BAU scenario sulfur emissions continue to grow, in some cases by as much as a factor of 4. The MAXF scenario results in S-emissions that are 80% lower than 2000 levels.

Table 1
Population and sulfur emissions from the megacities of Asia

Urban center	Country	Population (millions)	Total sulfur emissions (kt SO_2 per year)							
		2000	1975	1980	1990	2000	2010 BAU	2020 BAU	2010 MAXF	2020 MAXF
East Asia										
Beijing	China	12	128.7	173.0	270.3	261.6	406.5	385.1	76.7	64.4
Tianjin	China	9	91.7	120.9	195.5	275.9	444.9	469.9	71.5	50.8
Taiyuan	China	5	89.7	111.4	198.6	208.4	417.6	434.1	99.9	98.8
Wuhan	China	11	146.4	190.1	314.9	264.7	317.6	345.3	72.2	69.9
Shanghai	China	17	196.2	271.2	403.3	429.0	705.9	759.5	108.6	113.1
Guangzhou	China	10	79.4	104.6	275.1	167.4	493.7	580.8	61.4	61.2
Chongqing	China	11	451.8	589.9	968.5	704.5	635.8	632.2	119.7	114.7
Guiyang	China	4	152.5	189.4	337.8	300.6	335.3	278.9	45.2	41.6
Hong Kong	Hong Kong	9	58.8	86.0	153.6	119.4	256.3	103.8	28.0	24.4
Tokyo	Japan	29	173.2	142.4	173.7	97.9	84.7	87.8	39.7	38.5
Osaka	Japan	16	104.6	77.9	129.5	70.0	53.1	47.6	26.3	23.5
Seoul	Korea (S)	14	169.9	270.8	594.8	301.5	163.5	217.8	69.1	86.2
Pusan	Korea (S)	6	21.4	33.9	74.1	38.9	50.9	67.2	21.1	23.3
South Asia										
Dhaka	Bangladesh	22	11.5	15.0	14.3	22.4	56.1	106.2	23.2	29.5
New Delhi	India	27	21.6	25.9	44.3	68.4	228.3	335.1	29.7	46.8
Calcutta	India	32	20.6	24.4	39.1	64.6	200.7	310.6	25.8	42.5
Mumbai	India	14	77.0	90.3	139.8	206.7	286.4	526.4	53.3	94.6
Chennai	India	11	30.4	34.9	49.0	85.4	214.9	404.5	27.0	52.2
Lahore	Pakistan	14	7.0	8.1	11.3	16.6	111.8	157.5	20.0	27.3
Karachi	Pakistan	9	40.4	45.2	117.3	240.4	220.2	680.5	8.7	18.8
S.E. Asia										
Jakarta	Indonesia	32	21.8	40.0	70.3	93.4	110.7	156.3	29.0	37.2
Kuala Lumpur	Malaysia	8	3.5	3.8	14.3	11.8	143.7	128.2	14.4	15.2
Manila	Philippines	11	42.0	52.1	92.9	71.7	127.4	124.8	27.6	25.8
Singapore	Singapore	6	54.3	81.0	192.7	191.7	342.5	349.8	53.9	56.6
Bangkok	Thailand	11	71.9	94.2	248.2	243.6	364.5	491.4	54.9	67.6

3. Regional sulfur pollution from Asian urban centers

Cities with high emissions not only pose threats to their habitants, but also impact regional air quality as well. The impact of urban emissions on ambient sulfur levels was estimated using the ATMOS model, a three-layer Lagrangian puff transport model. Complete details on model formulation and evaluation are presented elsewhere (Arndt et al., 1997; Calori et al., 2001; Guttikunda et al., 2001). Calculations were performed for the years 1975, 1980, 1985, 1990, 1995 and 2000. Yearly runs were performed using meteorological data (precipitation, wind vectors, and potential boundary layer height at 6-h intervals) from the NCAR/NCEP reanalysis project (Kalnay et al., 1996). For evaluating the contribution of the Asian cities to total sulfur deposition and concentrations, two sets of simulations were conducted—one with all the emissions sources (area, LPS, shipping activities, and volcanoes) and one with the cities alone.

3.1. Modeling results for 1975–2000

Fig. 2 presents percentage contribution of the megacities to total sulfur deposition (dry + wet) averaged over the simulation period from 1975 to 2000. Over the simulation period, the percent contribution from the megacities remained approximately constant due to similar growth rates in the cities and the regions. A change in contribution from year to year is primarily due to changing precipitation and meteorological conditions–results of which are presented elsewhere (Calori et al., 2001). Total sulfur deposition due to the cities increased gradually over the Pacific Ocean, from an average of $<5\%$ in 1975 to $>10\%$ in 2000. It is important to note that the percent contribution in the region follows closely the emissions pattern and city location, with an average of $>50\%$ of sulfur deposition around Thailand coming from Bangkok, and similarly near Mumbai, Karachi and Singapore. Cities of Chongqing, Shanghai, Beijing, and Hong Kong show

