

Asian Aerosols: Current and Year 2030 Distributions and Implications to Human Health and Regional Climate Change

GREGORY R. CARMICHAEL,^{*,†}
 BHUPESH ADHIKARY,^{†,‡}
 SARIKA KULKARNI,[†]
 ALESSIO D'ALLURA,^{†,‡} YOUHUA TANG,^{†,§}
 DAVID STREETS,[‡] QIANG ZHANG,[‡]
 TAMI C. BOND,[§]
 VEERABHADRAN RAMANATHAN,^{||}
 ADITSUDA JAMROENSAN,[†] AND
 PALLAVI MARRAPU[†]

Center for Global and Regional Environmental Research,
 University of Iowa, 424 IATL, Iowa City, Iowa 52242, Decision
 and Information Sciences Division, Argonne National
 Laboratory, DIS/900 9700 South Cass Avenue, Argonne,
 Illinois, Department of Civil and Environmental Engineering,
 University of Illinois at Urbana–Champaign, Neumark Civil
 Engineering Laboratory, MC-250, 205 N. Mathews Avenue,
 Urbana, Illinois 61801, and Scripps Institution of
 Oceanography, University of California at San Diego, 9500
 Gilman Drive # 0221, La Jolla, California 92093

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Aerosol distributions in Asia calculated over a 4-year period and constrained by satellite observations of aerosol optical depth (AOD) are presented. Vast regions in Asia that include >80% of the population have PM_{2.5} concentrations that exceed on an annual basis the WHO guideline of 10 $\mu\text{g}/\text{m}^3$, often by factors of 2 to 4. These high aerosol loadings also have important radiative effects, causing a significant dimming at the surface, and mask ~45% of the warming by greenhouse gases. Black carbon (BC) concentrations are high throughout Asia, representing 5–10% of the total AOD, and contributing significantly to atmospheric warming (its warming potential is ~55% of that due to CO₂). PM levels and AODs in year 2030, estimated based on simulations that consider future changes in emissions, are used to explore opportunities for win–win strategies built upon addressing air quality and climate change together. It is found that in 2030 the PM_{2.5} levels in significant parts of Asia will increase and exacerbate health impacts; but the aerosols will have a larger masking effect on radiative forcing, due to a decrease in BC and an increase in SO₂ emissions.

* Corresponding author e-mail: gcarmich@engineering.uiowa.edu; tel: 319-335-3333; fax: 319-335-3337.

[†] Center for Global and Regional Environmental Research, University of Iowa.

[‡] Argonne National Laboratory.

[§] University of Illinois at Urbana–Champaign.

^{||} Scripps Institution of Oceanography, University of California at San Diego.

[‡] Now at ARIANET Srl, Via Gilino n. 9, 20128 Milano, Italy.

[‡] Now at Mesoscale modeling, NOAA/NCEP/EMC, W/NP2, NOAA, WWB #207, 5200 Auth Road, Camp Springs, MD, 20746.

[‡] Now at School of Engineering, Kathmandu University, P.O. Box - 6250, Dhulikhel, Nepal Email: bhupesh@ku.edu.np.

1. Introduction

High aerosol loadings are prevalent throughout the Asian atmospheric environment. This is illustrated in Figure 1a and c, where the four year mean (2001–2004) distribution of satellite-derived aerosol optical depth (AOD) and calculated annual mean PM₁₀ concentrations are shown. AOD is a measure of atmospheric extinction through a vertical column of atmosphere. The higher the AOD value, the more aerosols are within a column, and the lower the visibility within that column. AOD values <0.2 represent low aerosol amounts (high visibility). Vast regions (~80%) of Asia and the Middle East have AOD values greater than 0.3. These regions also have high PM₁₀ values (Figure 1c). The aerosol components contributing to AOD and PM in Asia include soot, sulfates, organics, and dust, among others. This rich mixture of aerosols and their precursors comprise what is commonly referred to as atmospheric brown clouds (ABCs). The anthropogenic component of ABCs consists of primary particles and secondary aerosols produced from chemical reactions involving pollutant gases, such as nitrogen oxides (NO_x), sulfur dioxide (SO₂), ammonia (NH₃), and hundreds of organic gases and acids. Widespread ABCs result from the combustion of biofuels used in cooking and heating, open biomass burning, and fossil fuels used broadly throughout diverse economic sectors. As a result of these activities aerosol emissions are high throughout large parts of Asia as shown by regional emissions of black carbon (BC, Figure 1d).

Worldwide, an estimated several billion people live under ABCs. The links between the high particulate levels associated with ABCs and human health are widely appreciated. We are also learning that ABCs have significant impacts on the climate system, altering radiative forcing over Asia, dimming radiation reaching the surface, and increasing solar heating of the atmosphere (1). These perturbations have given rise to major areas of concern, some of the most critical being the observed decrease in the Indian summer monsoon rainfall, the north–south shift in eastern China rainfall patterns, the accelerated retreat of the HKHT (Hindu Kush Himalayan–Tibetan) glaciers, and decrease in snow packs. These changes have important negative effects on water resources and crop yields, which are not yet fully understood (2).

