

## Radiative forcing due to major aerosol emitting sectors in China and India

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[1] Understanding the radiative forcing caused by anthropogenic aerosol sources is essential for making effective emission control decisions to mitigate climate change. We examined the net direct plus indirect radiative forcing caused by carbonaceous aerosol and sulfur emissions in key sectors of China and India using the GISS-E2 chemistry-climate model. Diesel trucks and buses ( $67 \text{ mW m}^{-2}$ ) and residential biofuel combustion ( $52 \text{ mW m}^{-2}$ ) in India have the largest global mean, annual average forcings due mainly to the direct and indirect effects of BC. Emissions from these two sectors in China have near-zero net global forcings. Coal-fired power plants in both countries exert a negative forcing of about  $-30 \text{ mW m}^{-2}$  from production of sulfate. Aerosol forcings are largest locally, with direct forcings due to residential biofuel combustion of  $580 \text{ mW m}^{-2}$  over India and  $416 \text{ mW m}^{-2}$  over China, but they extend as far as North America, Europe, and the Arctic.

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### 1. Introduction

[2] Recent studies [e.g., Ramanathan and Carmichael, 2008; Shindell et al., 2012; Bond et al., 2013] have identified primary anthropogenic emissions of aerosols, particularly black carbon (BC) emissions from industrializing countries like China and India, as targets for emission control to mitigate climate change. The reasons are compelling: their contribution to radiative forcing is large and positive, the emission reductions would achieve immediate reductions in forcing, the emission reductions would be relatively easy and economical to achieve [UNEP/WMO, 2011], and major human health benefits would accrue locally. However, there has been limited study of the contributions to radiative forcing caused by the major source categories that release primary aerosols in China and India. The determination of net radiative forcing is complicated by the contributions from coemitted species and the complex physical and chemical interactions that occur among these primary emitted species and other components of the atmosphere. We examined

emissions from the seven most important source categories in China and India and estimated the net radiative forcing from each of them, locally and around the globe.

[3] Previous studies have estimated regional, sectoral, and species contributions to aerosol and gas radiative forcing, using models that account for a variety of the effects that contribute to forcing. Impacts of emissions from various regions have been examined by many groups [e.g., Bernsten et al., 2005; Naik et al., 2005; Rypdal et al., 2009; Fry et al., 2012]. Early studies with the NASA Goddard Institute for Space Studies (GISS) general circulation model established the importance of biomass burning and the residential and transportation sectors to positive forcing from BC [Koch et al., 2007a, 2007b; Unger et al., 2008].

[4] Using both the GISS and the National Center for Atmospheric Research models, a study of the dual effects on air quality and radiative forcing of reducing regional emissions in particular economic sectors highlighted the largest benefit from reducing emissions in the North American transportation sector and the Asian residential sector [Shindell et al., 2008]. Shindell and Faluvegi [2010] focused on the net climate forcing of emissions from coal-fired power plants, emphasizing the sulfate masking of the positive forcing of  $\text{CO}_2$ . GISS model development enabled more comprehensive inclusion of both gases and aerosols as well as indirect aerosol effects, which has been used to assess mitigation aspects involving releases of multiple species [Shindell et al., 2011, 2012]. Other groups have studied the forcing due to emissions by sector, especially for transportation [e.g., Fuglestvedt et al., 2008, 2010] and how the impact of emissions varies according to their location [Henze et al., 2012]. In this work, we build on past region/sector studies to focus on the most significant aerosol emitting sectors and estimate their contributions to radiative forcing originating from China and India using the latest version of the NASA GISS model. The results show the local and the global effects of these sectors on radiative forcing and which of them might represent the best targets for mitigation efforts.