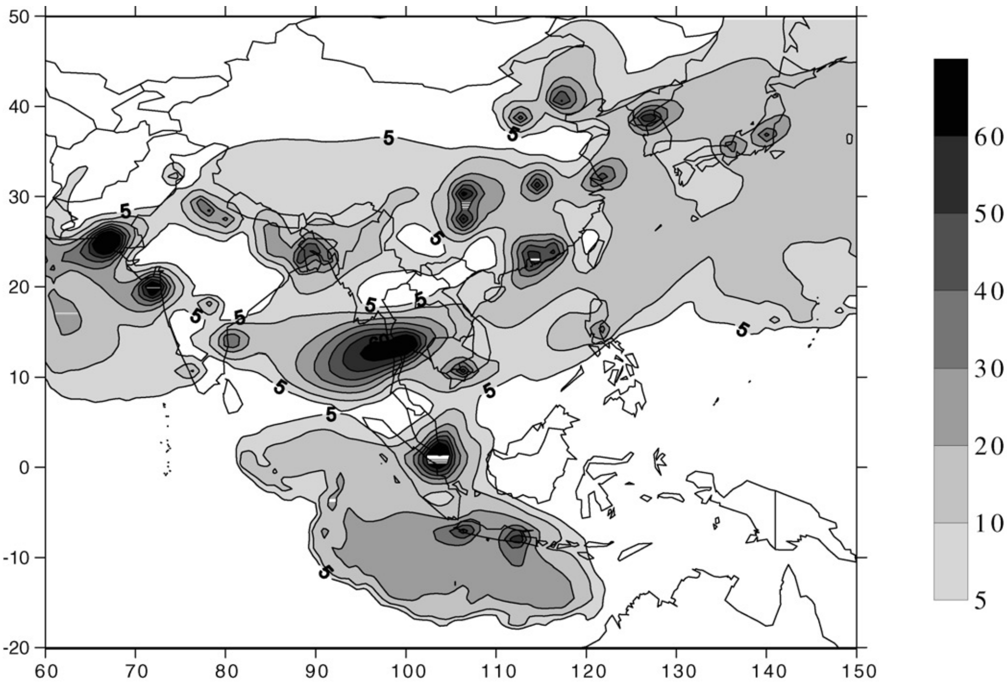


Fig. 2. Percentage contribution to total sulfur deposition due to SO_2 emissions from megacities and major urban centers in Asia averaged over 25 years between 1975 and 2000.

an average contribution of over 30% over large regions. South and Southeast Asian cities exert an even higher contribution. This reflects the fact that in these areas an even larger fraction of the industrial activities are concentrated in the big cities. In Japan the contribution from the cities is low due to high percentage of emissions from volcanic activity of Mt. Sakurajima and Mt. Miyakejima, and low S-emissions from their highly controlled industrial and power sectors (Guttikunda et al., 2001). Since many megacities are located in coastal environmental, their emissions have a large impact on sulfur levels and deposition over the Seas.

Figs. 3a–d present annual average SO_2 concentrations in $\mu g/m^3$ due to urban sulfur emissions alone for 1975, 1980, 1990 and 2000. For the period 1975–2000, the highest concentration levels were predicted around the city of Chongqing, ranging from $40\,\mu g/m^3$ in 1975 to $81\,\mu g/m^3$ in 2000, with a peak in 1990 of $120\,\mu g/m^3$. Similarly, cities in Japan and South Korea follow the decreasing emission trend during the 1990s. The contribution from the cities of the Indian Subcontinent increased from 1975 to 2000 corresponding to increased economic activity and dependence on fossil fuels. Total sulfur deposition and concentrations (in the form of SO_2 and sulfate) due to total (urban and regional) emission sources are presented in Table 2. The impact of the growth in S-emissions over the last 25 years is clearly seen. The highest levels of total sulfur deposition are calculated around the city of Chongqing, $\sim 3.4\,gS/m^2$ in 1975 and $10.3\,gS/m^2$ in 2000. Though the emissions from the Chongqing area show a decreasing trend from 1990 to 2000, deposition levels still show an increasing trend indicating the importance of long-range transport from regional sources in Southern China. From 1990 to 2000, the contribution of emissions from Chongqing to sulfur deposition levels is estimated to have reduced significantly due to the increased consumption of natural gas in the domestic and industrial sectors, and the installation of desulfurization equipment in power plants in and around the city (Gao et al., 2001). Shanghai, the most populous and industrialized city of China, also showed a decreasing trend in the 1990s (Shanghai EPB, 2000). In spite of these efforts SO_2 concentrations are estimated to be $22\,\mu g/m^3$ in Taiyuan and $167\,\mu g/m^3$ in Chongqing for the year 2000. These results point out that sulfur levels in large parts of China still exceed WHO guidelines for sulfur pollution and critical loads for sulfur deposition by at least a factor of 2 in some parts of China.