For the above reasons the study of Asian aerosols has expanded greatly over the past decade. Large-scale field experiments such as INDOEX (3) and ACE-Asia (4) have provided invaluable information regarding Asian aerosols, and have helped stimulate follow-on studies. One notable example is The United Nations Environmental Program (UNEP) international project ABC. The goal of project ABC is to create a holistic view of air pollution over Asia, one which integrates the science of air pollution and public policy (2). The project has set up experimental stations for long-term monitoring throughout Asia including sites in the Maldives, at the base camp of the Himalayas, and in Kyrgyzstan in central Asia. It has also conducted several intensive field experiments (5). As part of these studies, chemical transport models have been used to interpret observations and to integrate the observations over broader geographic scales. Chemical transport models also provide a means to link emissions with observed concentrations and in answering “what-if” questions for the policy makers. Several global model studies have studied the role of aerosols and their direct and indirect effects on climate forcing (6).

In this paper, we present results using our chemical transport model to help describe the regional distributions

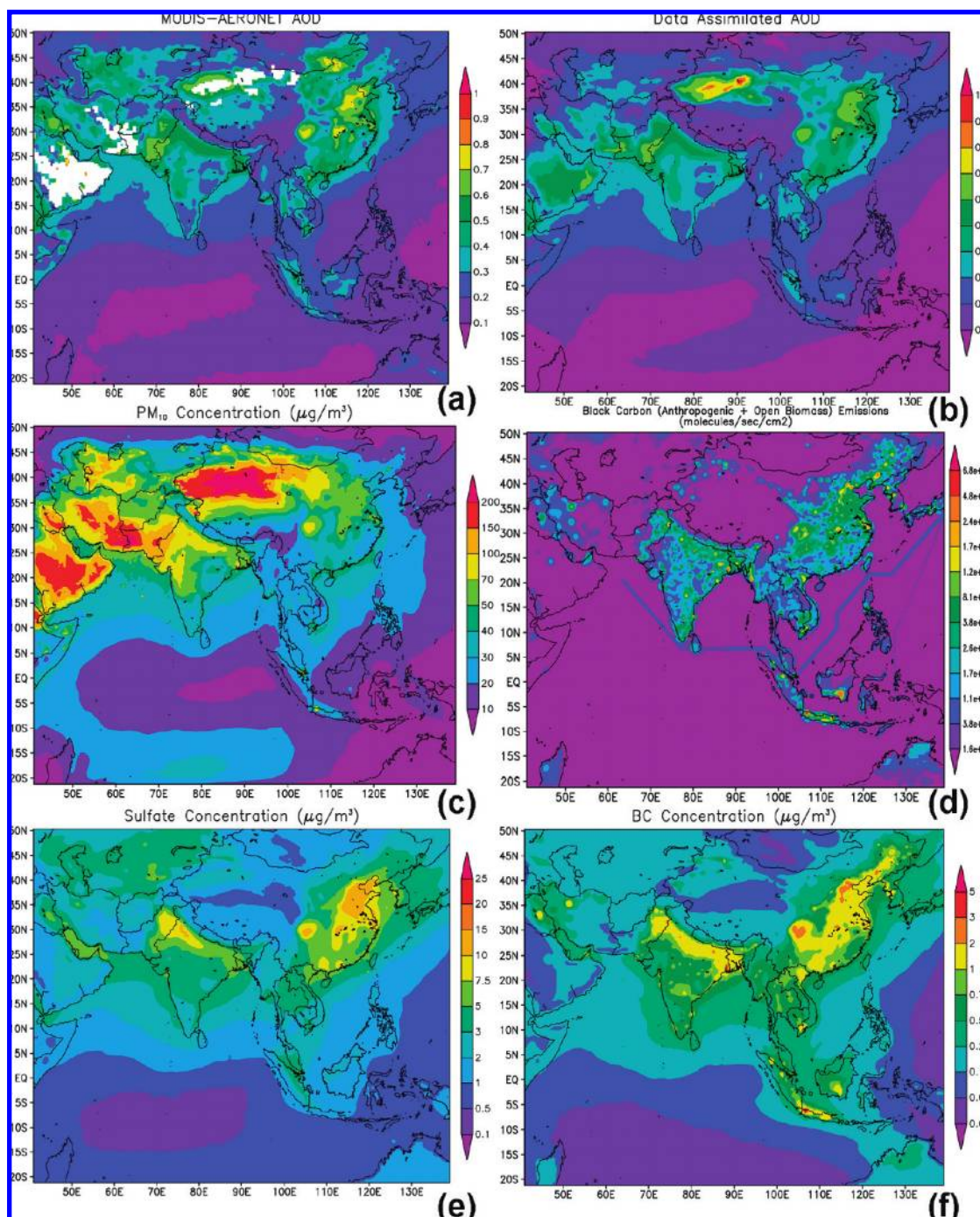


FIGURE 1. Four-year averaged MODIS & AERONET AOD (a); data assimilated STEM model AOD (b); PM₁₀ mass (c); BC emissions used in the model (d); SO₄ (µg/m³) (e); and BC (µg/m³) (f).

