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Particulate Pollution in Asia - Part 1:

Multi-pollutant Modeling of Sources, Contributions, & Health Impacts

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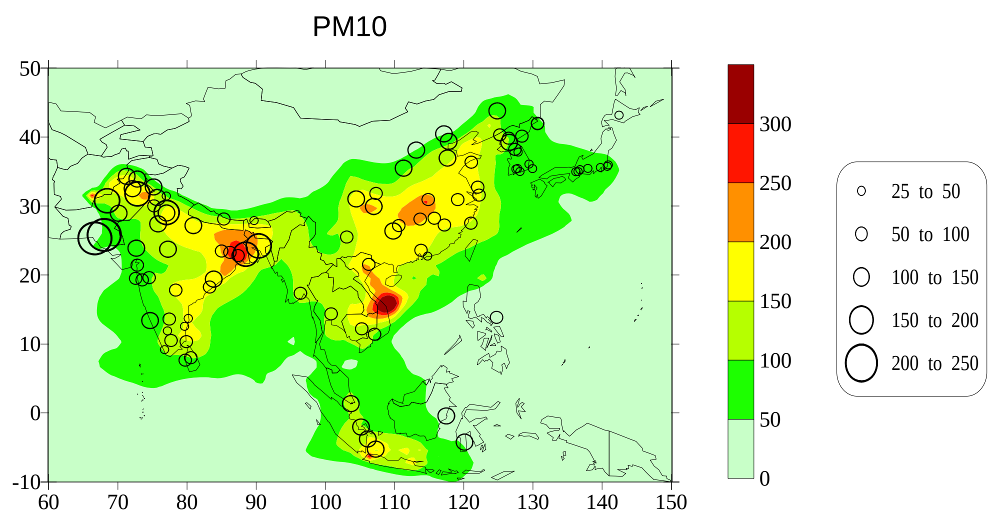

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Analysis & errors are sole responsibility of the author(s).

The emissions inventory's utilized in this study were developed as part of the TRACE-P & ACE-Asia field experiments.

Particulate Pollution in Asia – Part 1:
Multi-Pollutant Modeling of Sources, Contributions & Health Impacts [1]

Asia's increasing population and economic growth has meant that the energy demand is doubling every 10 years, which is more than twice the world average[2], resulting in an increased risk of human exposure to higher air pollution from fossil fuel burning. In countries, where more than third of the population lives in the urban areas, where industry accounts for more than third of GDP, the estimates of environmental costs dominated the damage to health, agricultural production, and natural resources caused by air and water pollution[3]. Air quality related health costs in urban China exceeded 20 percent of the urban income.

The air pollutants of concern are: particulates (PM), acid rain from sulfur dioxide (SO_2) and nitrogen oxide (NO_x), ground level ozone (O_3), and greenhouse gas emissions (GHGs)[4].

A new metric in use is the "**Air Quality Index**" (AQI) is an "index" determined by calculating the degree of pollution in the city or at the monitoring point and includes the five main pollutants - PM, O_3, SO_2, carbon monoxide (CO) and NO_x. Each of these pollutants have an air quality standard which is used to calculate the overall AQI for the city. Simultaneously, one can also establish the limiting pollutant(s), resulting in the estimated AQI[5] [6]. Asia contains many cities (including a growing number of secondary cities with population more than 2 million) that rank among those with the world's worst air quality (**Figure 1**).

Among the listed pollutants, recent epidemiological studies[7] have shown that the PM, especially PM_{10} (with an aerodynamic diameter below 10 micron) and $PM_{2.5}$ (with an aerodynamic diameter below 2.5 micron) is primarily responsible for increasing impact of

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[1] The modeling exercise presented in this study was conducted in 2005, using the 2000 emissions inventory as the baseline. This study will be updated for later years in Part 2.
[2] The World Energy Outlook (2008) published by International Energy Agency (IEA) @ http://www.worldenergyoutlook.org/
[3] "Cost of Pollution in China" (2007), published by the World Bank, Washington DC, USA @ http://go.worldbank.org/FFCJVBTP40
Ramanathan, et al., 2009, "Air pollution, greenhouse gases and climate change", Atmospheric Environment @ http://dx.doi.org/10.1016/j.atmosenv.2008.09.063
[4] WHO air quality guidelines (2008) @ http://www.who.int/mediacentre/factsheets/fs313/en/index.html
[5] In numbers, AQI is represented between 0 to 500 with 0 representing good air and 500 representing hazardous air. For better understanding and presentation, the AQI is broken down into six categories, each color coded with the number scale. **Good** (green) is for 0 to 50 meaning satisfactory air quality; **Moderate** (yellow) is 51 to 100 meaning acceptable air quality; **Unhealthy** for Sensitive Groups (tan) is 101 to 150 meaning sensitive individuals with sensitive skin may be affected; **Unhealthy** (red) is 151 to 200 meaning everyone may experience problems; **Very unhealthy** (pink) is 210 to 300 is a health alert, where everyone may have health problems; and **Hazardous** (purple) is over 300 and may contribute to emergency health problems and will affect most people. Link to AQI blog.
[6] Examples of online AQI results for cities around the world is available @ http://urbanemissions.blogspot.com/2009/02/air-quality-index-aqi-in-urban-centers.html
[7] In recent publications by Health effects institute @ http://www.healtheffects.org/

air pollution on human health[8]. The particulates are also known to alter the local climate by decreasing visibility in the urban centers via formation of smog with O_3 and regional climate due to its invariant composition of aerosols – black carbon (BC) and elemental carbon (EC) from the forest fires in the Southeast Asia and industrial soot in South and East Asia[9].

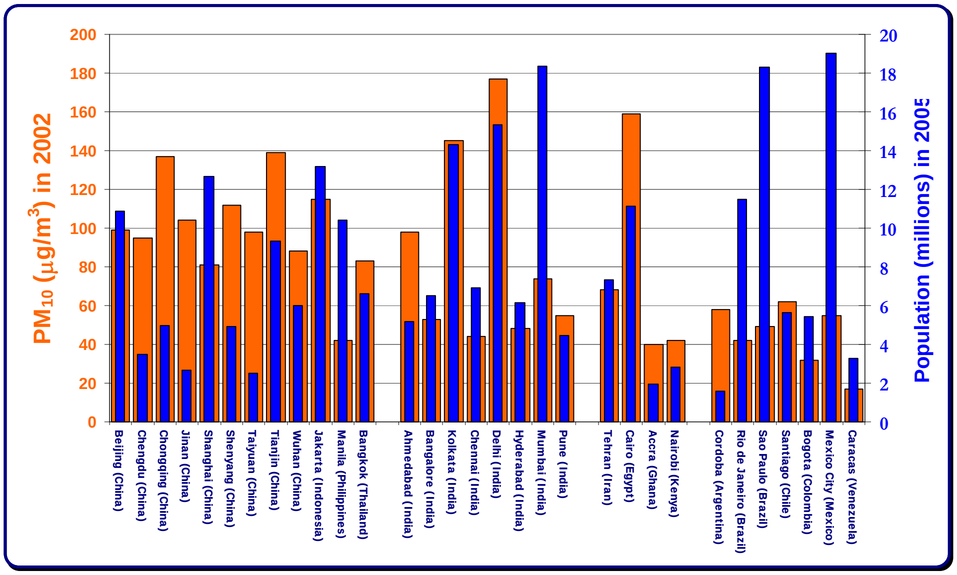

Figure 1: Population vs. PM$_{10}$ in Asian urban centers (WDI, 2007)[10]

Over the past twenty years and in the next twenty years, the megacities of the world are expected to expand and increase in number, putting more pressure on the need for better infrastructure, social circumstances, and environment (**Figure 2**). In both industrialized and developing countries, the air pollution from fossil fuel combustion has detrimental impacts on human health and the environment and major advances have been made in understanding the social and economic consequences of the air pollution[11].

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[8] The first coordinated Asian multi city study of air pollution and health (2008), published in the *Journal of Environmental Health Perspectives (EHP)* and conducted by the Health Effects Institute @ http://www.ehponline.org/docs/2008/116-9/toc.html

[9] "Black Carbon emerges as a major player in global warming debate" @ http://www.sciencedaily.com/releases/2008/03/080323210225.htm
"Climate adds fuel to Asian wild fire emissions" @ http://www.sciencedaily.com/releases/2009/04/090430144710.htm
"Clear Sky Visibility Over Land Has Decreased Globally, Indicative Of Increased Particulate Matter" @ http://www.sciencedaily.com/releases/2009/03/090312140850.htm

[10] World Development Indicators - http://devdata.worldbank.org/data-query/

[11] "Public health impact of air pollution and implications for the energy system" (2001) @ http://arjournals.annualreviews.org/doi/abs/10.1146/annurev.energy.25.1.601
WHO, 2005, "Comparative quantification of health risks" @ http://www.who.int/healthinfo/global_burden_disease/cra/en/index.html
"Regional atmospheric pollution and transboundary air quality management" (2005) @ http://arjournals.annualreviews.org/doi/abs/10.1146/annurev.energy.30.050504.144138
"Multimodel estimates of intercontinental source-receptor relationships for ozone pollution" (2009) @ http://www.agu.org/pubs/crossref/2009/2008JD010816.shtml
"UN reports pollution threat in Asia" (2008) @ http://www.nytimes.com/2008/11/14/world/14cloud.html

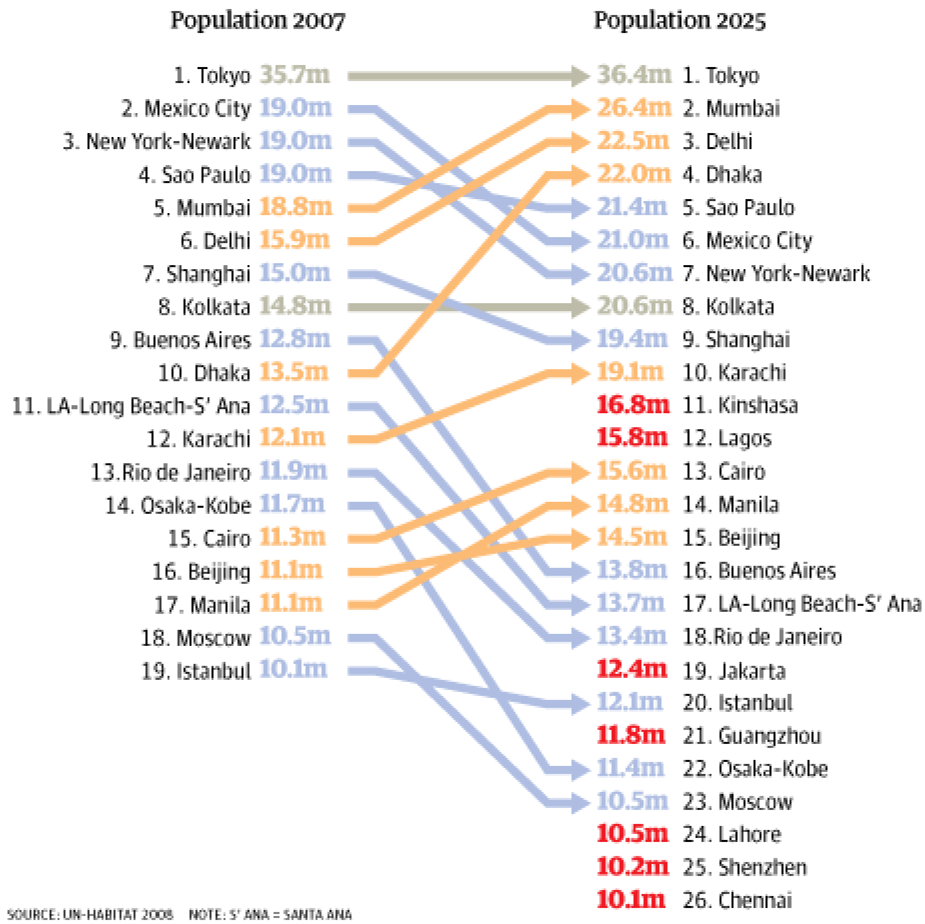

Figure 2: The World's megacities in 2007 and 2025

Studies in India have shown, for instance, that acute respiratory infections in children under 5 is the largest single disease category in the country, accounting for ~13 percent of the national burden of disease – children living in households using solid fuels have 2-3 times more risk of acute respiratory infections than unexposed children[12]. In March 2009, the Central Pollution Control Board of India declared that the Delhi is the India's Asthma Capital[13], and the increase in the number of cases is directly correlated to the growing air pollution levels in the cities of Delhi, Mumbai, Kolkata, and Chennai.