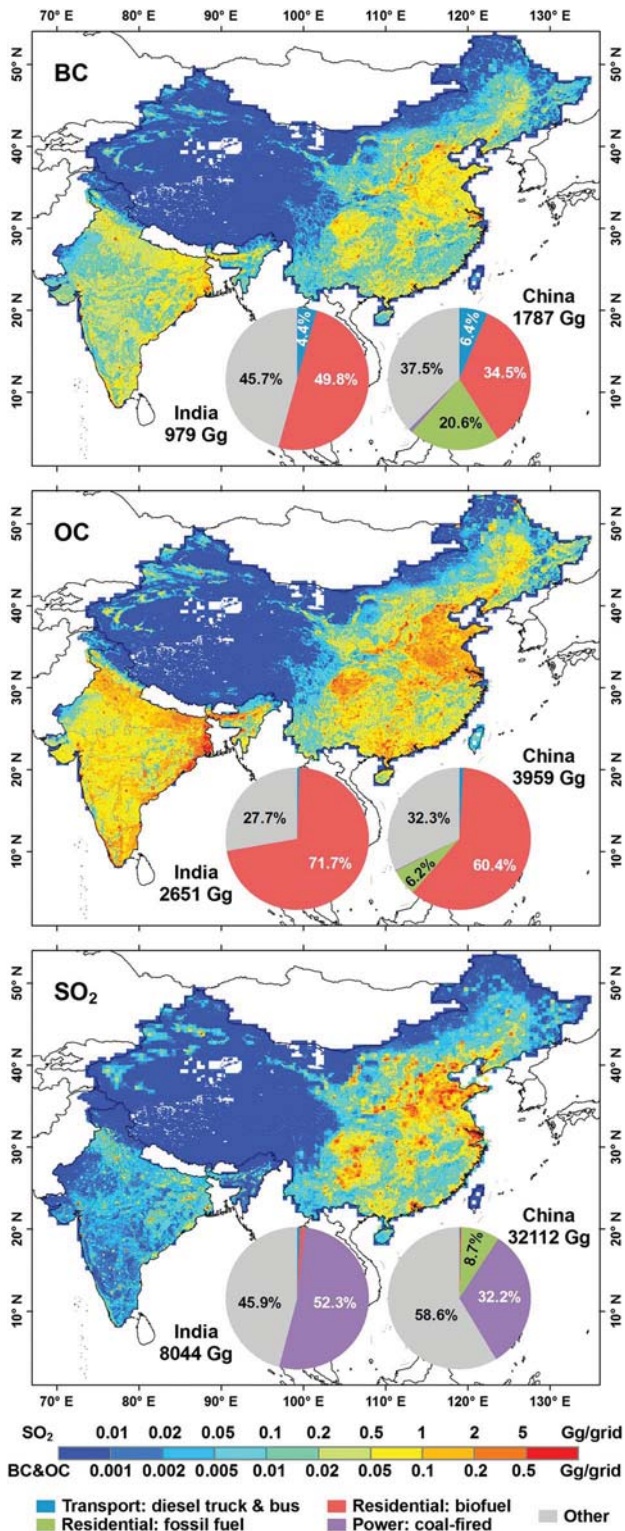
### 2. Data and Methods

[5] We used primary emissions of  $\text{SO}_2$ , BC, and OC for the year 2008 extracted from the 1996–2010 annual emission trends for China and India developed by Lu et al. [2011]. The emissions include all major anthropogenic sources as well as open biomass burning. Year-specific annual temporal distributions were developed for major sectors and gridded at a spatial resolution of  $0.1^\circ \times 0.1^\circ$ . Over the period 1996–2010, the emissions reveal generally upward trends with the exception of  $\text{SO}_2$  emissions in China that decline after 2006. Annual emissions in the year

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**Figure 1.** Emissions distributions in 2008 for China and India at  $0.1^\circ \times 0.1^\circ$  spatial resolution for (top) BC, (middle) OC, and (bottom) SO<sub>2</sub>, also showing totals for each species and shares for each source category.

selected for this study, 2008, are given in Figure 1. It should be noted that 2008 was the year of the Beijing Olympics; emissions were reduced somewhat from normal levels but only for a short time and in a small area, so this does not

materially affect our results. Figures 5 and 6 of *Lu et al.* [2011] provide a complete comparison of the emission estimates with other studies, as well as estimates of uncertainty at 95% confidence. They show that the residential sector contributes the most to overall emission uncertainties in both China and India (60%–65% for BC and 67%–74% for OC).