of Asian aerosols. We also discuss some of the important impacts of Asian ABCs on human health and the climate system. Finally, we look to the future and discuss the implications for aerosol emissions in Asia, and the opportunities for win-win strategies built upon addressing air quality and climate change together. Throughout this paper we focus special attention on black carbon (BC) because of its unique role as the aerosol that acts like a greenhouse gas and warms the atmosphere, and its importance in human health effects. Several studies have recommended that it should be a central target for climate change mitigation (7, 8).

2. Analysis Methodology

2.1. STEM Model. The STEM regional chemical transport model developed at the University of Iowa was used to

simulate the transport, transformation, and deposition of aerosols. The STEM model has been successfully used in the past to study the seasonal cycle and outflow of aerosols from South and East Asia (9, 10). We simulated aerosol distributions within the Asia domain shown in Figure 1a for a period of four years (January 2001 to December 2004). The meteorological variables necessary to drive chemical transport model were obtained from the MM5 model using a horizontal grid resolution of 50 × 50 km. The STEM domain extended to 14 km altitude with 23 layers between the surface and model top. The aerosols simulated for this study were sulfate, BC, OC, other PM_{2.5}, and other PM₁₀ (i.e., non carbonaceous aerosols such as fly ash, road dust, and cement, which were simulated as a single mass component with aerodynamic diameters less than or equal 2.5 µm, and between 2.5 and

10 μm , respectively, and referred to in this paper as $\text{OPM}_{2.5}$ and OPM_{10} , fine and coarse mode sea salt, and fine and coarse mode dust. These constituents comprise the primary components of $\text{PM}_{2.5}$ and PM_{10} . Secondary organic aerosol was not included in this analysis. The aerosol composition predictions using STEM have been compared to observations in Asia in numerous studies (9–12). In general the model does a good job in capturing the regional distributions of $\text{PM}_{2.5}$ including the relative contributions from sulfate and BC.

2.2. Assimilation. Model-derived estimates of aerosol distributions have significant uncertainty due to the uncertainties associated with emissions and key processes such as wet and dry deposition (11). To better constrain aerosol distributions, we performed an assimilation of aerosol optical depth (AOD) data. The STEM modeled aerosol mass distribution was used to calculate the AOD using aerosol-specific extinction coefficients. For this study, we used the extinction coefficients for aerosols as reported in the IPCC report by Penner et al. (13). Satellite and ground-based AOD, described in the next section, were then assimilated. We used an optimal interpolation technique described by Collins et al. (14), although our technique differs as we added both ground-based (AERONET) AOD and the aerosol fine-mode fraction from satellite observations. The fine-mode AOD data provide additional information to use in the adjustment of the fine-mode components such as BC and sulfate. Here we performed the assimilation on a monthly basis in postanalysis mode. The STEM modeled aerosol AOD was converted to a monthly mean AOD and used as input for assimilation. The ratio of assimilated AOD to modeled AOD was then used to recover the aerosol mass concentration, and the anthropogenic (BC, OC, sulfate, other $\text{PM}_{2.5}$) and natural (sea salt and dust) aerosols were adjusted separately by using total and fine mode AOD.

A detailed evaluation of the assimilated AOD distributions is presented elsewhere (15). This study showed that the satellite-constrained AOD distributions accurately predicted AOD values at locations with independent AOD data. On average the root-mean-square error in AOD was decreased by $\sim 50\%$ after the assimilation. The assimilation of AOD was also shown to significantly improve the predicted PM_{10} and $\text{PM}_{2.5}$ mass distributions as also discussed in Adhikary et al. (15).

2.3. Observations and Data Description. The observation data used in the assimilation was the AOD from Moderate Imaging Spectroradiometer (MODIS) daily level 2 onboard the National Aeronautics and Space Administration (NASA) Terra satellite. To constrain the satellite-based observations further we integrated AERONET level 2 (quality assured for cloud screening and calibration) with the MODIS data as described by Chung et al. (16). In our assimilation, we used AOD over land and the fine mode fraction information over oceans when available. The observations still have regions with data gaps, primarily over the desert regions of Asia. A new retrieval algorithm called “Deep Blue” can provide AOD over bright and desert surfaces (17). However, for this study, the algorithm was not yet available, and was not used.

