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Climate impact of black carbon emitted from energy consumption in the world's regions

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[1] We have used the Laboratoire de Météorologie Dynamique General Circulation Model (LMD GCM) to estimate the contribution of different regions to global black carbon (BC) atmospheric burden and direct radiative forcing (DRF). On the global scale, fossil fuels and biofuels account for 66% and 34% of energy-related BC emissions, respectively. East and South Asia together contribute more than 50% of the global surface, atmospheric, and top-of-atmosphere DRF by BC. The regional contributions to global mean forcings closely follow the respective contributions to atmospheric burden. The global warming potential (GWP) of BC for different regions ranges from 374 to 677 with a global mean of 480. Europe is the largest contributor (63%) to BC deposition at high latitudes. The indirect GWP due to the BC effect on snow albedo is estimated to be largest for Europe (possibly as large as 1200), suggesting that BC emission reductions from this region are more efficient to mitigate climate change. **Citation:** Reddy, M. S., and O. Boucher (2007), Climate impact of black carbon emitted from energy consumption in the world's regions, *Geophys. Res. Lett.*, *34*, L11802, doi:10.1029/2006GL028904.

1. Introduction

[2] The importance of atmospheric aerosols in the global climate change is now well recognized [*Ramaswamy et al.*, 2001]. Black carbon (BC) exerts a positive forcing as opposed to sulfate which exerts a negative forcing. In the recent years there has been increased attention in the aerosol research community about the potential of BC for global warming through direct effects, semi-direct effects [*Lohmann and Feichter*, 2001] and change in the albedo of ice and snow [*Jacobson*, 2001; *Hansen and Nazarenko*, 2004]. Black carbon is only emitted from combustion sources in contrast to sulfate and organic carbon (OC) which are also emitted from natural biogenic sources. The major sources of BC are from fossil fuels and biofuels (biomass burning for domestic energy) [*Bond et al.*, 2004]. The fossil fuel sources are primarily concentrated over the industrialized countries, while biofuel sources dominate over the developing countries. Over India and China both fossil fuels and biofuels are important sources. The atmospheric fate and climate impacts of BC from different regions could differ considerably [*Berntsen et al.*, 2006]. Understanding the radiative and climate impacts of BC from different geographical regions is a prerequisite for mitigation options. It is also of interest to understand the intercontinental transport of pollutants and influence on air pollution and regional climate effects under the Convention on Long-range Transboundary Air Pollution (CLRTAP) and Hemispheric Transport of Air Pollution (HTAP) [*United Nations*, 2004].

[3] Recent studies have shown the importance of BC as a global warming agent through its direct radiative forcing (DRF) [*Jacobson*, 2001] and change in the snow albedo [*Hansen and Nazarenko*, 2004]. Controlling BC emissions will benefit local air quality and global warming [*Bond and Sun*, 2005]. Options for climate change mitigation should therefore consider reduction in BC emissions. Global warming potential (GWP) is a measure of the efficiency of different species to induce global warming relative to CO_2. GWP is defined as the ratio of the cumulative radiative forcing due to the instantaneous release of a given mass of pollutant over a time horizon (typically 100 years) to the same quantity for the same mass of emitted CO_2. Despite its very short atmospheric lifetime, the GWP for BC is reported to be 680 (for a time horizon of 100 years), indicating the potential of reducing BC emissions to slow down global warming [*Bond and Sun*, 2005]. Recently we presented a study of global carbonaceous aerosol cycle and aerosol DRF in the Laboratoire de Météorologie Dynamique General Circulation Model (LMD GCM) [*Reddy and Boucher*, 2004; *Reddy et al.*, 2005a, 2005b]. Here we extend this work to estimate the radiative impacts of BC from energy sources (fossil fuels and biofuels) emitted from different regions of the world. We also estimate the GWP for BC emissions from different regions.