In China, air pollution[14] from fuel combustion is estimated to cause 218,000 premature deaths (equivalent to 2.9 million life-years lost), 2 million new cases of chronic bronchitis, 1.9 billion additional restricted activity days, and nearly 6 billion additional cases of

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[12] Smith et al, 2002, " Outdoor air pollution and acute respiratory infections among children in developing countries", @ http://ehs.sph.berkeley.edu/krsmith/publications/02_romieu_1.pdf
Lvovsky, et al., 2000, "Environmental Cost of Fossil Fuels", published by the World Bank @ http://www.cleanairnet.org/cai/1403/article-34285.html

[13] "Delhi is India's Asthma capital", March 1st, 2009, In Today News @ http://www.intoday.in/index.php?id=24240&option=com_content&task=view&sectionid=5

[14] "Clearing the Air: Health and Economic Damages of Air Pollution" by Harvard China Project @ http://chinaproject.harvard.edu/

respiratory symptoms[15]. The World Bank estimates that the cost of the air pollution impacts in China is ~520 billion yuan, which is ~3.2 percent of the total GDP in 2003, using the willingness to pay methodology[16]**.**

The culprit pollutant in both China[17] and India is believed to be PM and more particularly the fine particulates, $PM_{2.5}$. While the estimates of health impacts are effective in raising overall concern about air quality, they do not specifically answer the question of the sources of fine particulates, nor what measures should be taken to reduce the impacts associated with exposure.

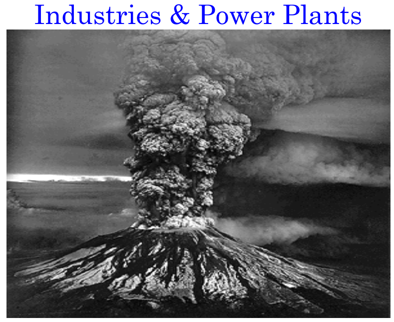
An associated regulatory constraint is in the monitoring procedures. In most of the developing countries, the PM_{10} is still considered the monitoring standard, which not only hinders focus on the criteria pollutant, but also on the source contributions.

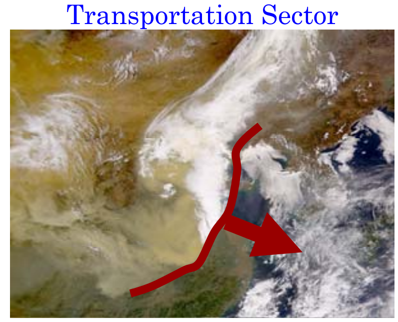

Domestic Sector


Industries & Power Plants


Transportation Sector


Biomass (Forests) Burning


Volcanoes


Dust Storms

Local and regional governments maintain monitoring networks studying the physical and the chemical composition of the PM[18]. Despite the improved knowledge about the seriousness of fine PM, it is often not targeted for reduction due to lack of understanding of their composition and nature[19].

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[15] "Clear Water & Blue Skies: China Environment 2020", (1997), The World Bank, Washington DC, USA @ http://go.worldbank.org/51MYSQ86B0

[16] "Cost of Pollution in China" (2007), published by the World Bank, Washington DC, USA @ http://go.worldbank.org/FFCJVBTP40

[17] "Can Coal and Clean Air Coexist in China?", August 7th, 2008, Scientific American @ http://www.scientificamerican.com/article.cfm?id=can-coal-and-clean-air-coexist-china

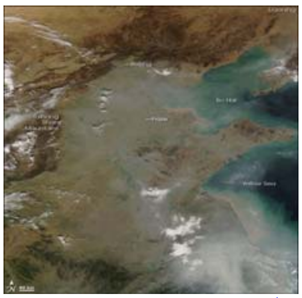
[18] Air quality monitoring network in Asia @ http://urbanemissions.blogspot.com/2009/01/air-quality-monitoring-in-asian.html

[19] "What is PM?", Working Paper SIM-10-2008 @ http://www.urbanemissions.info/simair/simseries.html

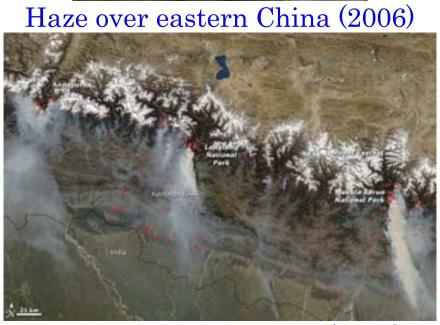
The health effects of PM are strongly linked to particle size and composition. Small particles are likely to be the most dangerous, because they can be inhaled deeply into the lungs, settling in areas where the body's natural clearance mechanisms can't remove them leading to acute respiratory morbidity and mortality[20]. The constituents in small PM also tend to be more chemically active and may even be acidic and therefore more damaging.

Particles in the air block out and scatter sunlight, reducing visibility[21]. See **SIM-10-2008** for the description of the observed visibility trend for 40 years in Bangkok, Thailand, measuring a reduction in the average visibility from 14 km in 1960's to 7 km in early 2000's.

In addition, a large share of fine PM originates from biomass burning (some of it is accounted for, but most is only observed in the satellite images of forest fires) and long range transport of dust storms[22] [23].


Haze over eastern China (2006)


Haze over Northern India (2008)


Forest fires over Nepal (2009)


Haze collects over Bangladesh (2009)

Also, a considerable portion of the fine PM is formed by chemical reactions in the air. For instance, sulfur and nitrogen emissions convert to sulfate and nitrate and organic compounds convert to organic aerosols – forming "secondary" particulates. In some Chinese cities, sulfate is believed to account for one-third to one-half of total fine particulates, because of the intense coal use. Nitrate can similarly account for a large

[20] Fine particles, PM2.5, designations @ http://www.epa.gov/pmdesignations/
[21] "Clear Sky Visibility Over Land Has Decreased Globally, Indicative Of Increased Particulate Matter" @ http://www.sciencedaily.com/releases/2009/03/090312140850.htm
[22] "Fire & Haze - Cost of Catastrophes", @ http://www.idrc.ca/openebooks/332-1/
[23] In April 1998, one the strongest dust storms crossed the Pacific and Atlantic Oceans in a period of 10 days, documented @ http://capita.wustl.edu/Asia-FarEast/
Satellite images of forest fires, dust storms, and haze over Asia are presented @ http://urbanemissions.blogspot.com/2009/05/dust-storm-haze-pollution-in-asia.html

percentage of fine PM in developed countries (and developing country mega-cities) where transport is a major fuel-consuming sector[24].

The particles, along with smog, soil and corrode metals, masonry, and textiles and are also often associated with irritating odors. Knowing the composition and sources of PM is important in better understanding their role on local and regional air pollution management and formulating control strategies.

Current trends in environmental regulation and industrial development are converging in a manner that encourages a thoughtful and consistent approach to provide a scientific basis that can be used to judge and select appropriate control measures with highest order of benefits to the human health and climate[25]. The Control measures can range from little or none on small sources (household stoves, small industrial boilers) to advanced controls on modern power plants (e.g., electrostatic precipitators, ESP's) and vehicles (e.g., diesel particle filters)[26].

The continued effect of economic growth and improved awareness on Asian environment depends on questions like

- What is the total PM pollution load and composition in a typical Asian environment?
- How will total pollution loads change with controls and regulations for various constituent pollutants?
- How will changes in pollution loads translate into higher or lower ambient exposures in Asian countries?
- What effects will alternative policy regimes have on ambient exposure?

The purpose of this paper (**Part 1**) is to estimate the total pollution levels and composition of fine and coarse PM in Asia (**in 2000 baseline**) and aims to identify the information needed for a sound assessment of the impact of PM pollution on public health. Also, to develop a broader perspective of understanding the air pollution mixture in Asia, that might affect the regulations and policy at the various levels.

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[24] Watson Environmental Forensics paper and couple of review papers by Judy Chow

[25] "Climate and Air Pollution Co-benefits" conference, organized by SEI in Stockholm, Sweden @ http://www.sei.se/gapforum/

[26] "Air pollution and health in rapidly developing countries", Published by Earthscan @ http://www.earthscan.co.uk/?tabid=994

"Urban Air Pollution in Asian Cities: Status Challenge and Management", Published by SEI @ http://www.sei.se/publications.html?task=view&catid=1&id=698

Primary Pollutant Emissions in Asia

In contrast to other air pollutants, PM pollution is challenging to estimate. Sulfur pollution, for example, can be estimated in a relatively straightforward manner through bottom-up modeling because there are fewer source controls and fewer sinks (chemical transformation). Also, there is little sulfur emitted from biomass burning, so knowing the sulfur content of coal and petroleum products is sufficient to provide a good estimate of the combustion emissions and easy to estimate the ambient sulfur pollution or deposition levels. However, this is not the case for PM pollution.

The analysis of particulate pollution, conducted in this study, includes the contribution of primary emissions and secondary contributions of SO_2, NO_x, and VOC's.