2.4. Emissions. Anthropogenic emissions were from the emission inventory developed by Streets et al. for Asia for the year 2000 (18). Monthly mean year-specific emissions of carbonaceous aerosols from open biomass burning were taken from the GFEDv2 database (19). In the 2001–2004 simulations, the anthropogenic SO_2 , BC, OC, $\text{OPM}_{2.5}$, and OPM_{10} emission rates were held constant throughout the four years. However total emissions of BC and OC varied on a monthly basis due to the monthly varying open burning emissions. Dust and sea salt emissions were calculated online with the changing meteorology. Figure 1d shows the 4-year mean total BC emissions within the model domain. Higher

BC emissions are seen in areas with high population density such as the Ganges Valley in India and Eastern China as well as areas with high open biomass burning such as Southeast Asian countries of Vietnam, Cambodia, and Indonesia. BC emissions over Pacific and Indian Oceans are from shipping and aviation.

One source of error in the emissions used in the simulations is that due to annual changes in anthropogenic emissions during 2001–2004. We have recently updated our estimates of Asian emissions for the year 2006 (20). Compared to the 2001 values, the BC and SO_2 emissions for 2006 are estimated to be $\sim 40\%$ and 60% higher, respectively. The significant uncertainty in the emissions is a compelling reason for using data assimilation to help constrain the predicted aerosol distributions. In the assimilation process the year to year changes in emissions, which are reflected in the observed AOD values, are used to estimate the differences between the observed and predicted AOD values, and this quantity serves as the basis for adjusting the mass distributions of PM_{10} and $\text{PM}_{2.5}$.

Future scenarios for the year 2030 were also analyzed. We focused the future simulations on the carbonaceous and sulfate aerosols as they play key roles in Asia from both climate change and health perspectives as discussed later in the paper. Future emissions for carbonaceous aerosols were taken from the work by Streets et al. (21). Gridded emissions for SO_2 , a precursor for sulfate aerosol, were not readily available for the same IPCC development pathways. However, growth rates by sector were available for IPCC defined geographical regions (22). The contributions of various sectors in the current emissions inventory were weighted and multiplied by these growth rates to estimate the future SO_2 emissions within that region. A similar technique was applied by the global model studies of Koch et al. (6). All other emissions were held constant at their 2004 levels.

3. Results and Discussion

3.1. Aerosol Distributions. *3.1.1. Regional Distribution of Aerosols.* The calculated 4-year mean AOD distribution derived from the STEM model calculations after assimilation is shown in Figure 1b, and can be compared with the satellite-derived distribution (Figure 1a). It is important to point out that the above discussion reflects the 4-year mean aerosol distributions. The seasonal variability of the aerosol mass and composition in Asia is large and is discussed elsewhere (9, 15)

The assimilated AOD distribution accurately captures the magnitude and spatial pattern of the observed AOD. The highest predicted AOD values occur over the desert regions of Gobi and Taklimakan in East Asia and desert regions of India–Pakistan border and the Middle East. These are also places where the assimilation process did not provide a significant constraint, as observed AOD data in these regions are limited in time coverage due to difficulties in retrieval over desert areas. Vast regions with $\text{AOD} > 0.3$ are seen throughout South and East Asia with significant contribution (60–80%) from the anthropogenic aerosols. Below we discuss in more detail the aerosol components contributing to these elevated AOD values.

The calculated 4-year mean distribution of PM_{10} is shown in Figure 1c. The high PM regions include areas in and downwind of major desert areas (e.g., Central China, Middle East, Pakistan), locations around heavily populated and industrialized areas (e.g., Indo Gangetic Plain, Eastern China), and areas impacted by biomass burning (e.g., Southeast Asia).

The $\text{PM}_{2.5}$ fraction represents an important subcomponent of the PM_{10} mass, and plays important roles in human health and radiative effects. The $\text{PM}_{2.5}$ fraction accounts for 60–80% of the total mass throughout South, Southeast, and East Asia. The regional distributions of sulfate and BC, important