[6] For this analysis, we selected seven cases representing those sectors in China and India that contribute the most BC, OC, and SO<sub>2</sub>. For BC, the sectors are diesel trucks and buses in the transportation sector (6.4% of total BC emissions in China and 4.4% in India), residential biofuel combustion (34.5% in China and 49.8% in India), and residential fossil fuel combustion (20.6% in China and very low in India). For OC, residential biofuel combustion (60.4% in China and 71.7% in India) and residential fossil fuel combustion (6.2% in China, very low in India) are important. For SO<sub>2</sub>, we selected fossil fuel combustion in the power sector, which contributes 32.2% of total SO<sub>2</sub> emissions in China and 52.3% in India, together with residential fossil fuel combustion in China, which contributes 8.7%. Figure 1 shows the spatial distributions of emissions of BC, OC, and SO<sub>2</sub> in China and India and the relative contributions of key sectors.

[7] These year 2008 emissions are used with the NASA GISS chemistry-climate model GISS-E2. This is the latest version of the GISS model updated from *Schmidt et al.* [2006] and including gaseous and aerosol chemistry as described in *Shindell et al.* [2013a] and references therein. All emissions other than those described above for BC, OC, and SO<sub>2</sub> in China and India are based on year 2000 of the historical transient emissions used in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [*Lamarque et al.*, 2010] and are held constant. Background conditions such as greenhouse-gas levels are for the year 2000, while ocean conditions are fixed at observed 1996–2004 averages. Simulations were performed by removing BC, OC, and SO<sub>2</sub> emissions from one region and sector at a time. We analyzed the last 32 years of 35-year simulations, examining the difference relative to a control simulation in all cases. The long integrations are required to allow diagnoses of indirect aerosol effects. We calculated the total effective radiative forcing (ERF), defined as the net top-of-atmosphere downward flux change after allowing for all responses other than those of the ocean (sea-surface temperatures and sea-ice cover are fixed). This forcing includes rapid adjustments in the atmosphere in response to aerosols, especially cloud responses, and has been shown to provide a better indication of the eventual climate response than the traditional radiative forcing that includes adjustment of stratospheric temperature only [*Hansen et al.*, 2005; *Lohmann et al.*, 2010]. ERF includes the response of clouds, water vapor, lapse rate, etc., as well as aerosol direct effects, and hence encompasses the indirect effects referred to as semidirect, cloud albedo, and cloud lifetime [*Shindell et al.*, 2013b]. We hereafter refer to ERF minus the direct forcing as the indirect forcing. In comparison with AERONET observations, the GISS-E2 model underestimates both aerosol optical depth and absorbing aerosol optical depth over East and South Asia by ~30%–50%, consistent with nearly all global models [*Shindell et al.*, 2013b]. These low biases suggest that the values reported here may be conservative.

**Table 1.** Global Mean, Annual Average Radiative Forcing Due to All Aerosols (Top-of-the-Atmosphere) and Ozone (Tropopause) Resulting From Emissions in the Indicated Sector/Region ( $\text{mW m}^{-2}$ )<sup>a</sup>