2. Method

[4] We use the LMD GCM for simulating the BC transport and radiative effects. The LMD GCM is a grid-point model with a resolution of 3.75° in longitude and 2.5° in latitude with 19 vertical layers. The carbonaceous aerosols transport in this model has been thoroughly described and evaluated by *Reddy and Boucher* [2004] and *Reddy et al.* [2005b]. Here we use BC emissions from recent inventory of *Bond et al.* [2004] allowing to separate the fossil fuel and biofuel sources. The BC emissions from fossil fuels and biofuels are regionally tagged: South America (SAM), North America (NAM), Africa (AFR), Europe (EUR), West and Central Asia (WCA), South Asia (SAS), East Asia (EAS), Australia and Pacific Islands (AUP), and Oceanic Regions (OCE) (Figure 1). Note that over the oceans BC is emitted only from shipping activities. Similar to our previous studies simulations are carried out by nudging the horizontal model winds to 6 hourly winds from ECMWF

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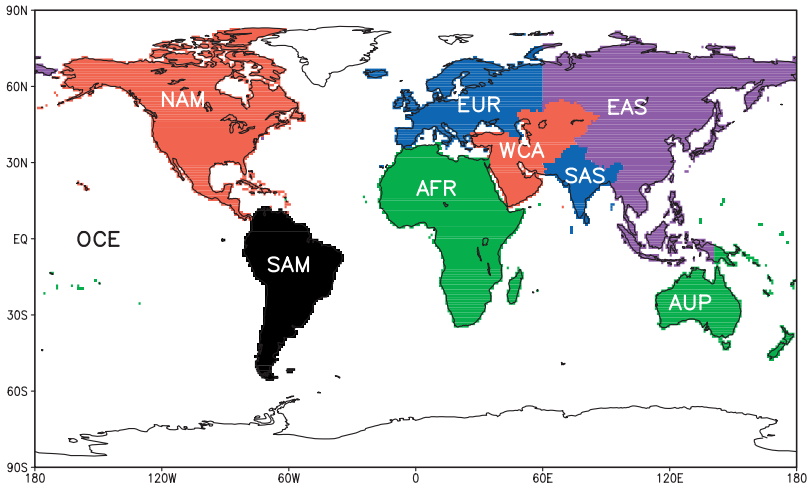

Figure 1. Different regions used in the study. SAM, South America; NAM, North America; AFR, Africa; EUR, Europe; WCA, West and Central Asia; SAS, South Asia; EAS, East Asia; AUP, Australia and Pacific Islands; and OCE, Oceanic Regions.

analyzes with a relaxation time of 0.1 days. Simulations are done for the year 2000 after allowing two months of spin up. We only consider emissions from energy related sources, which can be controlled to address climate change mitigation.

[5] The DRF is estimated in the shortwave (SW) spectrum, at the top of atmosphere (TOA) and at the surface by calling the radiation routine with and without the presence of BC. There is no feedback of the BC on the simulated meteorology. The radiative effect of BC in the longwave (LW) spectrum is negligible [*Reddy et al.*, 2005b] and is not presented here. We also present SW atmospheric absorption as the difference between the TOA and surface DRF.

3. Results and Discussion

3.1. Black Carbon Budget

[6] The model simulated BC surface concentrations and aerosol absorption optical depth, which largely relates to the BC burden, were compared with observations [*Reddy and Boucher*, 2004; *Reddy et al.*, 2005b]. The model performed generally well but has a tendency to underestimate surface BC concentrations and columnar absorption. The budget for the BC emitted from different world regions is given in Table 1. The global annual mean residence time of 5.3 days is shorter than our previous estimate of 7.2 days [*Reddy and Boucher*, 2004]. As mentioned above, the present study does not include open biomass burning, which is located in dry regions and results in longer residence times. The atmospheric residence time of BC ranges from 4 to 7 days depending on the region of emissions. The longer residence time is for the drier regions or regions with a dry season (west and central Asia and Africa), while the shorter residence time is for wetter regions (Europe, North America, and oceanic regions).