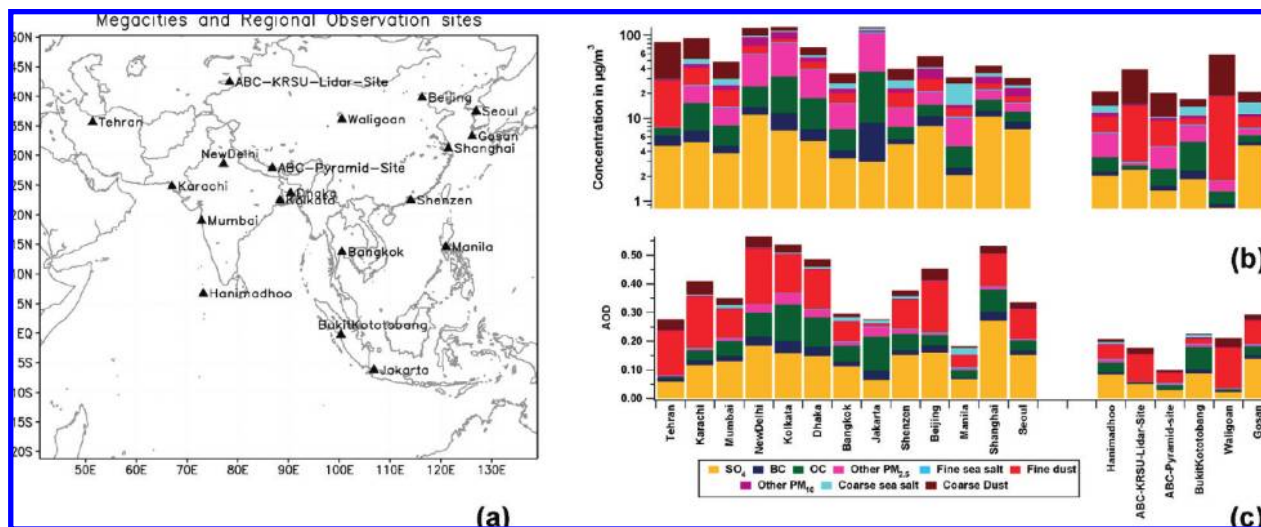


FIGURE 2. Location of the megacities and regional observation sites (a); species contribution to PM_{2.5} mass (µg/m³) (b) and AOD (c) at the megacities and regional observation sites. The PM_{2.5} is plotted using a log scale to highlight the pollution related aerosols, which are the major contributors to AOD.

constituents of PM_{2.5}, are also shown in Figure 1. The sulfate distribution (Figure 1e) shows the highest concentration in the Indo Gangetic plain and East China. These are highly populated areas with substantial fossil fuel consumption (largely coal), which leads to high sulfate concentrations. In contrast, the BC distribution in Figure 1f has high BC values extending into more rural regions, as shown in southern India and SE Asia. This reflects the fact that BC has additional emission sources including biofuels and open biomass burning.

To further illustrate the regional variability in the aerosol composition, the mean predicted aerosol mass and composition at selected megacities and regional ABC observation sites are shown in Figure 2b. The major cities of Asia have high aerosol amounts. In fact the ten most polluted world cities in terms of PM₁₀ are located in Asia (23). The levels of PM_{2.5} in these cities exceed the WHO annual guideline for PM_{2.5} of 10 µg/m³ by factors of 2 to 5. The contribution of anthropogenic aerosols to PM_{2.5} mass increases from west to east across the domain (cf, the Indian Megacities Mumbai, New Delhi, and Kolkata). The fine mode aerosol composition varies among the cities. Sulfate is a significant anthropogenic component of PM_{2.5} throughout Asia (cf, New Delhi and Beijing). The exception is in the Southeast Asian megacities (e.g., Jakarta) where the carbonaceous aerosols dominate the PM_{2.5} composition, consistent with high open burning emissions of the region. Virtually all the cities have BC levels exceeding a few µg/m³ (e.g., BC at Jakarta is ~6 µg/m³). Other PM_{2.5} (e.g., construction dust) contributes in important ways to PM_{2.5} in Asian megacities, in particular at New Delhi, Kolkata, Manila, and Jakarta. Dust is a significant contributor to PM throughout most of Asia, with the exception being Southeast Asia. Megacities in the Middle East and West Asia (Tehran and Karachi) have the highest fine mode dust contribution to PM_{2.5}.

Calculated PM concentrations at regional and background monitoring sites operated by ABC and the World Meteorological Organization Global Atmospheric Watch (WMO GAW) program are also shown in Figure 2. These sites have high PM₁₀ levels (20–70 µg/m³), reflecting the extent of the elevated levels of PM₁₀ in Asia. The Waliguan and ABC KRSU Lidar sites are located in the arid regions of West Asia and have high dust contribution to PM, while Gosan and Hanimaadhoo, located downwind of the populated regions of China and India, have significant anthropogenic contribution. Gosan has the highest sulfate concentration among the regional observation sites, reflecting the fact that it is in the

major pathway of the East Asia outflow and thus measures sulfate-rich aerosols from China throughout most of the year. Its composition is very similar to the Chinese cities (e.g., Beijing) with an added importance of sea salt, reflecting its island location. Bukit Koto Tabang has the highest carbonaceous aerosol contribution among the regional sites, reflecting the large contribution from open biomass burning.

The mean aerosol species contribution to AOD of the megacities and regional observation sites is shown in Figure 2c. Primary contributors to AOD are different from the primary contributors to aerosol mass. The fine mode and anthropogenic components dominate the AOD because they have higher optical efficiencies than coarse-mode particles. Relative humidity also plays a role, with AOD increasing with RH due to hygroscopic growth of aerosol particles (24). Throughout most of Asia sulfate is a major contributor to the AOD. However, fine mode dust is also an important contributor to AOD. The contribution of BC to AOD is significant, and in most regions the BC contribution represents 5–10% of the total AOD. The significant contribution of absorbing aerosol in Asia has implications for atmospheric radiative forcing, photochemistry, heterogeneous chemistry, and global climate change, which will be discussed in more detail in Section 4.