Region/Sector	BC Albedo	BC	OC	Indirect	SO <sub>4</sub>	NO <sub>3</sub>	O <sub>3</sub>	Total
India: diesel trucks and buses	0.8	3 (−3)	1 (2)	65 (−54)	0 (0)	3 (3)	−6 —	67 (−54)
India: residential—biofuel	3	53 (−62)	−8 (−19)	3 (−32)	2 (1)	0 (0)	−1 —	52 (−112)
India: coal-fired power	−0.3	−2 (1)	1 (2)	−18 (−45)	−19 (−19)	17 (17)	−10 —	−31 (−46)
China: diesel trucks and buses	0.9	11 (−8)	3 (4)	−12 (−42)	3 (3)	−1 (−1)	−3 —	2 (−44)
China: residential—fossil fuel	0.7	26 (−28)	2 (3)	−53 (−20)	−7 (−7)	5 (5)	1 —	−25 (−47)
China: residential—biofuel	2	51 (−56)	−7 (−16)	−56 (−2)	4 (3)	−2 (−1)	9 —	1 (−72)
China: coal-fired power	−0.5	0 (4)	3 (5)	−30 (−88)	−26 (−26)	20 (20)	1 —	−33 (−85)
China: coal-fired power (SO <sub>2</sub> only)	−0.7	2	1	−30	−26	17	5	−31

<sup>a</sup>Uncertainties due to internal variability in the model are  $3 \text{ mW m}^{-2}$  or less for direct forcings and  $1 \text{ mW m}^{-2}$  for BC albedo forcing. Indirect forcing is given by the ERF minus direct and includes all rapid adjustments to aerosol (and ozone) forcing, including indirect and semidirect effects and is calculated as all-sky values at the top-of-the-atmosphere but would be the same at the tropopause. OC includes SOA, but the contribution is  $2 \text{ mW m}^{-2}$  or less from SOA changes. Surface forcing due to ozone is not important and not calculated. Indirect forcing uncertainty is  $35 \text{ mW m}^{-2}$ . Values in parentheses are the corresponding radiative forcing estimates at the surface in the same units.