The sulfur pollution levels increased 3–4-fold between 1975 and 2000 for the cities of the Indian subcontinent and Southeast Asia. For example, Manila shows the largest change over the last 25 years ($\sim$600% and $\sim$1000% increase in SO_2 and sulfate concentrations, respectively).

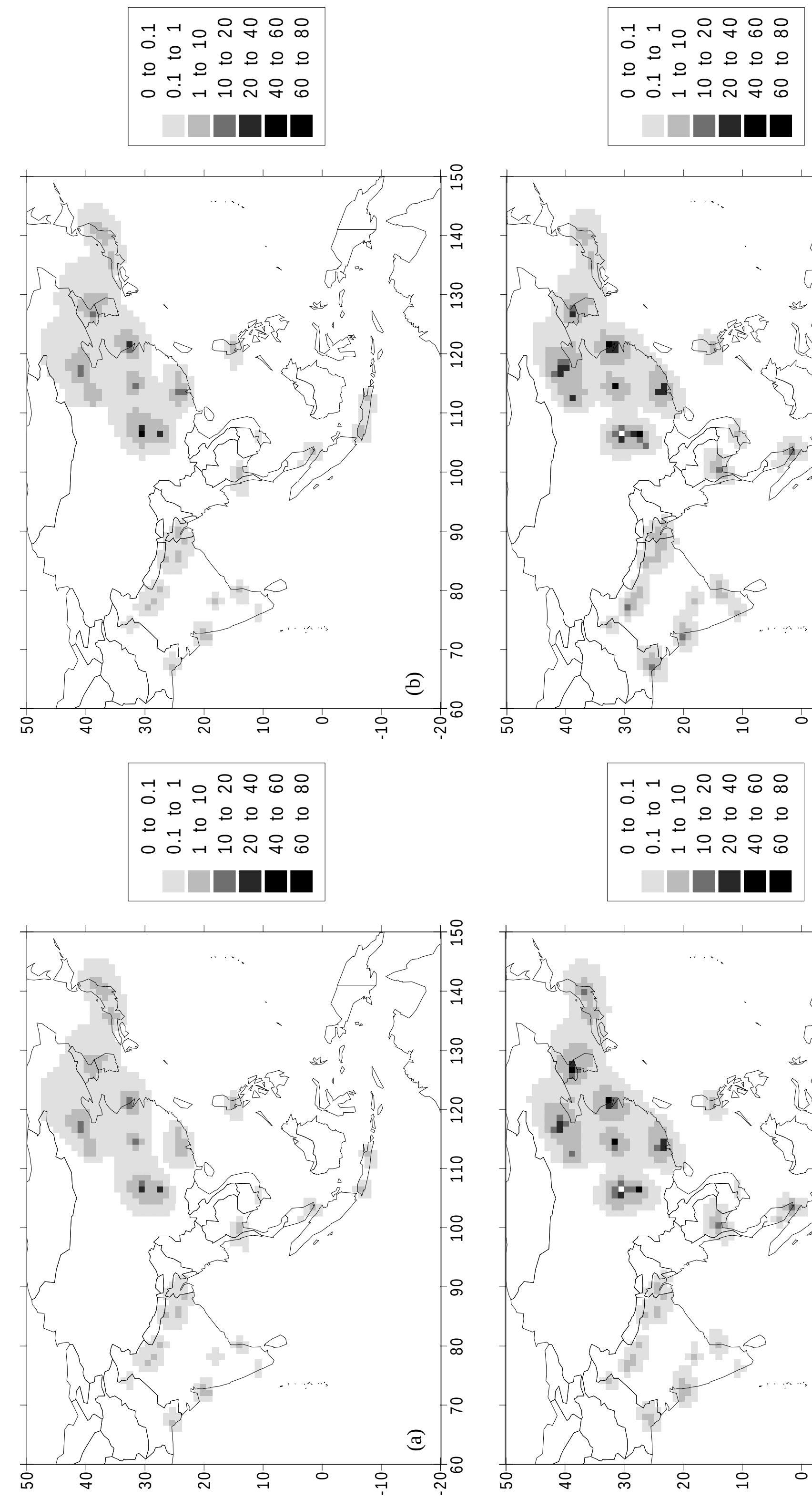


Fig. 3. SO_2 (in μg/m^3) due to SO_2 emissions from megacities and major urban centers in Asia for year (a) 1975; (b) 1980; (c) 1990; (d) 2000.