3.2. Implications and Impacts. The high aerosol loadings in Asia have important implications for the environment, including profound impacts on health and climate.

3.2.1. Human Health. High aerosol levels have a direct impact on human health. Throughout Asia humans are exposed to ABC particles both indoors and outdoors. The most serious health impacts of particles associated with ABCs include cardiovascular and pulmonary effects leading to chronic respiratory problems, hospital admissions, and deaths. The PM₁₀ values exceed the 2005 WHO Guideline (25) for annual mean PM₁₀ of 20 µg/m³ throughout ~80% of Asia; in some regions by factors of 2 to 4. Figure 3 shows the grid cell population exposure to PM_{2.5} levels greater than the WHO annual guideline of 10 µg/m³ (for grid cells with concentrations >10 µg/m³ the PM_{2.5} concentration is multiplied by the population in that grid using annual population from the Gridded Population of the World Version 3 (GPWv3) available at <http://sedac.ciesin.columbia.edu/gpw>). Over 3 billion people in Asia live in areas that exceed the WHO annual guideline for PM_{2.5}. This may represent a conservative estimate of exposure as seasonal exposure levels can be significantly higher than the annual mean values, and subgrid concentration “hot spots” also exist that cannot be repre-

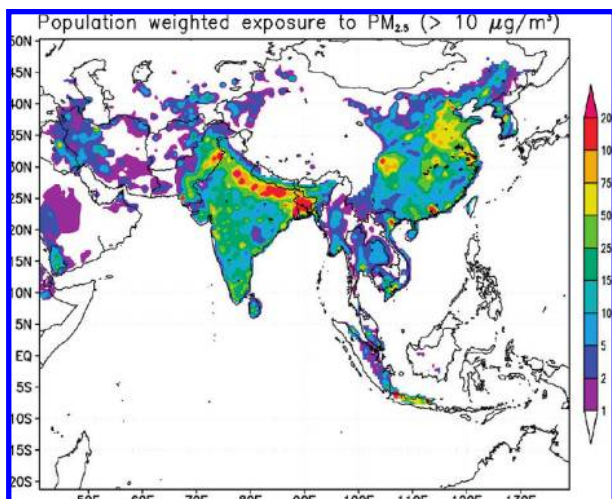


FIGURE 3. Population-weighted exposure to $PM_{2.5}$ levels greater than the WHO guideline of $10 \mu\text{g}/\text{m}^3$ (for grid cells with concentrations $>10 \mu\text{g}/\text{m}^3$ the $PM_{2.5}$ concentration is multiplied by the population in that grid using annual population from the Gridded Population of the World Version 3 (GPWv3) available at <http://sedac.ciesin.columbia.edu/gpw>). (Units: millions of people- $\mu\text{g}/\text{m}^3$ of $PM_{2.5}$).

sented by the grid spacing used in the present simulations. The result shows that the Ganges Valley in India, the Pearl River Delta and Eastern China regions, and the Asian megacities are primary hotspots for PM exposure. Recently these data have been used by health specialists in Asia to estimate the health impacts due to exposure to these levels of aerosol (2).

3.2.2. Climate Change. ABCs in Asia also have profound implications for the climate system. Ramanathan et al. (1, 2) estimate that ABCs cause significant dimming at the surface, with surface solar radiation decreasing by at least 6% over India and China when compared to preindustrial levels. They further estimate that ABCs mask $\sim 45\%$ of the warming by greenhouse gases (GHGs) (net forcing due to all GHGs is $3 \text{ W}/\text{m}^2$, while the net forcing of ABCs is $-1.4 \text{ W}/\text{m}^2$). Of particular importance is BC, whose warming potential is $\sim 55\%$ of that due to CO_2 (top of the atmosphere forcing of BC is $+0.9$ vs $+1.6 \text{ W}/\text{m}^2$ for CO_2). An additional concern regarding BC is significant soot deposition in the Hindu Kush-Himalaya-Tibetan (HKHT) glaciers and snow packs; this darkening of snow can speed melting. Collectively ABCs have given rise to major areas of concern, some of the most critical being the observed decrease in the Indian summer monsoon rainfall, the north-south shift in eastern China rainfall patterns, and the accelerated retreat of the HKHT glaciers and decrease in snow packs. All these have led to negative effects on water resources and crop yields in Asia (5).

The high aerosol loadings in Asia also reduce visibility, and provide surfaces for heterogeneous reactions to occur. They also alter the photolysis rate constants. The net effect of these processes can be to accelerate the production of aerosol sulfate, increase the lifetime of NO_x in the source regions, slow gas-phase ozone production and provide additional ozone loss mechanisms, and modify the lifetime and optical properties of the particles (10, 11).