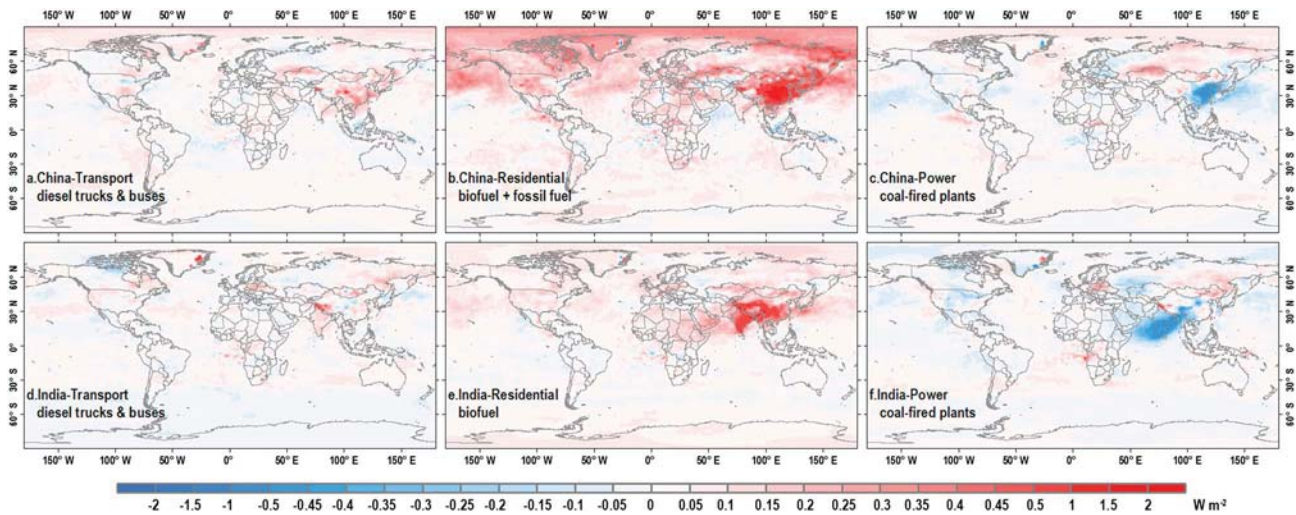
### 3. Results

[8] Table 1 presents global mean, annual average radiative forcings due to all aerosols and ozone resulting from the indicated sector in the given region. Biofuel combustion in the residential sectors of both India and China shows a significant positive direct radiative forcing from BC emissions of about  $50 \text{ mW m}^{-2}$ , roughly 5% of which is due to albedo effects. These effects are only slightly offset ( $\sim 15\%$ ) by the negative forcing due to coemitted OC, which is  $< 10 \text{ mW m}^{-2}$ . The positive forcing of BC is offset by large indirect effects from residential emissions for China, whereas indirect forcing is strongly positive for the diesel trucks and buses case in India. This positive indirect forcing suggests that in that instance, the semidirect impact of BC is larger than the microphysical aerosol-cloud impacts of BC and OC in this model, which was also seen in previous work [Shindell *et al.*, 2012]. Not only do different climate regimes influence the country comparisons, but the emissions contributions are not the same, which affects the balance of BC and OC emissions. With other effects from residential biofuel emissions being small, the net effect of emissions from residential biofuel combustion is  $52 \text{ mW m}^{-2}$  for India and near zero for China. Increasing the albedo forcing of BC by a factor of 3–5 to account for the stronger surface temperature response per unit forcing for this agent relative to others [Flanner *et al.*, 2007; Koch *et al.*, 2009] adds  $\sim 10 \text{ mW m}^{-2}$  to the net forcing.

[9] Residential fossil fuel use is an issue only for China and yields a positive direct BC forcing of  $26 \text{ mW m}^{-2}$ , partly offset by the negative forcing of SO<sub>4</sub> of  $-7 \text{ mW m}^{-2}$ . In this case, as in all cases where there is substantial sulfate forcing, nitrate forcing offsets much of the influence of sulfate. These two aerosols are closely coupled and of opposite sign because of their competition for a limited supply of ammonium in the atmosphere. The relative effect of OC is less for residential fossil fuel combustion because of a higher BC/OC emissions ratio ( $\sim 1/1$ ) than that for biofuel combustion ( $\sim 1/6$ ). Indirect forcing is strongly negative in this case due to the effect of sulfate. The net forcing due to residential fossil fuel combustion in China is  $-25 \text{ mW m}^{-2}$ .

[10] For coal-fired power plants in both India and China, we found negligible effects from carbonaceous aerosols due to their very low emissions, whereas the direct radiative effects of nitrate (positive) and sulfate (negative) roughly offset each other. Thus, negative indirect forcings of  $-18 \text{ mW m}^{-2}$  in India and  $-30 \text{ mW m}^{-2}$  in China largely drive the net forcings of  $-31 \text{ mW m}^{-2}$  in India and  $-33 \text{ mW m}^{-2}$  in China from this source type. An additional simulation for coal-fired power plants in China in which only SO<sub>2</sub> emissions were changed shows that it is the sulfate associated with high SO<sub>2</sub> emissions that contributes virtually all of the net forcing (Table 1). This simulation also demonstrates that the nitrate forcing is a response to the SO<sub>2</sub> changes.

[11] For the transportation sector, we examined the combined effect of diesel trucks and buses. The results for India and China are significantly different. For India, we found that all direct forcings are small, and it is the large indirect forcing that determines the net positive radiative forcing of  $67 \text{ mW m}^{-2}$ . In the case of China, the direct effect of BC is more pronounced, while the indirect forcing is comparable in magnitude but of the opposite sign, yielding a total net forcing of only  $2 \text{ mW m}^{-2}$ . The positive cloud forcing in response to diesel emissions in India indicates a strong positive indirect BC forcing, in contrast to the negative indirect forcing associated with sulfur-rich, coal-fired power-plant emissions (consistent with our knowledge of the cloud response to absorbing versus reflective aerosols). Interestingly, the magnitude of the positive indirect and BC direct forcings are comparable for the BC-rich and low-sulfur diesel transportation sector emissions from China, while for India the indirect forcing is much larger, indicating that this response is highly dependent upon conditions such as the regional aerosol residence times and/or background aerosol loading. Similarly, the indirect effect in response to residential biofuel emissions is substantially more negative for China than for India despite similar OC direct forcing. Given the positive indirect forcing in response to Indian diesel emissions, this suggests that the negative indirect effect of OC is greater relative to the indirect effect of BC for China than for India. Hence, indirect responses (primarily clouds) appear to be more positive for