[7] East and South Asia account for more than 50% of global energy related BC emissions. In their respective regions China and India account for most of the atmospheric burden. These emissions are from the transport sector and from biofuels which suffer from an inefficient combustion [*Reddy and Venkataraman*, 2002a, 2002b; *Streets et al.*, 2004]. In addition domestic coal combustion in East Asia accounts for a considerable fraction of BC emissions in this

Table 1. Global Mean Annual Budget of BC for Different Geographical Regions

Region	Emissions, Tg yr^{-1}	Contribution of Biofuels	Global Dry Dep., Tg yr^{-1}	Global Wet Dep., Tg yr^{-1}	Burden ×100, Tg	Residence[a] Time, days	Contribution to Surface Deposition North to 60°N and South to 60°S
SAM	0.314 (6%)[b]	5%[c] (25%)[d]	0.049	0.265	0.452 (6.5)%[e]	5.28	1%
NAM	0.522 (11%)	6% (20%)	0.092	0.430	0.697 (10.0%)	4.80	11%
AFR	0.483 (10%)	21% (72%)	0.088	0.395	0.947 (13.6%)	7.16	1%
EUR	0.602 (12%)	5% (13%)	0.128	0.474	0.823 (11.8%)	5.01	63%
WCA	0.157 (3%)	1% (11%)	0.040	0.117	0.312 (4.5%)	7.29	2%
SAS	0.602 (13%)	25% (68%)	0.120	0.483	1.086 (15.6%)	6.59	2%
EAS	2.038 (43%)	36% (29%)	0.333	1.708	2.565 (36.8%)	4.60	17%
AUP	0.036 (1%)	<1% (14%)	0.006	0.030	4.062 (0.7%)	4.62	1%
OCE	0.036 (1%)	– (–)	0.007	0.029	0.042 (0.6%)	4.24	2%
Global	4.791	34%[f]	0.860	3.931	6.970	5.32	–

[a]Residence time is estimated as the ratio of burden to the sources (or sinks) of BC.
[b]Percent contribution of each region to global emissions.
[c]Percent contribution of each region to global BC emissions from biofuels.
[d]Percent contribution of biofuels to energy-related BC emissions in the respective regions.
[e]Percent contribution to global burden.
[f]Percent contribution of biofuels to global energy-related BC emissions.

Table 2. Percentage Contribution of Each Region to the BC Load Over the World Regions

	Receptor Region								
Source Region	SAM	NAM	AFR	EUR	WCA	SAS	EAS	AUP	OCE
SAM	88.3	1.0	1.8	0.2	0.5	0.2	0.2	9.4	7.9
NAM	1.5	70.1	3.1	4.7	3.9	0.7	1.1	0.6	11.2
AFR	5.0	1.6	63.6	2.8	7.6	2.0	0.9	14.3	12.6
EUR	0.3	2.1	12.4	76.2	27.5	1.8	5.6	0.2	6.4
WCA	0.1	0.6	6.5	7.0	38.2	4.5	1.4	0.2	2.1
SAS	0.6	6.2	6.9	3.0	12.5	84.7	9.1	2.2	15.4
EAS	3.6	17.6	5.3	5.5	9.5	5.9	81.4	32.5	42.5
AUP	0.2	0.0	0.0	0.0	0.0	0.0	0.0	39.3	1.0
OCE	0.5	0.6	0.4	0.5	0.3	0.1	0.2	1.4	1.0

region. The contribution of different regions to the global burden follows the corresponding contributions to emissions. The largest contribution to the burden is from East Asia (37%) followed by South Asia (16%), Africa (14%), Europe (12%), North America (10%), South America (7%), West and Central Asia (4%), Australia (<1%) and Oceanic regions (<1%). The relatively longer atmospheric residence time for African emissions results in a contribution of 14% to the global BC burden, compared to a contribution of 10% to emissions.

[8] On the global scale biofuels account for about 34% of total BC emissions. Biofuels are the predominant source of BC over Africa (72%) and South Asia (68%). They also contribute moderately to BC emissions over South America (25%) and East Asia (29%). The respective contributions of emissions from fossil fuels and biofuels translate into similar contributions to the global atmospheric burden.