3.2.3. Future. Given the significance of ABCs in Asia, future trends in aerosol concentrations are of interest. The wide-ranging impacts of ABCs strongly suggest that reducing aerosol emissions can contribute to multiple environmental improvements. From the health perspective, reducing $PM_{2.5}$ levels will greatly reduce excess mortality and morbidity due to air pollution. From the climate change perspective, aerosols currently play an important role in masking the true impact of the greenhouse gases. Thus to minimize the impacts of

GHGs it is desirable to change aerosols in the future in a manner that maximizes the net cooling (masking) effect of ABCs (i.e., by decreasing the absorbing to scattering ratio in ABCs). Thus strategies to meet this goal should consider the effect of ABC composition on climate response. A win-win strategy is to reduce ABCs (thus decreasing the health impacts) in a manner where absorbing aerosols decrease more rapidly than the scattering components (thus minimizing the warming). This requires the identification of emission reduction strategies that preferentially reduce BC emissions. A further challenge arises as emissions of absorbing and scattering aerosols are often highly correlated. For example, open biomass burning produces large quantities of both BC and OC (21), and reducing that activity would decrease both absorbing and scattering aerosols. Below we take a closer look at possible futures for BC and sulfate aerosols in Asia, as they represent major absorbing and scattering components.

Additional simulations were performed to isolate the contributions of biofuel, fossil fuel, and open burning to the carbonaceous aerosol distributions. Their contribution to BC aerosols column amounts is summarized in Figure 4e. Biofuels used for domestic purposes (cooking and heating) currently are the largest source of BC in South Asia, and play a significant role in Southeast and East Asia. Fossil fuel sources (industrial and transport uses) are the major contributors to BC in China. The contribution of biofuels to surface concentrations can be larger than that shown. For example, over the Indian subcontinent the contribution of biofuels to surface BC can reach 70–90% while the values range from 20–80% over China.

We also performed simulations for future emission scenarios for Asia to see how $PM_{2.5}$ and the relative amounts of BC, OC, and sulfates may change by the year 2030. Here we chose the A1B, A2, B1, and B2 scenarios from IPCC-defined development pathways (26). Each of these simulations was done for a single year using 2004 meteorology and results were compared to the 2004 simulations using the base emissions. Figure 4a and b show the changes in $PM_{2.5}$ concentration at the surface layer in two future scenarios. These results show the influence of changes in emissions. In the A1B emission scenario the domain-wide BC and SO_2 emissions relative to the base case changed by -30% and $+130\%$, respectively. This scenario shows an annual increase of $PM_{2.5}$ mass concentration of more than $15 \mu\text{g}/\text{m}^3$ over the highly populated Ganges valley and eastern China regions. Significant increases in aerosol mass are also found in outflow regions as seen over the Bay of Bengal and the East China Sea/Pacific Ocean. The B1 emission scenario (with domain-wide BC and SO_2 emissions changes of -50% and $+12\%$, respectively, relative to the base case) also shows an increase in aerosol mass over much of South Asia, but only a slight increase over China. In both of these scenarios, the health impacts of ABCs would increase.

The ratio between BC and sulfate AOD over Asia for the current year is shown in Figure 4d. The areas with the highest BC to sulfate ratios are those with large contributions of biofuels and open burning, e.g., South and Southeast Asia, because biofuel sources have much higher BC than sulfur emissions. In the A1B, B1, and B2 scenarios, the BC from biofuels decreases significantly (see Figure 4e); however only for the B1 and B2 scenarios do the total BC levels in Asia decrease. The BC to sulfate ratio is shown for present and future emissions in Figure 4f for three megacities in Asia that have different emission source profiles. Model simulations show that for both A1B and B1 the BC to sulfate ratios decrease compared to the base year; however, only B1 shows a significant decrease in BC mass as well.

These future scenarios show that there are ways to decrease the BC contribution to ABCs. Targeting biofuel