**Figure 2.** Direct radiative forcing (instantaneous at the top of the atmosphere,  $\text{W m}^{-2}$ ) due to all aerosols and ozone resulting from the indicated sector's emissions in the given region, not including indirect effects. For the purposes of this figure, China's residential biofuel and fossil fuel impacts have been combined.

emissions from India than from China, perhaps because of the large difference in the surface albedo of the downwind Himalayas and Pacific Ocean, respectively.

[12] While the impacts of coemitted gaseous pollutants such as  $\text{NO}_x$  and CO are not considered here, they have been evaluated in prior studies with a similar GISS model [Shindell *et al.*, 2008]. In that work, radiative forcing due to ozone changes was  $-15\%$  of the sulfate direct forcing for the power sector and  $25\%$  and  $31\%$  of the BC forcing for the surface transportation and residential sectors, respectively. Adjusting the ozone responses found here to match those results would change the ozone forcing by  $<5 \text{ mW m}^{-2}$  for the power and transportation sectors, while adding  $17 \text{ mW m}^{-2}$  to the residential sector in India and  $7 \text{ mW m}^{-2}$  to both the residential subsectors in China. These values are well within the uncertainty in the aerosol indirect forcing. Global mean forcing at the surface is also presented in Table 1. Only the three residential cases have significant direct forcings, negative in each case due to BC. There is also a substantial reduction in surface forcing due to the indirect effect for most sectors, which may be related to the semidirect effect of BC. Biofuel combustion typically has the largest effect, with comparable forcing from coal-fired power generation in China.

[13] Figure 2 presents the spatial distribution of the direct plus BC-albedo radiative forcings for each of the seven cases. The indirect forcing values are typically not statistically significant at the local scale, so are excluded in this analysis. As expected, forcing is concentrated locally, where the emissions are highest. For China, however, effects extend throughout the Northern Hemisphere, particularly for the residential cases, primarily owing to long-range transport of BC. For India, maximum forcing is generally collocated with emissions, though Southwest China and the Himalayas also experience high values. For the cases of coal-fired power plants in both India and China, the forcing is significantly negative locally and in the global mean but contains major areas of positive forcing, which can be attributed to removal of ammonium during sulfate formation leading to reduced nitrate formation away from the source region. There are also positive forcings in cryosphere regions, for example, the Himalayas in the case of Indian power plants, which are attributable to BC direct and albedo forcing.

[14] Table 2 presents the direct radiative forcing estimates averaged over 10 world regions, as well as China and India themselves. The aerosol forcings are largest locally, with direct forcings as high as  $580 \text{ mW m}^{-2}$  averaged over India

**Table 2.** Effect of Emissions in the Indicated Sector/Region on Direct Radiative Forcing Due to All Aerosols and Ozone in Different World Regions ( $\text{mW m}^{-2}$ )<sup>a</sup>

	India T-DTB	India R-BF	India P-CF	China T-DTB	China R-FF	China R-BF	China P-CF
East and Southeast Asia	27	211	-21	97	154	278	-104
<i>in which, China</i>	46	340	-28	130	240	416	-145
Middle East, South Asia, and North Indian Ocean	29	202	-201	30	14	47	4
<i>in which, India</i>	103	580	-402	48	46	69	-1
North Asia	36	68	6	33	75	107	55
North America	17	42	-18	19	44	82	0
Europe	10	43	7	17	37	94	-3
North Africa	16	89	-10	24	22	56	10
Arctic	11	56	-22	50	96	147	52
North Pacific Ocean	4	45	-14	15	30	66	-26
North Atlantic Ocean	15	45	9	17	35	60	2
Southern Hemisphere	1	14	9	14	11	19	13
Global average	8	46	-9	21	30	56	3