In the last decade, a significant amount of air pollution research was conducted to better understand the contributing sectors in developing countries[27]. Many cities have carried out emission inventories, and while emission factor analysis has limitations, it provides a first approximation of the sources of air pollution[28]. Modeling of photochemical compounds and aerosols ($PM_{2.5}$, BC, and EC) has been conducted for China and the Asian region through a number of international research projects - RAINS-Asia, INDOEX, TRACE-P, and ACE-Asia[29]. Emission inventories for gaseous pollutants and aerosols by sector were completed for India by Reddy et al., 2002[30], for China by Wang et al., 2005[31], for Thailand by Thongboonchoo, 2007[32], for Nepal by Adhikary, 2009[33], and for the rest of Asia by the

[27] Handbook on particulate pollution source apportionment and review of case studies from around the world @ http://www.urbanemissions.info/pmsa

[28] Resources to average emission factors for emissions inventory development @ http://urbanemissions.blogspot.com/2009/01/average-vehicular-emission-factors.html

[29] UNEP Atmospheric Brown Cloud (ABC) assessment report (2008) @ http://www.unep.org/pdf/ABCSummaryFinal.pdf
Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) Asia (2009) by IIASA @ http://www.iiasa.ac.at/rains/gains_asia/main/index.html?sb=16
Fang et al., 2009, "Managing air quality in a rapidly developing China", Atmospheric Environment @ http://dx.doi.org/10.1016/j.atmosenv.2008.09.064
Shah et al., 2000, "Integrated analysis of acid rain in Asia", @ http://arjournals.annualreviews.org/doi/abs/10.1146/annurev.energy.25.1.339
Lelieveld et al., 2001, "The Indian Ocean Experiment: Widespread Air Pollution from South and Southeast Asia", @ http://www.sciencemag.org/cgi/content/abstract/291/5506/1031
NASA GTE Transport and Atmospheric Transport over Pacific and ACE-Asia (2003-07), JGR special issue @ http://www-gte.larc.nasa.gov/trace/TRP_Special.htm

[30] Reddy et al., 2002, "Inventory of aerosols and sulfur dioxide emissions in India, Atmospheric Environment @ http://dx.doi.org/10.1016/S1352-2310(01)00463-0
Garg et al., 2006, "The sectoral trends of multigas emissions inventory for India", Atmospheric Environment @ http://dx.doi.org/10.1016/j.atmosenv.2006.03.045

[31] Wang et al., 2005, "Emissions inventory for Eastern China in 2000", Atmospheric Environment @ http://dx.doi.org/10.1016/j.atmosenv.2005.06.051
Wang et al., 2006, "Impacts of air pollution in China on public health", Atmospheric Environment @ http://dx.doi.org/10.1016/j.atmosenv.2005.10.066

[32] Thongboonchoo, 2007, "Analysis of air pollution in Thailand", PhD Thesis, The University of Iowa

[33] Adhikary, 2009, "Analysis of air pollution in Northern India and Nepal", PhD Thesis, The University of Iowa

Streets et al., 2003[34]. Much of this work was conducted at the national or regional level, with the objective of contributing to the regional and global atmospheric photochemical modeling activities. **Table 1** presents annual anthropogenic and biomass emissions for each of the gaseous and particulate species by country.

Table 1: Country level annual total emissions for year 2000

Country	Total Annual Emissions for year 2000 (ktons/year)						
	PM_{10}	$PM_{2.5}$	SO_2	NO_x	BC	OC	VOC
East Asia							
China	8,704	6,508	20,826	9,847	1,010	3,271	17,171
Japan	262	138	801	2,199	38	54	1,923
Mongolia	73	44	96	196	16	129	346
North Korea	343	274	226	269	21	97	214
South Korea	139	62	828	1,322	19	24	1,159
Taiwan	78	30	376	521	8	10	510
South Asia							
Bangladesh	716	607	140	167	52	268	819
Bhutan	20	18	6	5	2	12	36
India	10,351	7,763	5,536	4,529	562	2,799	10,844
Nepal	261	239	38	54	21	135	346
Pakistan	1,511	1,169	1,416	508	82	365	1,344
Sri Lanka	211	169	58	73	11	56	286
South East Asia							
Brunei	4	3	6	18	0	0	43
Cambodia	110	101	40	109	14	89	305
Indonesia	2,014	1,899	892	1,466	214	1,200	7,190
Laos	35	32	26	105	24	179	674
Malaysia	180	116	273	479	25	150	1432
Myanmar	350	323	65	200	65	420	1,671
Philippines	263	239	711	554	33	181	1,347
Singapore	253	156	163	185	3	2	81
Thailand	418	349	961	1,099	66	358	3,052
Vietnam	891	817	208	385	104	570	1,920
Ships	270	185	1,083	1,292	68	0	27
Asia Total	**27,457**	**21,241**	**34,775**	**25,582**	**2,458**	**10,369**	**52,740**

The emissions inventory includes a detailed inventory of volatile organic compounds (VOC's) from both anthropogenic and biomass burning sources. They are calculated for combinations of four main activity sectors – industrial, domestic, transport, power and five fuels – coal, diesel, fuel oil, biofuels and gaseous fuels.

[34] Streets et al., 2003, "An inventory of gaseous and aerosol emissions in Asia in 2000", @ http://www.agu.org/pubs/crossref/2003/2002JD003093.shtml

The base emissions dataset was developed for the year 2000 for each of the species and the spatial resolution of the datasets is maintained at 1° x 1° for area sources and the large point sources (LPS) are assigned to their hundredths of longitude and latitude location.

The regional, national, and provincial datasets are then distributed to the grids based on the datasets of population, landuse, road networks, urban hotpots, shipping lanes, and specific information on large point sources[35]. The criteria utilized for the emissions distribution is presented in **Figure 3**.

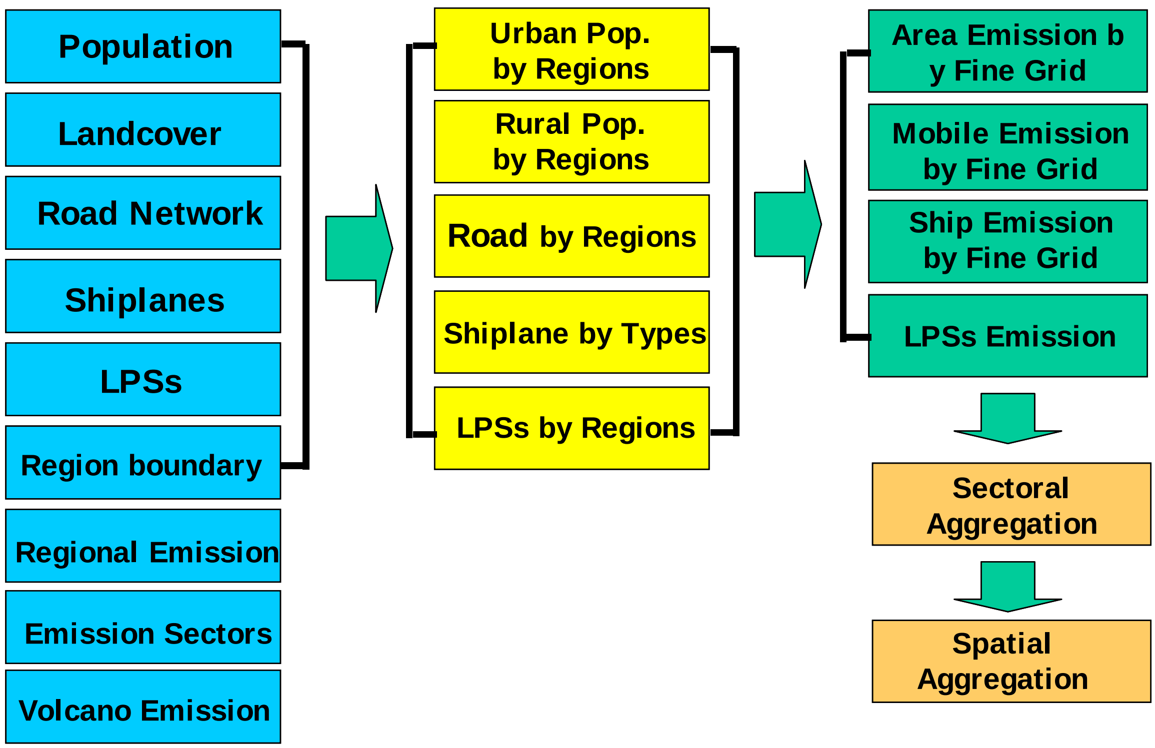

Figure 3: Framework for distribution of regional anthropogenic emission estimates to the modeling grid domain

For modeling purposes, the grid resolution was fixed at 1° x 1° ranging from Pakistan (60˚E) in the west to Japan and Pacific Ocean (150˚E) in the east and Indonesia and Philippines (20˚S) in the south to Mongolia (55˚N) in the north. This inventory was used as an input to a variety of atmospheric studies and the datasets performance was validated by a number of atmospheric models[36].

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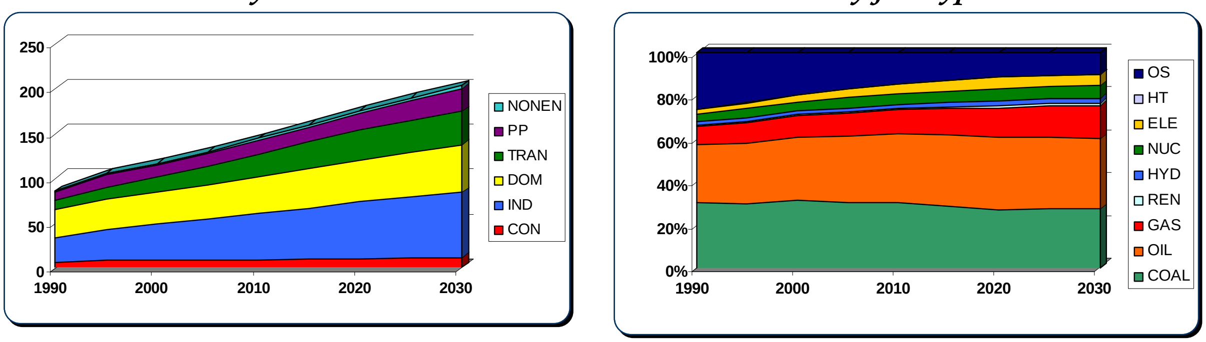
[35] Streets et al., 2003, "An inventory of gaseous and aerosol emissions in Asia in 2000" @ http://www.agu.org/pubs/crossref/2003/2002JD003093.shtml
Woo et al., 2003, "Biomass and biofuel emissions to trace gas distributions in Asia" @ http://www.agu.org/pubs/crossref/2003/2002JD003200.shtml
[36] Carmichael et al., 2003, "Regional scale chemical transport modeling" @ http://www.agu.org/pubs/crossref/2003/2002JD003117.shtml
Tang et al., 2004, "Impact of dust on Asian aerosol chemistry" @ http://www.agu.org/pubs/crossref/2004/2003JD003806.shtml
Guttikunda et al., 2005, "Impact of megacity emissions on Asian air quality" @ http://www.agu.org/pubs/crossref/2005/2004JD004921.shtml

Anthropogenic Emissions

Fossil fuel combustion is the primary source of pollution in most of the Asian countries. Because of its population and the degree of industrialization, China is, by far, Asia's largest energy consumer; its 41% of the region's total energy consumption is followed by Japan's (17%), and India's (16%). Total energy demand is estimated to have increased by 3.6% between 1990 and 2000, and is projected to rise by an average of 2.4 % per year between 2000 and 2010 and 2.0% per year thereafter until 2030. Energy demand in Asia is expected to reach 203,000 PJ in 2030. **Figure 4** presents the share of energy consumption by sector and fuel type.