Table 2
Sulfur Pollution in the Megacities of Asia for the period of 1975–2000

Urban center	Total sulfur deposition ($g S/m^2$)				SO_2 concentrations ($\mu g/m^3$)				Sulfate concentrations ($\mu g/m^3$)			
	1975	1980	1990	2000	1975	1980	1990	2000	1975	1980	1990	2000
East Asia												
Beijing	0.8	0.8	2.3	2.2	17.3	21.4	44.7	61.2	7.5	8.6	20.1	26.5
Tianjin	0.8	0.9	2.5	2.2	17.9	23.1	44.2	52.4	8.2	9.6	22.1	27.2
Taiyuan	0.6	0.6	1.7	1.6	8.7	10.6	23.7	21.8	4.1	5.2	12.0	13.5
Wuhan	1.6	1.7	4.0	4.0	17.2	21.6	51.3	65.2	6.9	9.0	24.3	29.8
Shanghai	2.2	2.6	4.3	4.8	33.4	49.4	75.1	110.2	14.2	20.7	35.1	46.2
Guangzhou	1.4	1.8	2.7	3.0	18.3	30.0	37.6	58.6	8.0	12.8	17.8	25.1
Chongqing	3.4	3.7	9.3	10.3	45.7	62.6	135.1	167.3	17.3	24.3	62.6	68.5
Guiyang	2.3	2.9	4.5	4.9	28.0	44.5	66.9	95.8	11.5	18.6	29.5	37.5
Hong Kong	0.6	0.7	1.7	1.5	7.0	10.9	33.5	29.4	3.4	5.0	14.9	13.4
Tokyo	1.7	1.4	1.8	1.8	10.4	7.9	13.4	7.7	4.1	3.6	6.0	3.6
Osaka	1.4	1.2	1.5	1.2	8.9	7.0	12.1	6.8	4.1	4.1	6.6	4.1
Seoul	1.0	1.2	3.5	2.0	11.3	15.9	53.6	27.4	5.6	7.7	22.0	12.8
Pusan	1.6	2.4	2.6	2.6	37.1	55.4	28.1	63.0	13.9	20.1	18.0	26.3
South Asia												
Dhaka	0.1	0.2	0.4	0.5	1.1	1.5	1.8	3.1	0.6	0.9	1.5	2.5
New Delhi	0.2	0.3	0.5	0.8	4.3	5.3	11.1	23.6	2.2	2.7	4.8	10.2
Calcutta	0.2	0.3	0.6	1.1	2.0	2.6	5.5	11.3	1.1	1.6	3.3	6.7
Mumbai	0.6	0.7	0.6	1.0	6.7	8.3	8.0	12.9	3.4	4.0	3.7	6.7
Chennai	0.3	0.4	0.7	1.2	5.2	6.5	10.6	22.2	2.4	3.1	4.2	8.7
Lahore	0.2	0.2	0.3	0.4	2.0	2.3	3.4	5.3	1.2	1.5	1.9	3.1
Karachi	0.2	0.2	0.4	0.7	3.1	3.4	7.1	12.8	1.4	1.6	2.8	5.2
S.E. Asia												
Jakarta	0.5	1.0	1.1	1.3	2.3	4.2	5.7	8.2	1.7	2.4	3.3	4.9
Kuala Lumpur	1.4	2.2	1.3	2.5	16.0	25.3	11.6	29.1	7.9	11.5	4.8	12.1
Manila	0.4	0.5	1.0	2.1	2.2	2.4	6.4	16.8	0.8	0.9	3.3	9.7
Singapore	0.7	1.1	2.4	2.5	4.4	6.2	13.0	14.0	2.4	3.0	5.4	6.5
Bangkok	0.5	0.8	2.2	2.6	4.4	6.2	17.1	19.0	1.6	2.3	6.8	8.0

3.2. Modeling results for 2010 and 2020

To assess possible environmental futures for 2010 and 2020, the ATMOS model was run for the BAU and MAXF scenarios utilizing the meteorological data for year 2000. For this set of runs, year 2000 is used as a base year to compare the expected range of change in sulfur pollution in 2010 and 2020 under the two scenarios. Table 3 presents sulfur pollution levels for the 25 megacities due to all the emission sources for 2010 and 2020. Fig. 4 presents the percentage change in SO_2 concentration levels due to urban sulfur emissions alone in year 2020 compared to year 2000 under BAU and MAXF. Under 2020 BAU, SO_2 concentrations around the city of Shanghai increase from 110 to 133 $\mu g/m^3$. In Karachi, SO_2 concentrations increase for 13–76 $\mu g/m^3$. On average sulfur pollution levels are projected to approximately triple in and around the cities of the Indian Subcontinent by 2020. Sulfate concentrations, an important surrogate of harmful $PM_{2.5}$ (particulate matter below 2.5 μm in diameter) are projected to reach levels of 50 and 61 $\mu g/m^3$ in Shanghai and similar levels in the other cities in 2010 and 2020, respectively, exceeding WHO guidelines 2–3-fold and increasing the risk of mortality and morbidity associated with fine particulates (OECD, 2000).