<sup>a</sup>Uncertainties in the net regional forcing due to internal variability in the model are  $\sim 15 \text{ mW m}^{-2}$  or less, except for the Arctic where they are  $\sim 20 \text{ mW m}^{-2}$ . T-DTB, transportation—diesel trucks and buses; R-BF, residential—biofuel; P-CF, power—coal fired; R-FF, residential—fossil fuel.

for the residential biofuel case and  $416 \text{ mW m}^{-2}$  averaged over China also for the residential biofuel case. In addition, however, aerosol transport leads to significant direct forcings in remote regions, particularly due to emissions from Chinese sources, which are as high as  $82 \text{ mW m}^{-2}$  averaged over North America,  $94 \text{ mW m}^{-2}$  averaged over Europe, and  $147 \text{ mW m}^{-2}$  in the Arctic. The spatial distribution of surface forcing is similar to the direct forcing shown in Figure 2.

[15] There is substantial uncertainty in radiative forcing by short-lived species, especially for aerosols. Two recent assessments have examined the forcing due to BC and OC in particular, as well as sulfate [UNEP/WMO, 2011; Bond *et al.*, 2013]. Bond *et al.* [2013] provide a best estimate of the historical BC direct forcing that is larger than in the GISS model, but they also attribute a large negative indirect forcing to OC. UNEP/WMO [2011] also provide a best estimate of the historical BC direct forcing that is larger than that in the GISS model but attribute a weaker indirect effect to BC. Scaling our results to match either study's direct forcing estimates and indirect/direct forcing ratios (as in UNEP/WMO [2011]) causes the net forcing from Indian or Chinese residential biofuel emissions to increase to  $\sim 100 \text{ mW m}^{-2}$ , roughly doubling the Indian value. For Indian diesel, while the scaled value using Bond *et al.* [2013] also produces a positive indirect forcing, due to the dominance of BC's indirect effects over OC's (as in our modeling), its value is weaker and the UNEP scaling gives near zero indirect, leading to substantially lower (60%–80%) net forcing estimates. In the most extreme case, a weaker indirect forcing estimate using the scaled results leads to a positive net impact for the Chinese residential fossil fuel case rather than the negative value found here. A positive indirect forcing for Chinese diesel leads to a much larger net positive forcing using either set of estimates than the near-zero result found here. Forcing due to Indian and Chinese power-plant emissions is quite similar, however, unsurprisingly as this results almost exclusively from the negative indirect effect of sulfate while the indirect effect for other sectors is the result of offsetting positive and negative values due to BC and OC, respectively. Thus, the large positive impacts estimated here for emissions from Indian biofuels are robust; for Chinese transportation and residential biofuel, they appear to be conservative, while for Indian transportation, they may be on the high side, based on the values in the GISS model relative to these other two studies. Note that the scaling is based only on global mean forcings and does not account for the large regional variations found here for indirect effects. As such, the internally calculated results may be more accurate, but analysis of additional models is required to confirm those results.

[16] The radiative forcing effects caused by emissions from these seven sector/region combinations gives some indication of which of them should be preferential targets for emissions control under a climate mitigation policy. However, a direct intercomparison can be misleading because there are widely differing amounts of energy generated and fuels consumed in the seven cases. It is useful to normalize the forcings according to the amount of energy associated with each case. Normalizing to the energy amounts reported by Lu *et al.* [2011], we calculated total forcings (from Table 1) per exajoule of associated energy to be dominated by Indian diesel trucks and buses at  $81 \text{ mW m}^{-2} \text{ EJ}^{-1}$ , followed by

Indian residential biofuel at  $6.6 \text{ mW m}^{-2} \text{ EJ}^{-1}$ . These sectors could be considered as preferred targets for mitigation actions on the basis of their contributions to forcing; of course, other attributes such as cost and feasibility need to be taken into account, as well as the ancillary impacts on human health, but nevertheless, these sectors match well with mitigation targets recommended in other work [e.g., Shindell *et al.*, 2012].

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