Figure 4: Energy consumption and demand in Asia

By sector *By fuel type*



Source: Author based on RAINS-Asia estimates @ http://www.iiasa.ac.at/rains/index.html

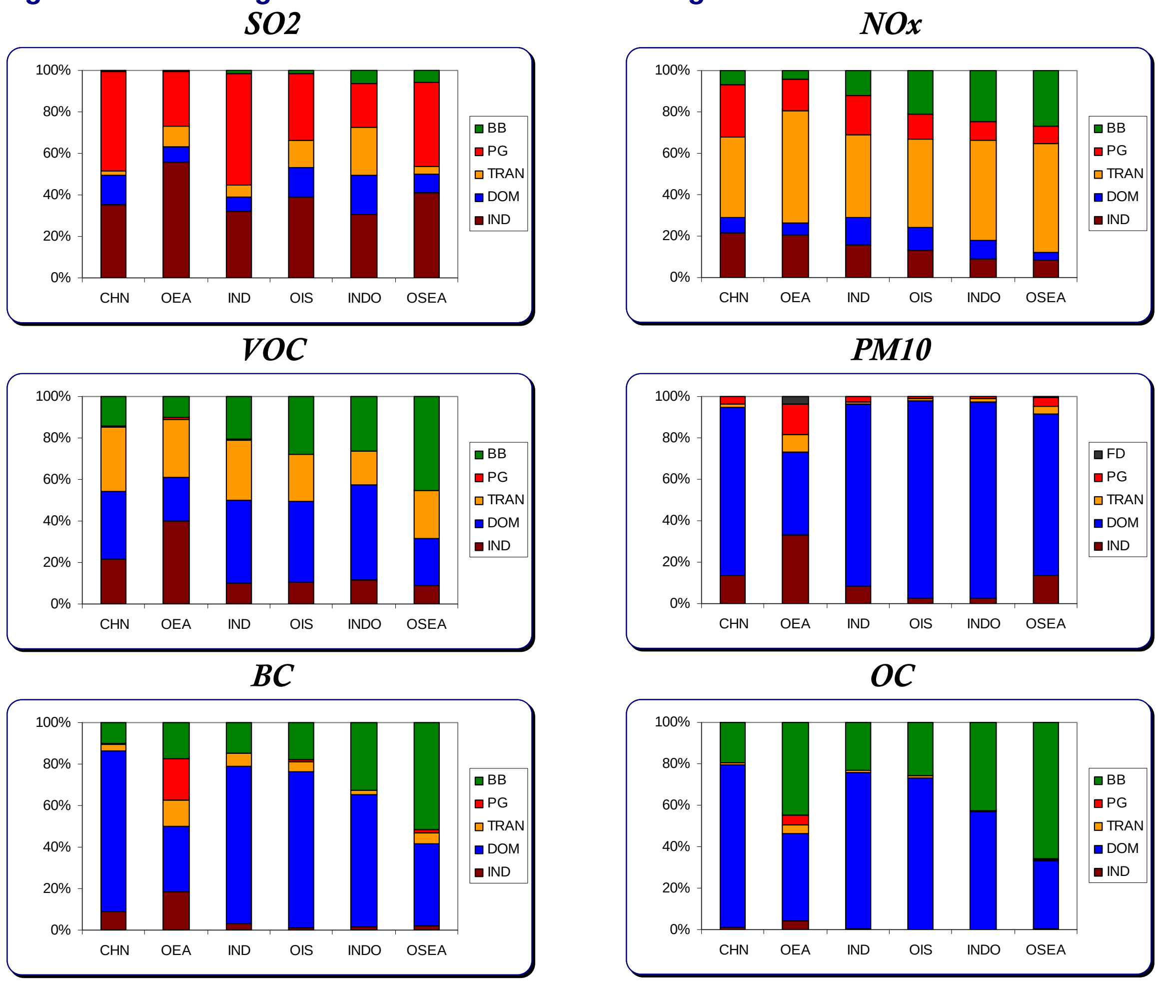
In Asia, coal and fuel oil are the dominant sources of energy followed by the other solids and natural gas. Much of the coal and fuel oil is consumed by the large-scale industries and power plants. The share of coal in total primary energy requirements is expected to remain constant. Whereas, the contribution of other solids, mainly in the form of biofuels (cow dung, wood, field residue, agricultural waste) and other forms of non-commercial energy is expected to decrease through 2030 due to increased use of natural gas and also due to reduction in rural population, where biofuels are used the most. The countries that rely on oil for the majority of their primary energy requirements - Japan, South Korea, Malaysia, the Philippines, Taiwan, and Thailand, will continue efforts to reduce their oil dependence, while Asia's other countries will increase oil's share in their energy mix.

The contributions of economic sectors that dominate the emissions sources are - domestic (DOM), industrial (IND), transport (TRAN), power generation (PG) and seasonal biomass burning (BB). **Figure 5** presents fraction of emissions from each of the sectors in Asia.

For SO_2, ~60% of total anthropogenic emissions come from China due to high amount of coal consumption. In China, a large portion of the SO_2 emissions originate from the provinces of Sichuan, Yunnan, Jiangsu, Shandong, Hebei, Shanxi and Henan, mainly from

Adhikary et al., 2007, “Regional scale modeling of aerosols in South Asia” @ http://www.agu.org/pubs/crossref/2007/2006JD008143.shtml the power generation sector, and each more than 1.5 Tg SO_2 per year. The Shanghai and Beijing each emitted ~0.5 Tg of SO_2 in 2000.

Figure 5: Percentage contribution of sectors to regional emissions estimates in Asia



Source: Author based on Streets et al., 2003; Sector acronyms: Biomass Burning (BB), Power Generation (PG), Transport (TRAN), Domestic (DOM), Industrial (IND), and Fugitive Dust (FD). Regional acronyms: China (CHN), Other East Asia (OEA), India (IND), Other Indian Subcontinent (OIS), Indonesia (INDO), and Other South east Asia (OSEA)

Similarly, the other urban centers in Asia like Seoul, Bangkok, Mumbai, Calcutta, Dhaka, and Hong Kong, each had emissions of more than 0.1 Tg of SO_2 in 2000[37]. In general, power and industry dominate the SO_2 emissions with percentage contributions ranging from as high as 30-50% in China and India to as low as 10-30% in Indonesia, and Vietnam. The transportation sector contributes very little to SO_2 emissions in Asia. **Figure 6** presents the percentage contribution of the major economic sectors at the provincial level. The domestic sector dominates in under-developed countries like Bangladesh, Nepal, Myanmar, due to high percent use of bio-fuels for household cooking and heating purposes. Seasonal biomass burning also contributes to local SO_2 pollution in Southeast Asia up to 5%. Inventory also

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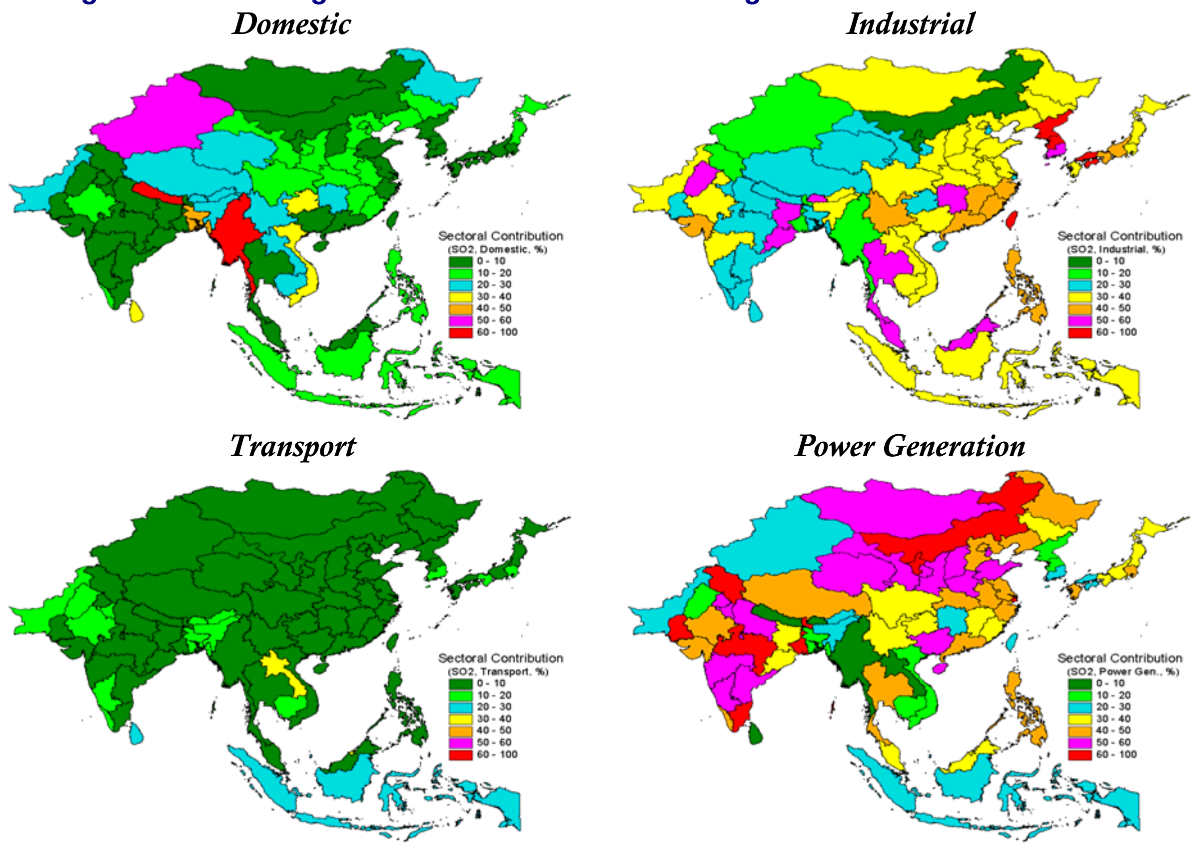
[37] Guttikunda et al., 2003, "Contribution of megacities to sulfur pollution in Asia " Atmospheric Environment @ http://dx.doi.org/10.1016/S1352-2310(02)00821-X

includes sulfur emissions from international and regional shipping in Asian waters[38], which contribute significantly to enhanced acid deposition levels in Southeast Asia.

Figure 6: Percentage contribution of sectors to regional SO2 emissions in 2000



Unlike SO_2, transportation sector dominants for NO_x and VOC emissions from coastal China, India, Thailand, Korea's and Japan due to increasing number of automobiles and unchecked emissions from two-stroke and four-stroke engines, especially in the urban areas. These two pollutants generate secondary pollutants such as O_3 and smog, contributing significantly to regional haze problems[39].

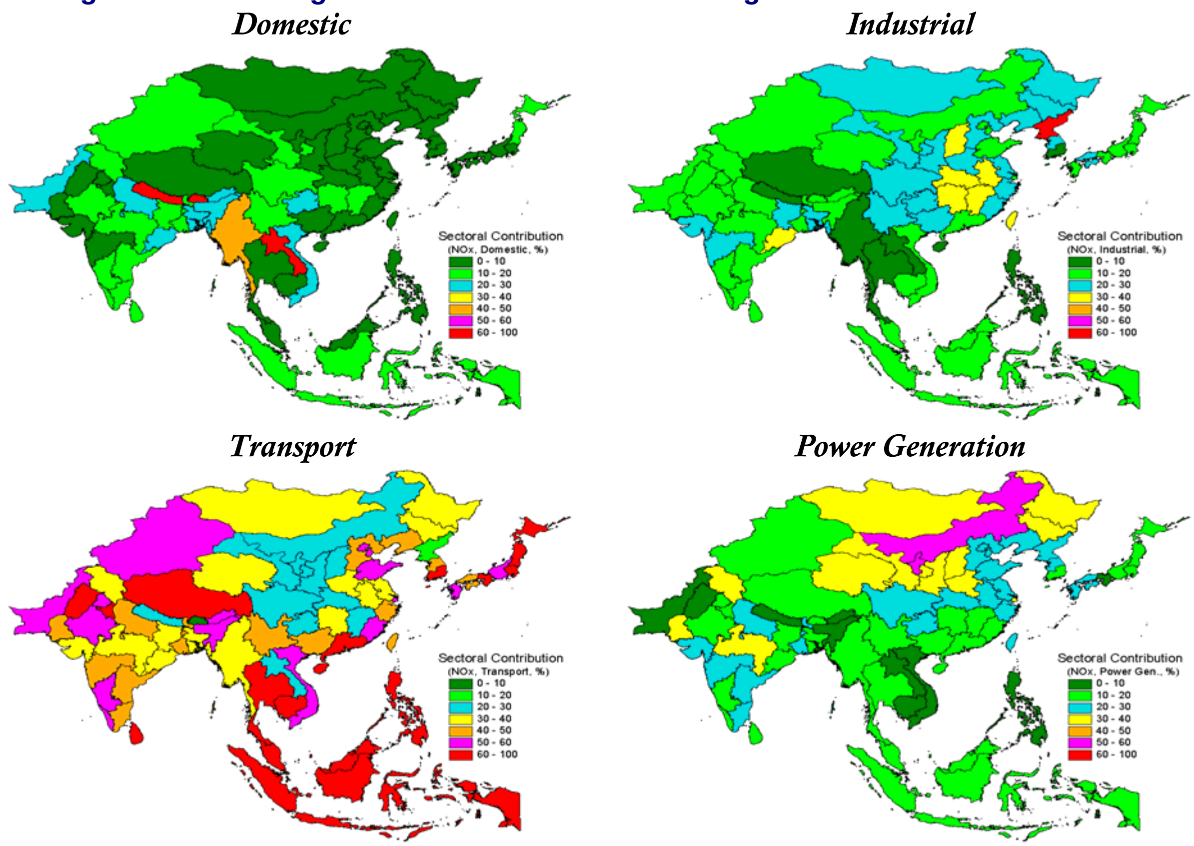
Motor vehicles continue to be the most significant contributor to air pollution in most cities in Asia. The contribution is growing rapidly, with fleet sizes doubling every seven years. Bangladesh and Thailand are extreme examples: vehicle numbers increased almost 10 fold over the last decade. China, India, Indonesia, Japan, South Korea and Thailand emit more than 1 Tg of NO_2 in 2000. Of the rest, countries on the raise are Malaysia, Pakistan, Philippines and Taiwan with each emitting ~0.5 Tg of NO_2/yr. **Figure 7** presents the percentage contribution of the major economic sectors at the provincial level. On average the transport sector contributes from 30% in China to more than 50% in Southeast Asian