These results suggest that in Asian urban centers, concerns about sulfur emissions and their potential impact on human health through secondary sulfate formation, and on the agricultural and forestry sector through acid deposition, will become more important and therefore are unlikely to remain unchecked. Results under the MAXF scenario show a reduction of ~5-fold in total annual deposition in Asia due to urban emissions. The maximum levels of total sulfur deposition under MAXF are reduced from ~5.5 gS/m^2 under BAU to ~1.0 gS/m^2, levels lower than those observed in 1990. From Fig. 4, it can be seen that most of the urban centers would reduce sulfur pollution levels below those of 2000 by at least 60% under the MAXF. Using cost information from RAINS-Asia, MAXF is estimated to require control cost of US $87 billion per year (in 1995

Table 3
Sulfur pollution in the megacities of Asia in 2010 and 2020

Urban center	Total sulfur deposition (g S/m^2)				SO_2 concentrations (μg/m^3)				Sulfate concentrations (μg/m^3)			
	2010 BAU	2020 BAU	2010 MAXF	2020 MAXF	2010 BAU	2020 BAU	2010 MAXF	2020 MAXF	2010 BAU	2020 BAU	2010 MAXF	2020 MAXF
East Asia												
Beijing	4.5	4.3	0.9	0.8	89.5	86.5	14.1	16.2	49.7	48.7	8.8	8.1
Tianjin	4.6	4.4	0.9	0.7	93.4	92.6	12.8	15.9	54.0	53.1	9.2	8.1
Taiyuan	3.9	3.9	0.8	0.8	62.4	65.4	13.5	12.8	34.6	35.7	6.6	7.0
Wuhan	5.5	6.2	1.2	1.1	77.5	99.4	12.3	12.4	40.2	47.9	7.2	7.1
Shanghai	6.4	7.4	1.0	1.1	108.2	133.0	13.1	12.2	50.6	61.8	6.3	6.7
Guangzhou	6.2	7.1	0.8	0.8	79.3	102.6	8.2	7.9	36.8	44.6	4.4	4.5
Chongqing	8.1	8.0	1.5	1.5	94.4	94.6	14.6	15.4	46.1	45.7	8.0	7.6
Guiyang	5.2	4.6	0.8	0.7	71.8	55.6	7.1	7.9	34.7	29.3	4.6	4.3
Hong Kong	3.1	2.2	0.4	0.4	46.3	23.9	4.1	4.8	22.5	15.4	3.1	2.8
Tokyo	1.8	1.8	1.0	1.0	7.5	8.6	3.4	3.5	3.8	4.5	1.7	1.7
Osaka	1.5	1.2	0.6	0.5	6.8	11.6	2.6	3.0	4.2	6.2	1.8	1.6
Seoul	3.5	2.0	0.8	0.9	26.9	35.2	13.3	10.8	15.8	19.5	5.1	6.0
Pusan	2.6	2.6	0.5	0.6	13.4	16.7	5.7	5.5	11.1	14.1	4.0	4.4
South Asia												
Dhaka	0.9	1.5	0.3	0.3	6.1	11.3	3.0	2.4	4.2	7.4	1.3	1.7
New Delhi	1.4	2.1	0.2	0.3	35.1	54.4	5.5	3.6	14.7	22.7	1.6	2.5
Calcutta	0.6	1.1	0.3	0.5	25.1	40.5	4.2	2.6	12.7	21.3	1.5	2.4
Mumbai	0.6	1.0	0.3	0.5	18.6	33.0	6.6	3.7	9.1	15.8	1.7	3.0
Chennai	0.7	1.2	0.2	0.3	15.6	32.7	3.3	1.7	6.8	13.6	0.8	1.5
Lahore	0.3	0.4	0.2	0.2	19.2	27.7	4.2	3.1	9.4	13.3	1.4	2.0
Karachi	0.4	0.7	0.0	0.1	23.5	75.9	2.1	1.0	10.9	35.0	0.5	1.1
S.E. Asia												
Jakarta	1.1	1.3	0.5	0.6	13.9	19.7	3.3	2.6	8.2	11.2	1.6	1.9
Kuala Lumpur	1.3	2.5	0.3	0.3	24.3	16.5	1.5	1.9	10.9	7.9	1.0	0.8
Manila	1.0	2.1	0.4	0.5	15.0	21.2	2.2	1.8	7.9	11.2	1.0	1.3
Singapore	2.4	2.5	0.7	0.8	25.0	25.7	4.4	4.1	11.6	12.0	2.0	2.1
Bangkok	2.2	2.6	0.7	0.8	35.3	52.4	6.2	4.9	15.2	22.5	2.2	2.8