3.2. Inter-Regional Transport

[9] The BC atmospheric residence time of 4 to 7 days results in transport of emissions from one region of the world to another. Except for WCA and AUP, emissions from a particular continental region account for the majority of the atmospheric burden over that region (Table 2). Over North America, emissions from East and South Asia contribute to 18% and 6% of the total BC burden, respectively. In contrast, North American emissions account for only 5% of BC over Europe. Over South and East Asia, the local emissions account for more than 80% of BC burden with complements from other regions. The estimated BC burden over Australia is smaller by a factor 3 to 4 compared to other regions. Interestingly BC over Australia is mostly transported from other parts of the World with a contribution of 32%, 14%, and 9% from East Asia, Africa, and South America, respectively. East and South Asia are dominant contributors over the oceanic regions. In the future the relative strengths of emissions and transport between different regions are expected to change.

3.3. Atmospheric Absorption of BC

[10] The total global annual mean DRF at TOA from fossil fuels and biofuels is estimated to be +0.2 Wm^{-2}. Following the atmospheric loadings the largest DRF at TOA by BC is predicted over East and South Asian regions with annual

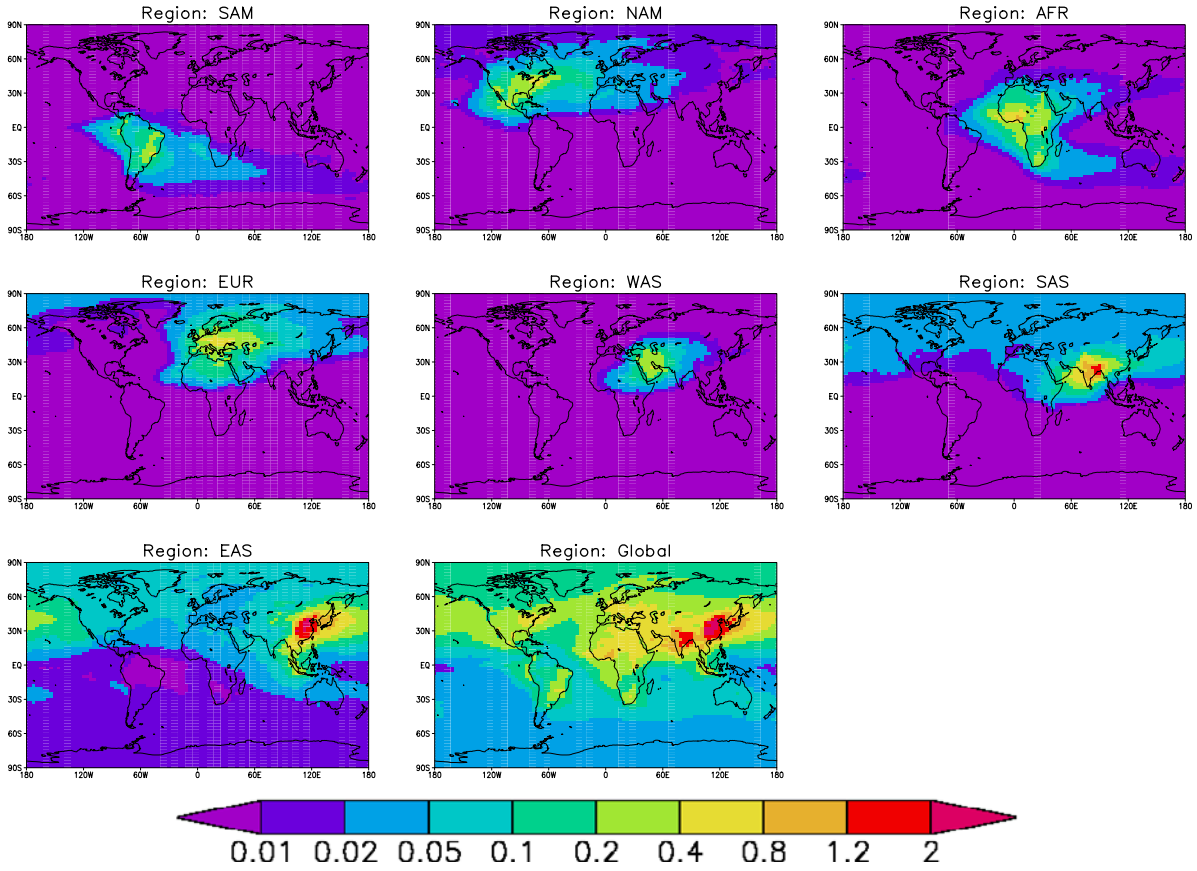

Figure 2. Global distribution of all-sky SW DRF (Wm^{-2}) at top-of-atmosphere due to BC emissions from different regions. DRF from AUP and OCE regions is not shown because it is too small.

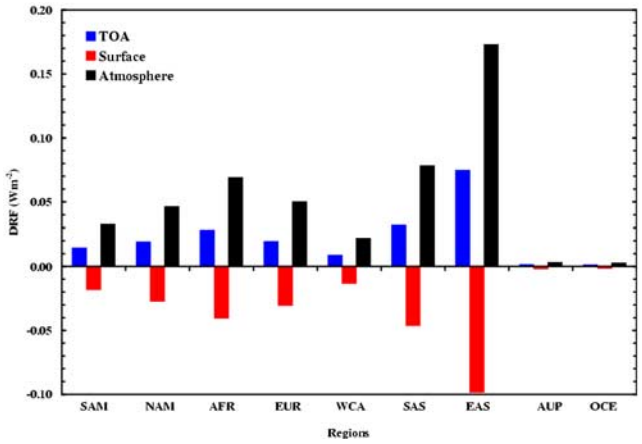

Figure 3. Global annual mean all-sky SW DRF at top-of-atmosphere (left bar), at surface (middle bar), and in the atmosphere (right bar) by BC emissions from different regions.