[38] Streets et al., 2003, "Contribution of shipping emissions to Asian air pollution", Atmospheric Environment @ http://dx.doi.org/10.1016/S1352-2310(00)00175-8

[39] Satellite images of forest fires, dust storms, and haze over Asia are presented @ http://urbanemissions.blogspot.com/2009/05/dust-storm-haze-pollution-in-asia.html

nations. Megacities of East Asia – Shanghai, Beijing, Tainjin, Taiyuan, Wuhan, Chongqing, Seoul, Pusan, Tokyo and Osaka emit more than 0.1 Tg NO_2 in 2000[40]. All of the coastal provinces in China, which are industrially more advanced, experience emissions of more than 0.5 Tg of NO_2. Also, in these provinces, NO_x to VOC emission ratio, which is critical in explaining the regional O_3 forming potential, is higher.

Figure 7: Percentage contribution of sectors to regional NOx emissions in 2000



The hydrocarbon emission inventory was established using species specific emission factors and by industrial processes. Unlike SO_2, NO_x and CO emissions, major fraction of the VOC's are emitted from non-combustion sources such as industrial solvent extraction processes. **Table 1** presents only the total VOC's which are further disaggregated into various hydrocarbon species such as Ethane, Propane, Butane, Ethene, Propene, Acetylene, Acetone, Formaldehyde, Acetaldehyde, Halogen compounds, Cresols, Benzene, Toluene, Xylene, and higher order alkanes, alkenes, alkynes, ketones, aldehydes, and aromatics, as described in *Streets et al., 2003*.

While the formation of inorganic aerosol from SO_2 and NO_x is relatively well investigated, the composition and formation processes of the secondary organic aerosols (SOA) are not as well known due to a their complex nature of formation involving a numerous oxidation and reduction reactions of VOC's with O_3, NO_x and hydroxyl radicals in the atmosphere. In this

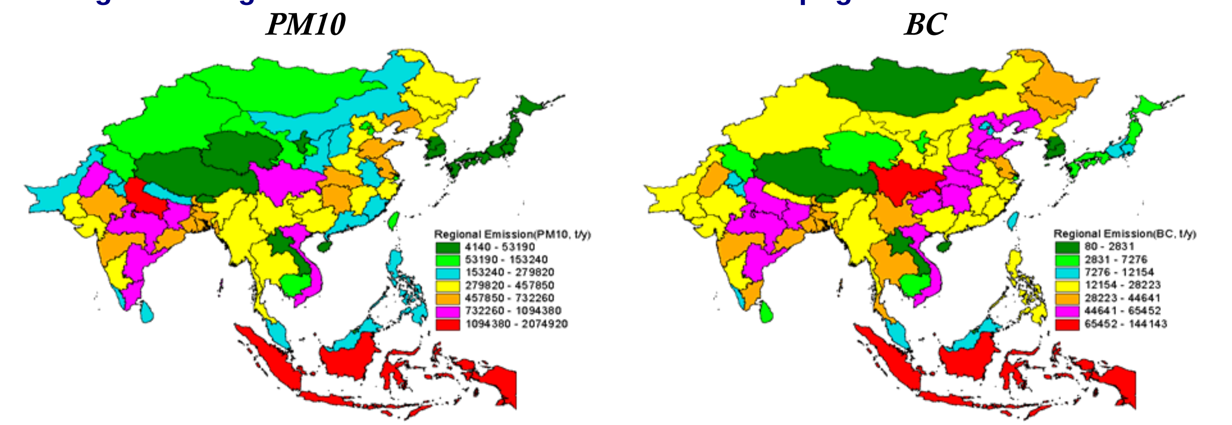
[40] Guttikunda et al., 2005, "Impact of megacity emissions on Asian air quality" @ http://www.agu.org/pubs/crossref/2005/2004JD004921.shtml

study, the estimation of SOA is established utilizing the "fractional aerosol coefficient" (FAC) methodology as discussed in Sienfeld et al., 1995 and Dusek et al., 2000[41].

The FAC is a coarser approach to parameterize the aerosol formation potential. It summarizes both gas-phase chemistry and gas/particle conversion in one constant and provides a rough estimate of what percentage of a VOC precursor will end up as aerosol. *Dusek et al., 2000* presents further details on the FAC and resource methodologies to estimate FAC for various hydrocarbons.

Household and transportation sectors dominate the contributions to primary PM_{10} and $PM_{2.5}$ emissions in Asia. Besides combustion sources, construction activities and re-suspension of dust along the road corridors, also known as fugitive dust, are common sources in Asia[42]. **Figure 8** presents the regional distribution of the PM_{10} and black carbon (BC) emissions inventory in 2000. The $PM_{2.5}$ found in diesel exhaust particles is a growing concern for many of the motorized cities. The inventory utilized in this study is the first of its kind in quantifying the emissions of primary PM for all of Asia.

Figure 8: Regional estimates of PM10 and BC anthropogenic emissions in 2000



Organic aerosols are those in which carbon is a primary constituent - elemental carbon particles (EC) and organic carbon particles (OC). EC particles are essentially soot BC and graphite carbon and OC particles are directly emitted by sources (primary OC) or formed due to condensation of VOC's (SOA) in the atmosphere. Together, they account to a total of ~13 Tg C/yr of primary emissions in Asia with domestic biofuels (wood, cow dung, and field residue) dominating the sources from as low as 30% in Japan to ~75% in China and Indian Subcontinent[43]. **Table 2** presents a comparison of fraction of primary $PM_{2.5}$, BC, and OC emissions to total primary PM_{10} in Asia.

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[41] "Atmospheric Chemistry and Physics" by Sienfeld and Phadnis @ http://www.amazon.com/Atmospheric-Chemistry-Physics-Pollution-Climate/dp/0471178160
Dusek, et al., 2000, "SOA formation mechanisms and source contributions", by IIASA @ www.**iiasa**.ac.at/~rains/reports/IR0066.pdf

[42] Dorwart, 2001, "Particulate Matter emissions inventory for Asia", MS Thesis, The University of Iowa

[43] Bond et al., 2004 "A technology-based global inventory of BC & OC emissions from combustion" @ http://www.agu.org/pubs/crossref/2004/2003JD003697.shtml
"Inventory of BC emissions from China", 2009 @ http://www.climatechange.cn/qikan/manage/wenzhang/15.pdf

Table 2: Fraction of primary and carbonaceous PM in total PM_{10} in 2000

	Primary-$PM_{2.5}$	BC	OC
East Asia			
China	0.75	0.08	0.25
Japan	0.53	0.11	0.15
Mongolia	0.60	0.07	0.59
North Korea	0.80	0.05	0.21
South Korea	0.45	0.10	0.13
Taiwan	0.38	0.08	0.10
Average	***0.58***	***0.08***	***0.24***
South Asia			
Bangladesh	0.85	0.05	0.26
Bhutan	0.90	0.06	0.35
India	0.75	0.04	0.20
Nepal	0.92	0.05	0.32
Pakistan	0.77	0.04	0.19
Sri Lanka	0.80	0.04	0.20
Average	***0.83***	***0.05***	***0.25***
S. E. Asia			
Brunei	0.75	0.00	0.00
Cambodia	0.92	0.07	0.42
Indonesia	0.94	0.06	0.35
Laos	0.91	0.10	0.75
Malaysia	0.64	0.07	0.42
Myanmar	0.92	0.08	0.50
Philippines	0.91	0.07	0.38
Singapore	0.62	0.01	0.01
Thailand	0.83	0.08	0.43
Vietnam	0.92	0.07	0.36
Ships	0.69	0.20	0.00
Average	***0.84***	***0.06***	***0.36***
Asian Average	***0.77***	***0.06***	***0.26***

Highest density of the emissions are observed over agriculturally dominant states and provinces, viz., central India, central China, Indonesia and Vietnam[44]. In these states, the contribution of the domestic sector is high due to the biomass combustion for cooking and heating[45]. In these parts, the indoor air pollution due to cooking and heating is known to be

Streets, et al., 2004, "On the future of carbonaceous aerosol emissions" @ http://www.agu.org/pubs/crossref/2004/2004JD004902.shtml

44 WHO, 2005, "Evaluation of the costs and benefits of household energy & health interventions" @ http://www.who.int/indoorair/publications/evaluation/en/index.html

45 New York Times, 2009, "Stove soot is targeted for climate flight" @ http://www.nytimes.com/2009/04/16/science/earth/16degrees.html

a major health hazard. On an average international shipping activity contributes ~20% to the BC emissions. Southeast Asian nations emit a higher fraction (~40%) of total carbonaceous PM than the rest of Asia (~30%). Except for countries which are more dependent on oil and gas based fossil fuels (viz., Japan, South Korea, Taiwan, Singapore, all the countries experience a primary $PM_{2.5}$ fraction of more than 60% emphasizing the importance of fine PM control in industrialized vs. developing nations.

Besides forming a significant portion of the fine $PM_{2.5}$, optically active BC/OC aerosols, typically in the sub-micron size range, effects visibility and climate forcing in urban and rural areas and contribute for photochemical reactions affecting tropospheric O_3 formation and removal of oxidizing species[46].

Biomass Burning Emissions

The major sources of primary and secondary PM remain the gasoline and diesel combustion in the transport sector, industrial combustion processes, cooking, automobile tire wear, road dust, and use of pesticides. However, the other significant source of emissions is from seasonal biomass burning (BB), combined anthropogenic sources, exacerbates the existing air pollution. Biomass burning[47] emissions have a very strong signature in Southeast and East Asia, especially for CO, OC and BC contributing to regional haze problems from increased photochemical interactions between aerosol surfaces and gaseous pollutants[48].