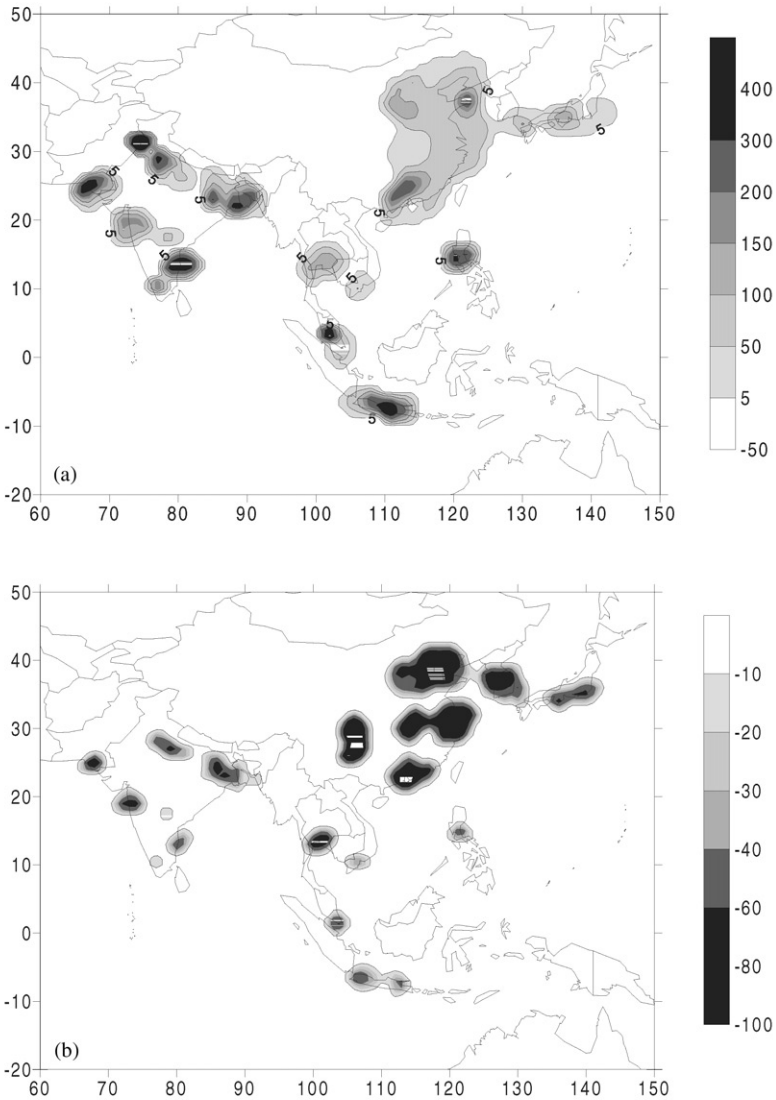


Fig. 4. Percentage change in SO_2 concentrations due to SO_2 emissions from megacities and major urban centers in Asia from year 2000 in (a) 2020 under BAU scenario and (b) 2020 under MAXF scenario.

US$). These results help to frame the policy discussions, and they raise a key challenge for the formulation and implementation of a cost-effective emission regulatory framework for emission reductions not only at an urban level, but also at the national level, particularly through establishment of local standards, regional pollution control plans, monitoring and enforcement.

4. Urban scale sulfur pollution analysis

Urbanization and industrialization of Asia will surely continue. Sulfur pollution levels, if not controlled, will continue to rise, and pose increasingly serious threats to large portion of the population. The management of emissions requires a better understanding of emission sources and their controls within Asian megacities. The results obtained by ATMOS provide an estimate of the contribution of Asian megacities to sulfur pollution at the regional level. Since the model operates on a $1^\circ \times 1^\circ$ grid, it is difficult to capture actual conditions within a megacity and further analyze the benefits of control options since the concentrations will be much higher in some parts of the city than the averages predicted by ATMOS. More detailed analysis of urban scale sulfur pollution was conducted for four cities—Shanghai, Chongqing in China; Seoul in South Korea; and Mumbai in India, using a modified version of the ATMOS model—the Urban Branch Trajectory (UrBAT) model. This finer-resolution analysis provides a framework to evaluate effective control measures (Calori and Carmichael, 1999). Due to their distinct fuel consumption mix and geographical location, these cities provide a unique set to evaluate the effectiveness of pollution control measures in various economic sectors (Guttikunda et al., 2001).