mean forcings larger than +2 Wm^{-2} locally (Figure 2). One of the striking features is that emissions from East Asia spread all over the Northern Hemisphere (NH) with significant forcing over the Pacific Ocean. The BC emissions are projected to increase over the Asian region [*Streets et al.*, 2004] in the coming decades, which will result in an even larger radiative forcing. The radiative forcing from ship emissions is smaller than +0.005 Wm^{-2} over any part of the world.

[11] The BC forcing efficiency of the present study (1460 W (g BC)$^{-1}$) agrees well with that of *Reddy et al.* [2005b] (1453 W (g BC)$^{-1}$). There are uncertainties in this quantity, with estimates ranging from 700 to 2000 W (g BC)$^{-1}$ [*Schulz et al.*, 2006], due to uncertainties in state of mixing, optical properties and atmospheric radiation transfer. The global annual mean DRF at the surface is −0.3 Wm^{-2} resulting in an atmospheric forcing of +0.5 Wm^{-2}. The global annual mean DRF at surface and TOA follows the emissions from the respective regions (Figure 3). Once again the largest atmospheric forcing is from emissions from East Asia (+0.17 Wm^{-2}) and South Asia (+0.08 Wm^{-2}).

3.4. Global Warming Potentials of BC

[12] We estimate the direct GWP for BC emissions from different regions (Table 1). GWPs are estimated from annual mean values to eliminate seasonal variation in transport, scavenging and radiative forcing efficiency. The GWP for global emissions is estimated to be 480 for a time horizon of 100 years. The present value is somewhat lower than the estimate of 680 by *Bond and Sun* [2005]. The GWP for BC emissions from different regions ranges from 374 to 677. The differences in GWP for different regions arise largely from different BC atmospheric residence time and amount of insolation.