For biomass burning emissions, for more realistic temporal variability, fire emissions were estimated using on-line information on a day-to-day basis from the Advanced Very High Resolution Radiometer[49] (AVHRR) to "spot" fires, and aerosol index from Total Ozone Mapping Spectrometer[50] (TOMS), satellite cloud coverage, and precipitation data to reduce noise due to dust storms, industrial dust and cloud water from AVHRR data (*Woo et al., 2003*). In general, BB emissions are more dominant during the spring time in Southeast Asia and during the summer months in Indonesia and Philippines.

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[46] Guardian, 2008, "Scientists warn of soot effect on climate" @ http://www.guardian.co.uk/environment/2008/mar/24/climatechange.fossilfuels

[47] Satellite images of forest fires, dust storms, and haze over Asia are presented @ http://urbanemissions.blogspot.com/2009/05/dust-storm-haze-pollution-in-asia.html

[48] Galanter, et al., 2000, "Impacts of biomass burning on tropospheric CO, NO x , and O3" @ http://www.agu.org/pubs/crossref/2000/1999JD901113.shtml

Streets, et al., 2003, "Biomass burning in Asia: Annual and seasonal estimates and atmospheric emissions" @ http://www.agu.org/pubs/crossref/2003/2003GB002040.shtml

Woo et al., 2003, "Contribution of biomass and biofuel emissions in Asia" @ http://www.agu.org/pubs/crossref/2003/2002JD003200.shtml

[49] AVHRR @ http://eros.usgs.gov/products/satellite/avhrr.php

[50] TOMS @ http://jwocky.gsfc.nasa.gov/

Particulate Pollution Dispersion Modeling

The atmospheric concentrations of primary PM_{10} and $PM_{2.5}$ were calculated using a modified version of Sulfur Transport Eulerian Model (STEM-2K1) - eulerian regional chemical transport model for particulate matter. The model uses a three-dimensional eulerian transport numerical scheme, which accounts for transport, chemical transformation and deposition of gaseous and particulate pollutants[51]. The current version is designed in a flexible framework to run in both on-line and off-line modes, and consists of a series of plug-and-play modules for advection and chemical transformation. The model's input-output framework is modified to adapt meteorological inputs from dynamic meteorological model - Regional Atmospheric Modeling System (RAMS)[52].

The photochemical mechanism includes ~300 chemical reactions and ~100 species, including radicals, and a module to calculate online photolysis using TUV. The preliminary version of the model doesn't consider physical or chemical transformation processes on the aerosols such as coagulation and nucleation.

For this analysis, the STEM-2K1 model is modified for PM pollution analysis to estimate and evaluate the contribution of various sources to PM pollution, regional transport of PM pollution in Asia, the human health impacts and incurred costs. **Figure 9** presents the schematics of the STEM-PM (STEM for particulate matter) model along with the pre- and post-processors.

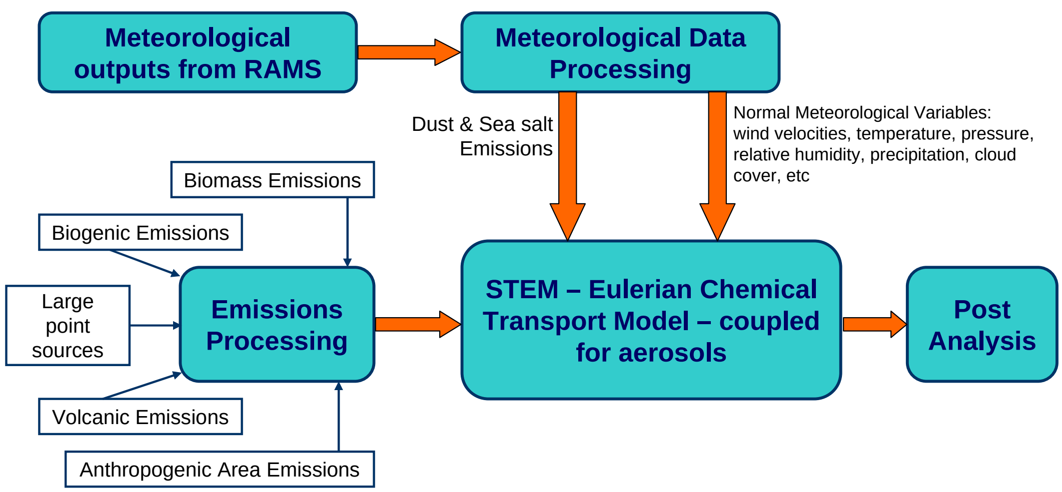


Figure 9: Schematics of STEM-PM – Eulerian Chemical Transport Model for PM

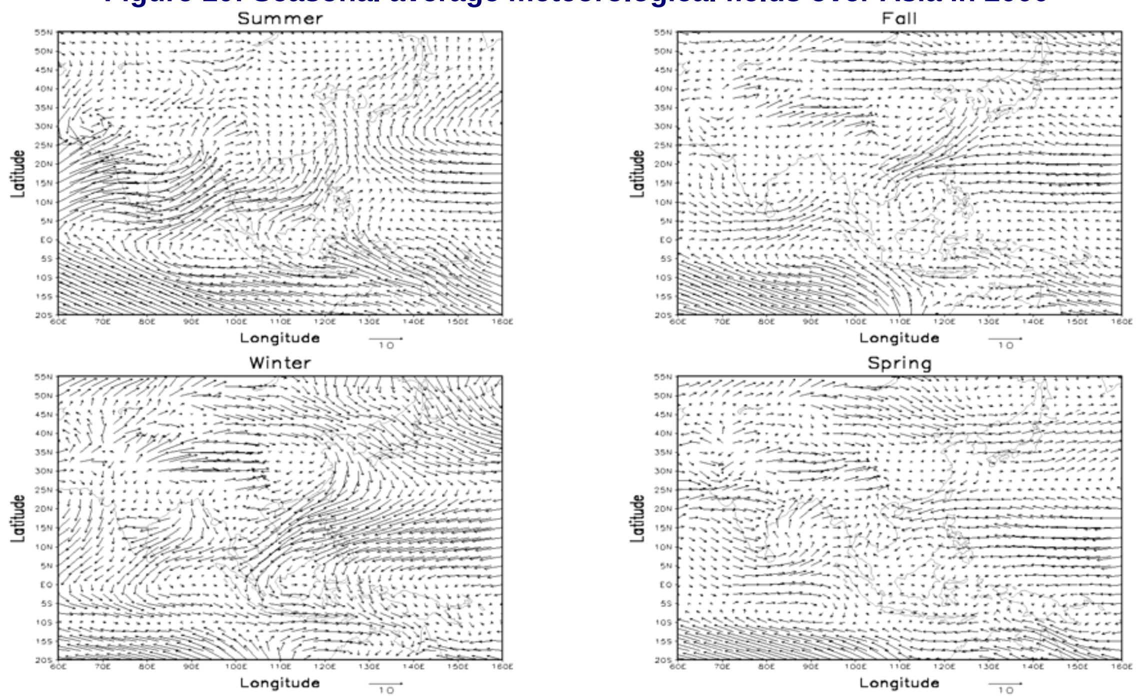
Hence, the chemical mechanism in STEM-PM was simplified for faster simulations, keeping in the mind the complexity of the photochemistry and its necessity to advance the

[51] Carmichael et al., 2003, "Regional scale chemical transport modeling" @ http://www.agu.org/pubs/crossref/2003/2002JD003117.shtml
Tang et al., 2004, "Impact of dust on Asian aerosol chemistry" @ http://www.agu.org/pubs/crossref/2004/2003JD003806.shtml
[52] RAMS @ http://atmet.com/

conversion of NO_x and VOC emissions. For the formation of the secondary aerosols from the chemical conversion of SO_2, NO_x and VOC emissions, a semi-linear mechanism is adopted from *Arndt, 1997*[53]*, Holloway, 2002*[54] *and Sienfeld, 2005*[55], respectively. The dry deposition parameterization was modified to allow for a distinction of removal processes according to particle size and land use type.

The simulations were conducted for base year of 2000, using the meteorological fields generated by the RAMS model and NCEP reanalysis data. **Figure 10** presents seasonable average wind field patterns over Asia for 2000. Initially RAMS is run offline generating time dependent meteorological fields and deposition schemes at 6-hr interval for the year 2000 for all of Asia at 80 km grid resolution.

Figure 10: Seasonal average meteorological fields over Asia in 2000



Source: Author ; Seasons are Summer = JJA ; Fall = SON ; Winter = DJF ; Spring = MAM

The PM pollution is modeled in two bins – fine (particles less than 2.5 μm in diameter) and coarse (particles less than 10 μm in diameter). The primary BC and OC and secondary sulfate, nitrate and organic aerosols are categorized as fine and added together in the post-

[53] Arndt, et al., 1998, "Seasonal source-receptor relations for sulfur pollution in Asia", Atmospheric Environment – This analysis was conducted as part of the RAINS-Asia program at IIASA for acid rain analysis and control @ http://dx.doi.org/10.1016/S1352-2310(97)00241-0

[54] Holloway et al., 2002, "Transfer of reactive nitrogen in Asia: Development of a source–receptor model" – This is an adaptation of the ATMOS model with the nitrogen to nitrate conversion using the monthly mean OH fields from global GCTM to simulate the chemical conversion of NOx and related species in the modeling system @ http://dx.doi.org/10.1016/S1352-2310(02)00316-3

[55] FAC's for VOC to SOA conversion "Atmospheric Chemistry and Physics" by Sienfeld and Phadnis – the fractions for each of the species were utilized to pre-calculate the VOC to SOA emissions and later simulated in the model for advection @ http://www.amazon.com/Atmospheric-Chemistry-Physics-Pollution-Climate/dp/0471178160

processing stage. In this analysis the natural emissions, such as sea salt and wind blown dust, which are calculated online using the simulated meteorological conditions, are not presented. These modules will be updated for seasonality and contribution in the **Part 2 of the paper**.

Particulate Pollution in Asia

The STEM-PM model provides calculations of average PM concentrations and composition in two bins - fine and coarse [56]. **Figure 11** shows the total annual average PM_{10} concentrations calculated for the year 2000. The analysis results also include seasonal variations, not presented in this paper.