For this study, UrBAT model simulations were conducted at $0.1^\circ \times 0.1^\circ$ resolution using meteorological data from the NCAR/NCEP Reanalysis project and the emissions inventory presented in Table 1 for 2000 and 2020. For 2020, two sets of simulations were performed—i.e., the BAU and MAXF scenarios. The simulation domains cover an area of approximately $1^\circ \times 1^\circ$ grid, with a population of approximately 19, 16, 20, and 16 million for Shanghai, Chongqing, Seoul, and Mumbai, respectively (LandScan, 2000). The sulfur emissions were distributed within the city limits using population database at 30-s resolution (LandScan, 2000) for domestic and industrial sector emissions, and transport sector emissions were allocated using road maps. Fig. 5 presents calculated SO_2 concentrations for the year 2000 and 2020 under BAU and MAXF. It is important to note that the urban scale simulations were conducted for the city emissions only to illustrate the importance of urban scale modeling, exposure analysis, and the cost-effectiveness of control measures. The contributions from emissions outside the city limits due to long-range transport are not accounted for in this set of simulations, but can be obtained from ATMOS results. The annual average peak SO_2 concentrations calculated in the simulation domain were $140\,\mu g/m^3$ ($110\,\mu g/m^3$) for Shanghai, $258\,\mu g/m^3$ ($167\,\mu g/m^3$) for Chongqing, $117\,\mu g/m^3$ ($27\,\mu g/m^3$) for Seoul, and $101\,\mu g/m^3$ ($13\,\mu g/m^3$) for Mumbai, in 2000 (numbers in parentheses indicate annual average SO_2 concentration calculated using the ATMOS model for the $1^\circ \times 1^\circ$ grid cell covering the city limits (see Table 2)).

The SO_2 levels in Chongqing exceed WHO air quality standards by at least 4 times, ranging from an average of 400 to $200\,\mu g/m^3$ during the period of 1991–1998 (Gao et al., 2001). One of the largest cities in China, Chongqing is located in a region rich in mineral resources, which provide raw materials for its coal-based industry. In addition to high emissions, high pollutant levels are in part due to the geography of Chongqing, which is surrounded by mountains that hamper dispersion and transport away from the city. The most populated urban area in China, Shanghai, is a major industrial and commercial region with most of its sulfur pollution coming from power plants and large-scale industries in and around the city. Greater Seoul has the lowest concentrations of the four cities, following its decreasing trend in emissions triggered in part by usage of fuel oil and more stringent sulfur control measures in the industrial and power sectors. Mumbai is a major industrialized port and shipping yard contributes significantly to the sulfur pollution besides increasing industrial and motor vehicle activity (Streets et al., 2000a). Under the BAU for 2020, peak SO_2 concentrations reach $248\,\mu g/m^3$ ($133\,\mu g/m^3$) for Shanghai, $288\,\mu g/m^3$ ($94\,\mu g/m^3$) for Chongqing, $82\,\mu g/m^3$ ($35\,\mu g/m^3$) for Seoul, and $226\,\mu g/m^3$ ($33\,\mu g/m^3$) for Mumbai.

The WHO standard for annual average SO_2 concentrations is $80\,\mu g/m^3$ in an industrial area and $60\,\mu g/m^3$ in a residential area. Taking $80\,\mu g/m^3$ as an upper limit, we estimate the number of people exposed to dangerous levels of SO_2 due to city emissions alone for each of the $0.1^\circ \times 0.1^\circ$ grids. Under the BAU scenario in 2020, the population exposed to SO_2 pollution levels above $80\,\mu g/m^3$ is 12.6, 7.6, 5.2 and 10.8 million for Shanghai, Chongqing, Seoul, and Mumbai, respectively. Under the MAXF scenario concentrations are reduced to below $40\,\mu g/m^3$. From the RAINS-Asia EMCO module, control costs under MAXF scenario are estimated to be US$1031 million, US$413 million, US$1532 million, and US$540 million per year in 2020 (in 1995 US$) for Shanghai, Chongqing, Seoul, and Mumbai, respectively.

5. Conclusions

By 2020, over half of Asia's population is expected to live in cities. Unplanned and rapid urbanization is taking its toll on human health due to increasing air pollution and exposure to pollutants such as particulates and ozone, a situation driven by industrialization, and increasing vehicle use in urban environments. Because of their large human health effects, urban environmental problems are of greater concern to local decision makers than global problems, and therefore will have a greater near-term impact on urban environmental policy. In recent years, sulfur pollution and its control has been a focal point for most Asian megacities. In East Asia, the growth rate of sulfur emissions declined during the 1990s, while in the Indian Subcontinent and Southeast Asia, the growth rate increased, primarily due to high energy demand, availability of cleaner fuels, and pollution control technologies. A corresponding increase in deposition levels was observed with an average of more than 30% of the sulfur deposition levels estimated to have originated from the megacities. Further, for year 2010 and 2020, two sets of scenarios; "business as usual" (BAU) and "maximum feasible control" (MAXF) were evaluated using the energy consumption and fuel characteristic information from the RAINS-Asia model (version 7.52). The MAXF scenario, which represents the range of possible emissions reductions, reduce the