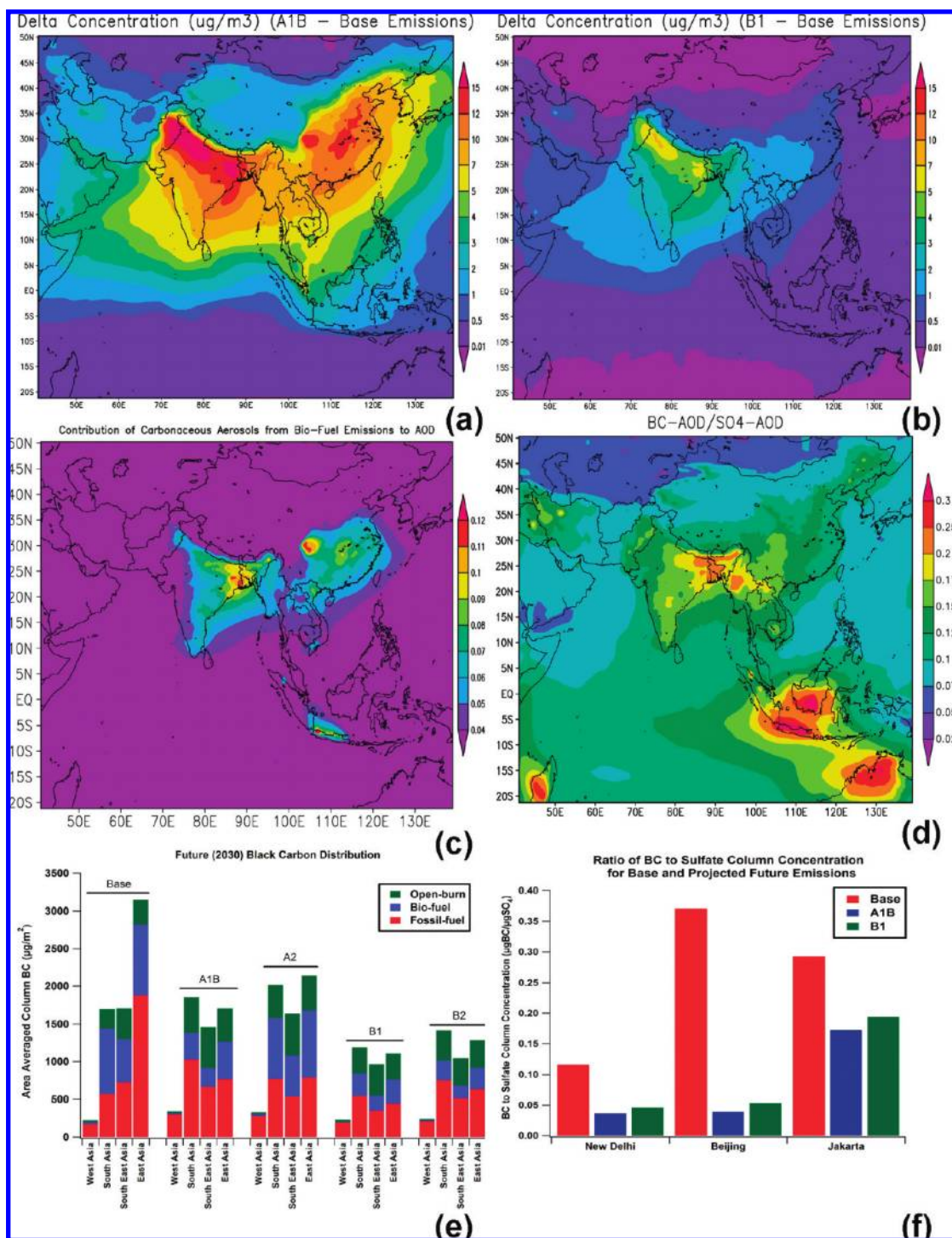


FIGURE 4. Change in surface layer PM_{2.5} concentration from the year 2030 to the base year via IPCC A1B emissions pathway (a); B1 emissions pathway (b); carbonaceous aerosols (from biofuel emissions alone) contribution to AOD (c), modeled BC/SO₄ AOD (d), and regional average BC column concentration (μg/m²) illustrating the sectoral contribution (e) and ratios of BC/sulfate column loadings from base and projected future emissions at selected megacities (f). The region west of Afghanistan is designated west Asia; South Asia region is designated for the countries of Pakistan, Nepal, India, Bangladesh, Bhutan, and Sri Lanka. Southeast Asia is defined by the countries south of 25 degree latitude and east of Bangladesh within our model domain. East Asia is defined by the region enclosed by the area from 20–40 N latitude and 100–125 E longitude.

reductions is a key strategy and has the added benefit of reducing indoor levels of carbonaceous aerosol, dramatically decreasing human exposure. Controls focused on diesel emissions from vehicles are also an important target for BC emission reductions.

Unfortunately, these future scenarios still show an increase in PM_{2.5} levels due to increases in energy consumption and continued reliance on coal with attendant increases in SO₂

emissions. However, there are ways to reduce both BC and sulfate. For example, a variety of emission reductions measures were put into place for the recent Beijing Olympics. These included permanent measures (e.g., improved quality of transport fuels, closing of some industries) as well as temporary ones (e.g., banning cars from use on certain days, halting of construction) (27). Our preliminary analysis suggests that these measures reduced emissions of both SO₂

and BC in the region, and that the BC to sulfur ratio was also reduced (i.e., SO₂ emissions were decreased by ~15% and BC emissions were reduced by ~40%). There are lessons to learn from these efforts, and clearly more work is needed (including extending the analysis beyond BC and sulfate, to include the future health and climate contributions from additional secondary aerosol components such as SOA and nitrates) to identify possible actions that can improve both health and climate impact, as both must be considered when identifying mitigation targets.

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