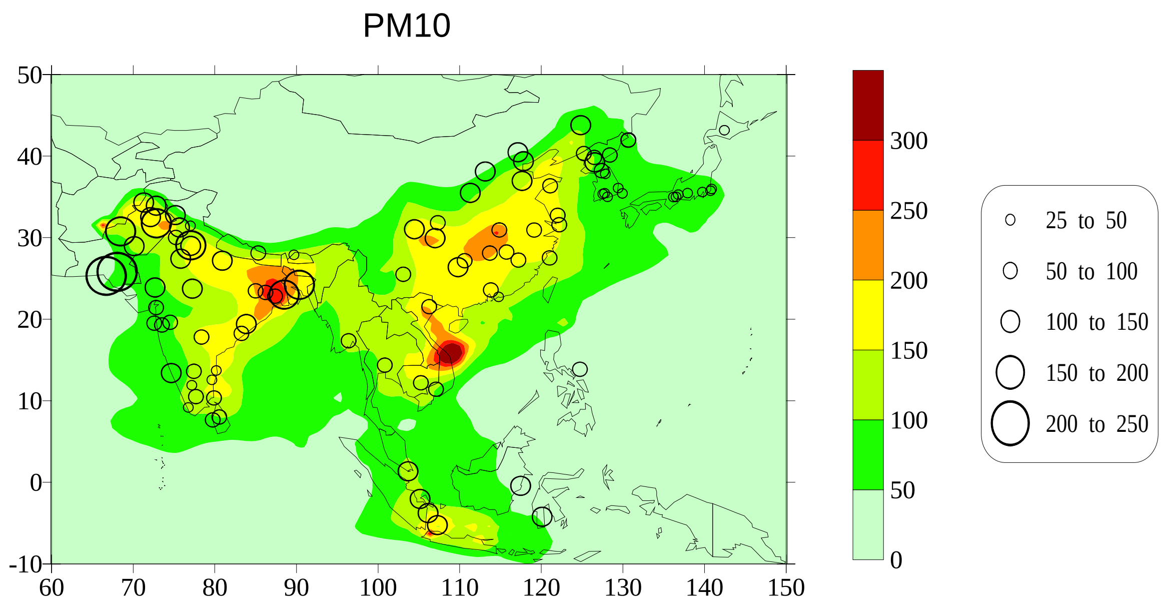


Figure 11: Estimated total annual average PM_{10} overlaid with annual average observations from WHO AMIS 3.0 in 2000

Annual average PM_{10} concentrations ranged from 30-200 μg/m^3 with highs estimated around the areas covering the cities of Shanghai, Chongqing, Beijing, Shenyang, Wuhan, Bangkok, Delhi, Kolkata, Chennai, Islamabad, Karachi, and Jakarta. The highest pollution levels over the Northern India and Bangladesh, the areas with highest population density in Asia, were due to a combination of the fossil fuels in the industries and biofuels in the domestic sector. **Figure 12** presents a composite from a recent study by *Ramanathan, et al. 2008*, on the importance of the carbonaceous emissions in the domestic sector in Asia.

Also overlaid are measured concentrations of PM_{10} from WHO AMIS 3.0 program (presented in **Annex 1**). Quantitatively, the overlap between the measurements and the modeling results is misrepresented for some areas. For example, the high concentrations measured in the Western Pakistan are missing in the modeling results due to the lack of dust storm calculations in this module, which form a major part of the daily air pollution,

[56] Note that all the model results presented here should be regarded as interim and subject to possible changes as the work on model formulation and emissions are being updated and analyzed simultaneously.

especially in the summer months. Similarly, in the Northern China, the presented annual average calculations do not include the pollution due to the dust storms from the Gobi desert and Taklamakan desert, which are frequent in the spring time. The Southeast Asia is dominated with the carbonaceous emissions from biomass burning (forest fires), discussed earlier and the details presented in *Woo et al., 2003*[57].

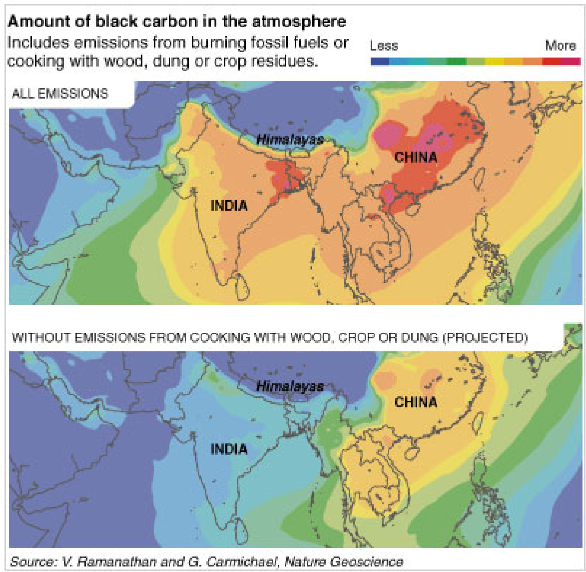


Figure 12: Carbonaceous emissions with and without domestic biofuels in Asia
@ http://www.nytimes.com/2009/04/16/science/earth/16degrees.html

The secondary contributions (sulfates, nitrates and organics) play a vital role in regional photochemistry and PM pollution levels in Asia. To analyze the impact of various source categories, the modeling exercise was conducted in separate pollutant bins. **Figure 13** presents the percent contribution of carbonaceous PM and secondary PM - sulfates, nitrates, to the total PM_{10} mass concentrations. The contribution of the secondary organic aerosols is not presented in this figure because of low estimates, less than 2 percent.

Please note that the estimates in **Figure 13** represent percentages and not the absolute numbers. The areas with high percentages DOES NOT translate to high pollution levels. The relative importance of these contributions also needs further validation.

Initial results indicate that the carbonaceous pollution is the dominating PM component, accounting for 20-50% of concentrations over the region. The largest shares over the Southeast Asia are due to the abundance of the biomass burning and the remaining areas accounting for the domestic usage. The Sulfates and Nitrates contribute up to 20%, with significant shares over the Indian and Pacific Oceans, representing the shipping activity, mostly using the bunker fuels[58].

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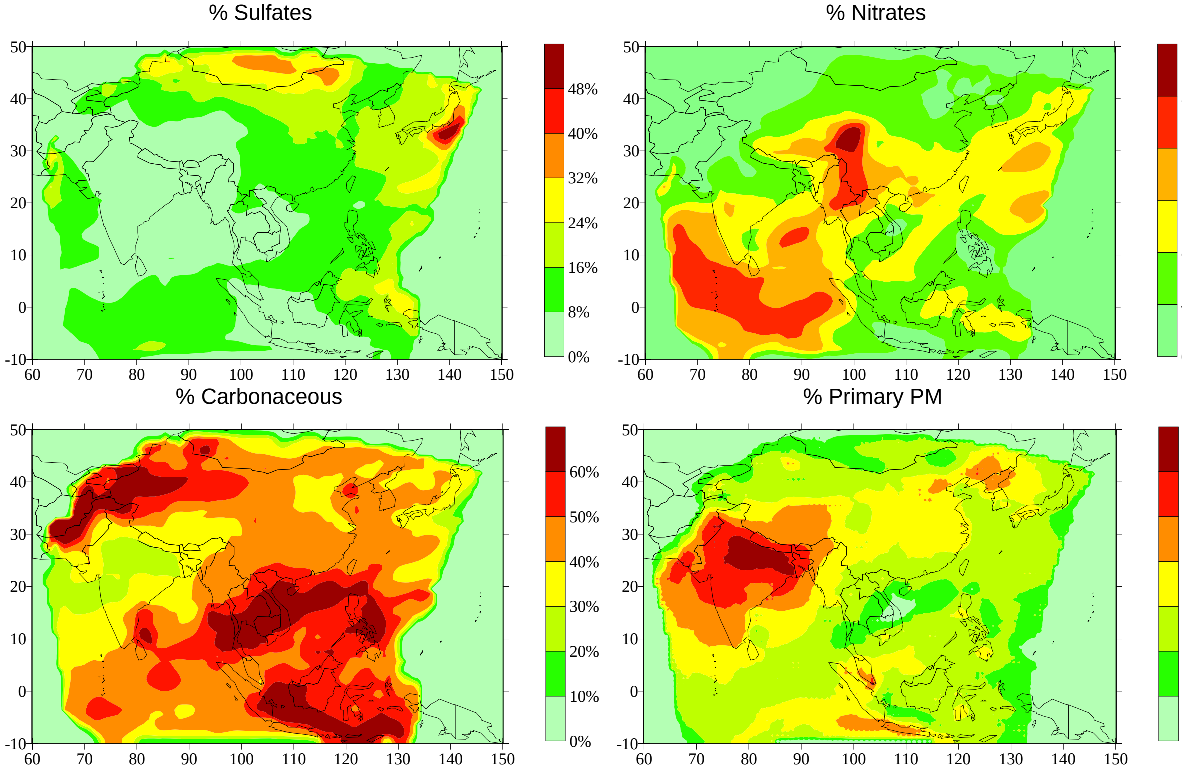
[57] Woo et al., 2003, "Contribution of biomass and biofuel emissions in Asia" @ http://www.agu.org/pubs/crossref/2003/2002JD003200.shtml
[58] Guardian, 2009, "Health risks of shipping pollution have been underestimated" @ http://www.guardian.co.uk/environment/2009/apr/09/shipping-pollution

Figure 13: percent contribution of various pollutants to total annual PM_{10} in 2000



Source: Author's calculations

Also presented in **Figure 13** (right-bottom panel) is the percentage of the primary PM, representing the direct PM emissions from industries, transport, power plants, and domestic sectors to the total PM_{10} mass concentrations. In India, up to 50% of the PM pollution can be attributed to the primary PM and importance of the sectors for major benefits in the PM pollution reduction.

For most of the major cities in Asia, the PM_{10} levels exceeded the 100 $\mu g/m^3$ mark. The **Annex 1** presents a table of PM_{10} concentrations overlaid in the **Figure 11** for the Asian cities. However, recent epidemiological studies indicate that the $PM_{2.5}$ (fine PM) is more harmful to health than the PM_{10} (coarse) and needs more frequent monitoring and detailed analysis.

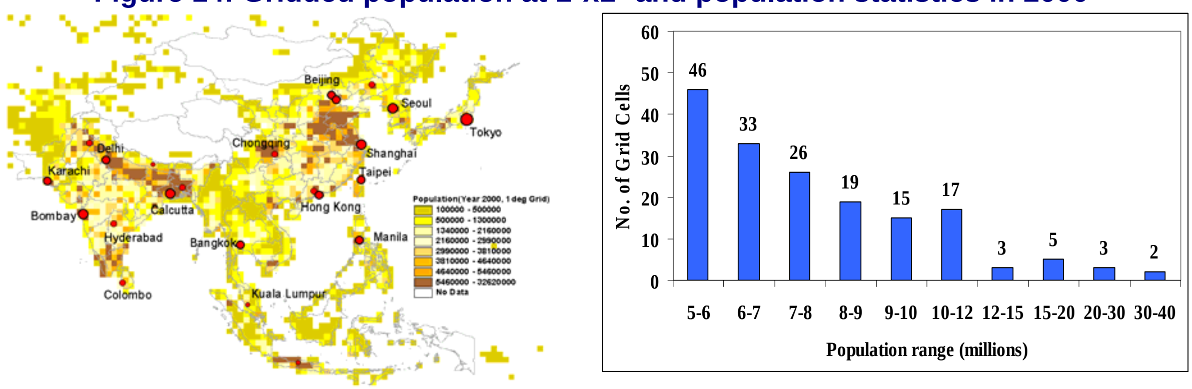
Acid News, 2007, "Cost-effective to cur ship emissions" @ http://www.acidrain.org/pages/publications/acidnews/2007/AN3-07.asp#editorial
Streets et al., 2003, "Contribution of shipping emissions to Asian air pollution", Atmospheric Environment @ http://dx.doi.org/10.1016/S1352-2310(00)00175-8

Estimated Health Impacts of PM_{10} Pollution

The modeled PM_{10} concentrations in 2000 were further utilized to estimate the health impacts based on the methodology presented in **SIM-06-2008**[59]. Three main parameters utilized for these calculations are the exceedances of the PM_{10} pollution in the city's with population over 5 million, an incidence rate 150 people per 1000, and a dose response function of 0.6% increase in the mortality per 10 $\mu g/m^3$ increase in the PM pollution is assumed.

Figure 14 presents gridded Asian population for year 2000 along with Asian megacities (with population over 10 million) and industrialized urban centers (with population over 5 million)[60].

Figure 14: Gridded population at 1°x1° and population statistics in 2000



Asia's ~35% of total urban dwellers is projected to grow at an average of 4% per year to ~3 billion by 2025 (~55% of the projected total population). **Figure 14** also presents the statistics of gridded population. In 2000, there are at least 169 grid cells with population of over 5 million and 30 grid cells (at 1° x 1 ° degree resolution) with population over 10 million. Cities of Jakarta, Tokyo, Calcutta and Dhaka are presented to have population of over 20 million per grid, highest population density in Asia. The 169 grid cells account for 1.4 billion (~35%) population covering only 4% of the land in the region and emitting ~10-20% of the emissions for various species.