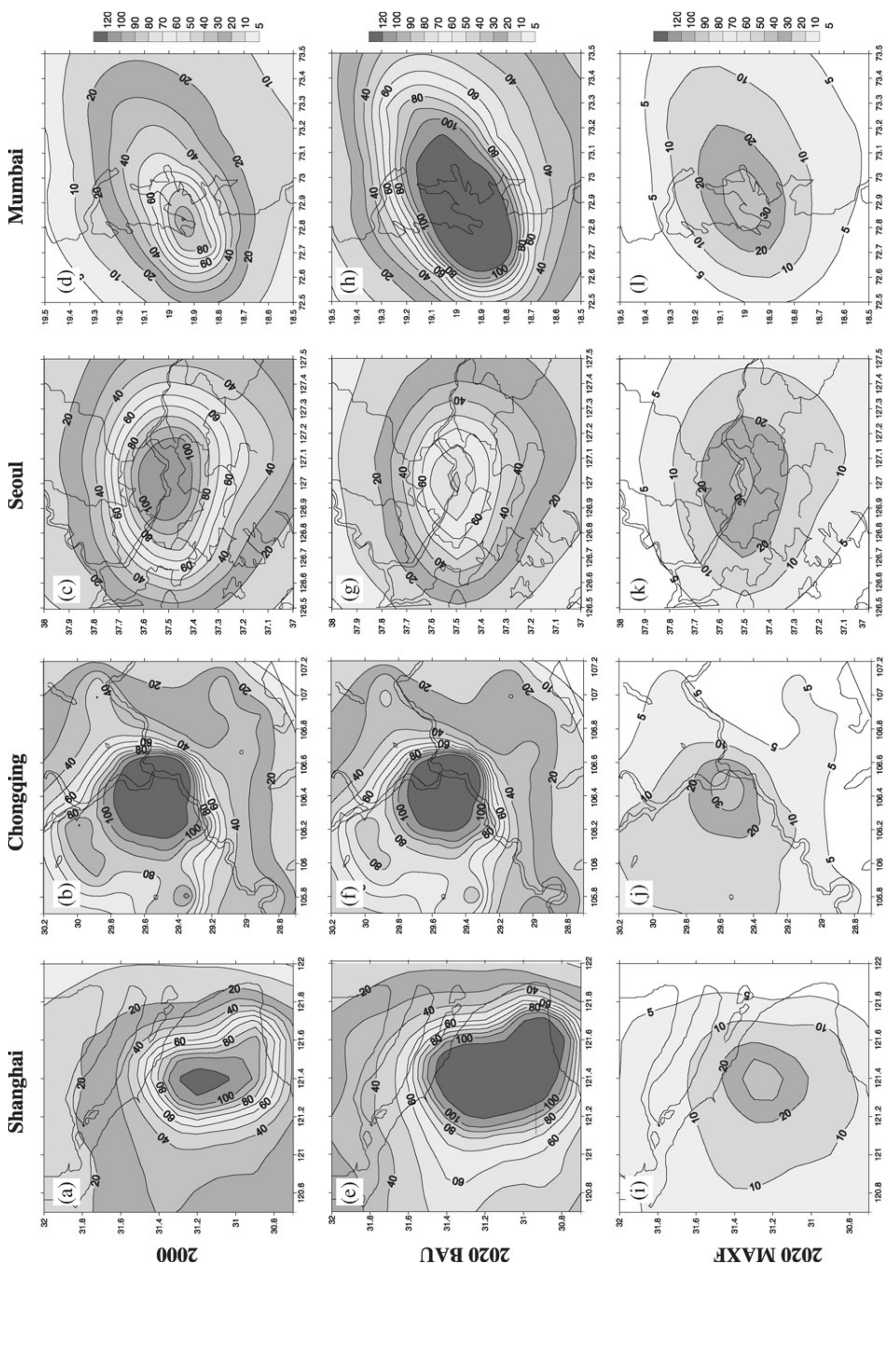


Fig. 5. Annual average SO_2 concentrations (in $\mu g/m^3$) for year 2000 (a) Shanghai; (b) Chongqing; (c) Seoul; (d) Mumbai for year 2020 under BAU; (e) Shanghai; (f) Chongqing; (g) Seoul; (h) Mumbai, and for year 2020 under MAXF; (i) Shanghai; (j) Chongqing; (k) Seoul; (l) Mumbai.

sulfur pollution by at least 5-fold around the megacities in 2020 with control costs estimated at US$ 87 billion for all of Asia.

Besides regional contributions, increasing health and environmental damages within the urban environment strengthens the need for an integrated air quality management approach in the assessment of economically cost-effective, technically sound, financially viable, and environmentally sustainable pollution control options. Urban scale dispersion modeling for sulfur pollution was conducted using the UrBAT model for four cities—Shanghai, Chongqing in China; Seoul in South Korea; and Mumbai in India. In 2020, it is estimated that under BAU, a total of more than 36 million people will be exposed to SO_2 levels of over $80\,\mu g/m^3$ (WHO guideline for sulfur pollution in an industrial area), if the emissions go uncontrolled in these four cities. Further advancements in modeling activities like nested grid analysis, will help better understand and integrate urban air quality management including other criteria pollutants whose influence on regional and global air quality is growing more than ever.

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