[13] To assess the regional contributions to the climate impacts of BC through change in snow and ice albedo, we also estimate the contribution of different regions to BC deposition north to 60°N and south to 60°S. Previous studies suggest that radiative forcing from change in snow/ice albedo could be +0.15 Wm^{-2}, with a reported range of +0.04 to +0.24 Wm^{-2} [*Hansen and Nazarenko*, 2004; *Hansen et al.*, 2005; *Jacobson*, 2004]. This decreased surface albedo may accelerate the melting of the snow [*Hansen and Nazarenko*, 2004]. The total deposition of BC over high-latitude regions is 0.20 Tg yr^{-1} (0.18 and 0.02 Tg yr^{-1} from wet and dry deposition, respectively), or about 4% of global BC deposition. As expected, 98% of this deposition occurs over the Northern Hemisphere (NH). The deposition of BC north to 60°N ranges between 5 and 10 mg m^{-2} yr^{-1}. The largest contribution to deposition at high latitudes is from Europe (63%), followed by East Asia (17%) and North America (11%). All other regions together account for the remaining 9% of total deposition. The proximity of Europe and North America to the snow/ice covered areas result in a more effective contribution to surface concentration and surface deposition at high latitudes per unit of emission. However the contribution of Europe to the DRF at high latitudes is only modest at about 20% (Figure 2). This is because at high latitudes the BC from European emissions is preferentially found close to the surface where it contributes to surface deposition but little to the DRF because of an important cloud cover. We observe that, at high latitudes, the regional contributions to the total deposition follow the contributions to surface concentrations, whereas the regional contributions to the DRF follow the contributions to the column burden.

[14] Here we make an attempt to estimate the indirect GWP due to the snow albedo effect of BC assuming a value of +0.1 Wm^{-2} for the corresponding RF. The BC snow albedo RF for different regions is apportioned according to their contribution to BC deposition at high latitudes. The global indirect GWP for BC is estimated to be 281 or about half of the direct GWP. However there are large regional variations. The indirect GWP for European emissions is largest (1210) due to a very large contribution to BC deposition (63%) at high latitudes. We are aware that these estimates are very uncertain, but they suggest that it would be more efficient to mitigate BC emissions over Europe as compared to other regions. These results need to be confirmed by a more detailed and validated model of the BC effect on snow.

[15] One should also be aware of the limitations of the GWP concept for very short-lived species. The concept of GWP does not factor in the fact that a RF exerted at the very beginning of the time horizon (e.g. 100 years) is less effective in producing a temperature change at the end of the time horizon as compared to a RF which decays more slowly with time (such as the CO_2 RF following a pulse emission). *Shine et al.* [2005] introduced the concept of Global Temperature change Potential (GTP). A GTP for pulse emission is defined as the global mean temperature change for a time horizon of 100 years after a pulse emission of 1 kg ratioed to the same quantity for a 1 kg of CO_2 pulse emission. It can be shown that the 100 year GTP for a very short-lived species is typically 5 to 7 times smaller than its corresponding GWP. We presented our results in terms of GWP because the concept is more established than that of GTP. Considering GTPs rather than GWPs would not change the present conclusions, which calls for a more robust analysis of the climate benefit of BC mitigation.

4. Conclusions

[16] We have simulated the atmospheric cycle of energy-related BC from different regions and estimated the regional

contributions to the global BC burdens and DRF. The largest contribution to the global annual mean BC burden is from East Asia (37%) followed by South Asia (16%), Africa (14%), Europe (12%), North America (10%), South America (7%), West and Central Asia (4%), Australia (<1%) and Oceanic regions (<1%). The regional contributions to atmospheric burden largely follows emissions from the respective regions. The atmospheric residence time for BC emissions from different continental regions varies between 4.6 to 7.3 days. A fraction of BC emissions from South and East Asia reaches North America and account more than 20% of the total burden there. Europe is the largest contributor to the BC deposition at high latitudes although the contribution from North America may be underestimated because our model underestimates BC concentration in this region. The global annual mean DRF is estimated at +0.20 Wm^{-2}. The regional contributions to global mean forcing closely follow respective contributions to annual mean burden. To address the benefits of controlling BC emissions in the context of climate change mitigation, we also estimated the direct and indirect GWP of regional BC emissions. The global mean direct and indirect GWP of BC are estimated at 480 and 281, respectively. There are significant variations in GWPs for BC emissions from different regions, especially for the indirect GWP. Our results suggest that it would be more efficient to control BC emissions from Europe to mitigate climate change. Additional research is needed to make these results more robust.

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