For the described emissions in 2000 and the model calculations of PM_{10} pollution, the estimated **mortality is ~902,000 in Asia**.

[59] SIM-06-2008, "Estimating health impacts of urban air pollution" @ http://www.urbanemissions.info/simair

[60] Global World Population provides gridded global population and population density of the world at 2.5' (~3,000 meters) or 1/4 or 1/2 or 1 degree grid resolution for the years 1990, 1995, 2000, 2005, 2010, and 2015. These datasets are developed by the SocioEconomic Data & Applications Center (SEDAC) and available @ http://sedac.ciesin.columbia.edu/gpw/global.jsp?file=gpwv3&data=pdens&type=ascii&resolut=25&year=00

Future Research Directions

In this paper, "*Particulate Pollution in Asia: Part1*", the modeling framework was established for further analysis of air pollution in Asia. The **Part 2** of this work will have the following objectives

- The business as usual scenario of the emissions (anthropogenic and biomass) will be updated to a more recent inventory, currently @ 2006
- The dispersion modeling mechanisms will be updated to include online calculations of the dust storms and sea salt, to account for the seasonal contributions to the local air pollution
- The health impact analysis will be updated using recent epidemiological studies in Asia to include both mortality and morbidity
- The analysis will be extended to 2020 and 2030, under business as usual and for multiple scenarios in a co-benefit framework described in the **SIM-08-2008**, titled "*Co-Benefits: Management Options for Local Pollution & GHG Emissions Control*", covering the industrial, transport, and domestic sectors

Annex 1: Measured PM_{10} Concentrations in Asian Cities (Used in Figure 11)

From WHO AMIS 3.0, for year 2000

Country	City	Population	PM_{10} ($\mu g/m^3$)
Bangladesh	Dhaka	4702752	174
Bhutan	Thimpu	44046	41
Myanmar	Yangon	4101000	85
Cambodia	Phnom Penh	919174	69
Sri Lanka	Colombo	735259	98
Sri Lanka	Jaffna	154225	96
Sri Lanka	Kandy	124336	65
China	Beijing	9301628	106
China	Changsha	1678985	97
China	Chengdu	4401448	103
China	Chongqing	3945199	147
China	Guangzhou	4949982	75
China	Guiyang	2103180	84
China	Hongkong	6743204	38
China	Jinan	3037126	112
China	Kunming	2036549	84
China	Nanjiang	3298203	110
China	Qingdo	6474716	73
China	Shanghai	10366885	87
China	Shantou	1117524	56
China	Shenyang	5881443	120
China	Shijianzhuang	1733511	123
China	Tai'an	4832156	94
China	Taiyan	2810516	105
China	Tianjin	7332755	149
China	Wuhan	4841995	94
China	Wuxi	4020094	87
China	Xiamen	807858	55
China	Xiangtan	1934401	86
China	Zhuzhou	1922730	80
India	Bombay	15796662	79
India	Calcutta	13822335	153
India	Delhi	10558181	187
India	Madras	6799588	46
India	Hyderabad	5448259	51
India	Bangalore	5179700	56
India	Ahmedabad	4153775	104
India	Pune	3127652	58
India	Kanpur	2545638	136
India	Lucknow	2093311	136
India	Nagpur	2086792	69
India	Surat	1904881	92
India	Jaipur	1903984	113
India	Coimbatore	1380420	36
India	Patna	1379042	105
India	Madurai	1361820	50
India	Bhopal	1332797	126
India	Visakhapatnam	1325708	67
India	Ludhiana	1307676	136

Country	City	Population	PM_{10} ($\mu g/m^3$)
India	Jamshedpur	1039844	85
India	Thiruvananthapuram	1036150	40
India	Ranchi	771000	83
India	Pondicherry	503433	42
India	New Delhi	377850	143
India	Kharagpur	332132	72
India	Ahmednagar	278516	78
India	Shimla	138400	34
Indonesia	Jakarta	10844963	103
Indonesia	Surabaya	3198024	120
Indonesia	Bandung	2803673	119
Indonesia	Palembang	1600965	106
Indonesia	Ujung Pandang	1292564	132
Indonesia	Balikpapan	492732	102
Japan	Tokyo	12482692	43
Japan	Yokohama	3366178	32
Japan	Osaka	2626274	39
Japan	Nagoya	2196134	36
Japan	Sapporo	1779520	26
Japan	Kobe	1549203	26
Japan	Kyoto	1477193	30
Japan	Fuji	233828	31
North Korea	Pyongyang	3136000	109
North Korea	Nampo	872849	91
North Korea	Hamhung	855835	78
North Korea	Chongjin	677004	53
North Korea	Sinuiju	421531	95
North Korea	Kaesong	395983	82
North Korea	Anju	261860	63
South Korea	Seoul	11548321	45
South Korea	Busan	4074757	43
South Korea	Daegu	2417435	49
South Korea	Inchon (Incheon)	2360956	45
South Korea	Kwangchu (Gwangju)	1324894	39
South Korea	Daejean	1267690	46
Malaysia	Kualalumpur	1529698	24
Nepal	Kathmandu	641908	53
Pakistan	Karachi	11561917	220
Pakistan	Lahore	5955023	178
Pakistan	Faisalabad(Lyallpur)	2192142	183
Pakistan	Peshawar	1958076	133
Pakistan	Gujranwala	1942630	148
Pakistan	Rawalpindi	1506578	131
Pakistan	Hyderabad	1292711	239
Pakistan	Islamabad	965968	134
Philippines	MANILA	10432038	60
Viet Nam	Ho Chi Minh	4718649	67
Viet Nam	Hanoi	3674638	96
Thailand	Bangkok	7296365	82

Annex 2: Summary of Anthropogenic Emissions in Asia in 2000

Region	Emissions from Energy, Industry, and Agriculture (Tg)								
	SO_2	NO_x	CO_2	CO	CH_4	NMVOC	BC	OC	NH_3
China	**20.30**	**10.53**	**3534**	**100.0**	**36.84**	**14.74**	**0.94**	**2.66**	**13.34**
Other East Asia	**2.31**	**4.33**	**1941**	**15.03**	**4.36**	**3.73**	**0.10**	**0.20**	**0.88**
of which, Japan	*0.80*	*2.19*	*1199*	*6.58*	*1.03*	*1.88*	*0.052*	*0.062*	*0.35*
of which, Rep. of Korea	*0.83*	*1.32*	*408*	*2.66*	*1.10*	*1.13*	*0.021*	*0.022*	*0.17*
Southeast Asia	**3.15**	**3.06**	**1173**	**34.04**	**19.50**	**11.06**	**0.32**	**1.37**	**2.96**
South Asia	**7.10**	**4.76**	**2033**	**62.3**	**40.85**	**10.67**	**0.66**	**2.82**	**9.42**
of which, India	*5.46*	*4.05*	*1687*	*51.1*	*31.11*	*8.63*	*0.52*	*2.19*	*7.23*
International Shipping	**1.08**	**1.29**	**51**	**0.12**	**0.00**	**0.03**	**0.068**	**0.051**	**0.00**
Asia Total	**33.95**	**23.97**	**8731**	**211.1**	**101.5**	**40.23**	**2.09**	**7.09**	**26.60**

Region	Emissions from Biomass Burning (Tg)								
	SO_2	NO_x	CO_2	CO	CH_4	NMVOC	BC	OC	NH_3
China	**0.08**	**0.82**	**283**	**15.74**	**0.54**	**2.69**	**0.11**	**0.73**	**0.23**
Other East Asia	**0.00**	**0.21**	**62**	**3.14**	**0.12**	**0.54**	**0.021**	**0.20**	**0.05**
Southeast Asia	**0.17**	**1.06**	**522**	**31.63**	**1.84**	**5.69**	**0.21**	**1.55**	**0.41**
of which, Indonesia	*0.05*	*0.31*	*150*	*8.96*	*0.53*	*1.61*	*0.059*	*0.44*	*0.12*
South Asia	**0.10**	**0.71**	**269**	**16.60**	**0.61**	**2.99**	**0.11**	**0.86**	**0.23**
of which, India	*0.07*	*0.54*	*199*	*12.26*	*0.42*	*2.21*	*0.083*	*0.65*	*0.17*
Asia Total	**0.37**	**2.80**	**1137**	**67.1**	**3.10**	**11.92**	**0.45**	**3.33**	**0.92**

Region	Total Anthropogenic Emissions (Tg)								
	SO_2	NO_x	CO_2	CO	CH_4	NMVOC	BC	OC	NH_3
China	**20.39**	**11.35**	**3817**	**115.8**	**37.38**	**17.43**	**1.05**	**3.38**	**13.57**
Other East Asia	**2.33**	**4.53**	**2003**	**18.17**	**4.47**	**4.28**	**0.12**	**0.39**	**0.92**
of which, Japan	*0.80*	*2.20*	*1203*	*6.81*	*1.04*	*1.92*	*0.053*	*0.074*	*0.35*
of which, Rep. of Korea	*0.83*	*1.32*	*411*	*2.82*	*1.11*	*1.16*	*0.022*	*0.028*	*0.17*
Southeast Asia	**3.32**	**4.12**	**1695**	**65.7**	**21.35**	**16.75**	**0.53**	**2.92**	**3.37**
South Asia	**7.19**	**5.47**	**2302**	**78.9**	**41.45**	**13.66**	**0.77**	**3.68**	**9.65**
of which, India	*5.54*	*4.59*	*1886*	*63.3*	*31.53*	*10.84*	*0.60*	*2.84*	*7.40*
International Shipping	**1.08**	**1.29**	**51**	**0.12**	**0.00**	**0.03**	**0.068**	**0.051**	**0.00**
Asia Total	**34.32**	**26.77**	**9868**	**278.6**	**104.7**	**52.2**	**2.54**	**10.42**	**27.52**

NOTES: Emissions are presented as follows: SO_2 as SO_2, NO_x as NO_2, CO_2 as CO_2, CO as CO, CH_4 as CH_4, NMVOC as full MW of constituent compounds, BC as C, OC as C, NH_3 as NH_3. This inventory only includes anthropogenic emissions (e.g., no volcanic SO_2, biogenic VOC, or wetlands CH_4). CO_2 emissions are from direct releases only; they do not include C uptake by growing vegetation. Biomass burning is considered to be an anthropogenic source; biomass burning values presented are annual average emissions typical of the mid-1990s (see worksheet 12). Speciated NMVOC emissions can be found on worksheet 8. Release date of this inventory is 07/01/2002.

This work is sponsored by the TRACE-P project of the National Aeronautics and Space Administration. See the following web site for further information on this inventory, including access to gridded emissions data: http://www.cgrer.uiowa.edu/EMISSION_DATA/index_16.htm. For additional information, contact: dstreets@anl.gov or call (630) 252-3448.

Citation: A year-2000 inventory of gaseous and primary aerosol emissions in Asia to support TRACE-P modeling and analysis, Streets, D.G., T.C. Bond, G.R. Carmichael, S. Fernandes, Q. Fu, D. He, Z. Klimont, S.M. Nelson, N.Y. Tsai, M.Q. Wang, J.-H. Woo, and K.F. Yarber, in preparation for the *Journal of Geophysical Research* special TRACE-P issue, 2002.