

Interactive comment on “Quantifying immediate radiative forcing by black carbon and organic matter with the Specific Forcing Pulse” by T. C. Bond et al.

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Black carbon (BC) is the focus of numerous national and international studies, largely because of its immense potential for mitigating climate change. The important point to note is that BC impacts both global and regional climate change (Ramanathan and Carmichael, 2008 and numerous references therein). One major difficulty faced by scientists and decision makers alike in assessing the importance of BC is the large difference between the life time of black carbon (days to weeks) and that of the major

C6227

greenhouse gas, CO₂ (decades to centuries to thousands of years). Bond et al (hereafter referred to as B2010), are making a fresh new attempt at defining proper metrics for evaluating the mitigating potential of BC. Reviewer 1 of the paper has provided comments on their new approach and terminology (see the ACPD site) and we will instead focus on their recommended estimate for the BC forcing.

B2010's estimate is based on the NCAR general circulation model (GCM) (version CAM3). They have revised the model and obtained a BC forcing of 0.51 Wm⁻² for 2000 BC level (we denote this by BCT for BC total); from which they derive an anthropogenic (since 1750) BC forcing (denoted as BCA for BC anthropogenic) of 0.43 Wm⁻² by subtracting an assumed forcing of 0.08 Wm⁻² for the pre-industrial forcing. The estimate for BCA includes 0.38 Wm⁻² due to atmospheric solar absorption and 0.05 Wm⁻² due to increased absorption by the cryosphere (resulting from darkening of snow and ice by BC).

There are two major issues which we would like to raise about B2010

1) B2010 do not give any quantitative uncertainty estimates for the final forcing values. They somewhat boldly give a single value in the abstract as well as in the text. They do cite some narrow range of values from model studies but these are not to be confused with true uncertainties. For example, the starting point of all GCM studies of BC forcing is the emission inventory (usually Bond et al's, 2007) but as shown in the Bond et al (2007) paper, the global (and regional) emission inventory is subject to an uncertainty as high as a factor of 14 (figure shown later). We would like to urge B2010, to set a new trend in GCM studies of BC forcing, and quantify the true uncertainties by factoring uncertainties in the model input parameters. We are aware this is not a straight forward task, but it is not an impossible one either. 2) B2010 ignores three well understood and non-controversial (at least in an experimental sense) direct positive forcing effects of BC and organic carbon (OC). We urge them to either include these in their BC/OC forcing number (BCT and BCA) or give the bias in their final value due to the neglect of these three direct forcing effects.

C6228

Figure 1, compares anthropogenic forcing values published by major modeling groups. Also shown in the figure are two top-down empirically based approaches (2 right-most bars) that are constrained by satellite and ground network. The forcing results include only atmospheric solar absorption and do not include the cryospheric absorption. The models developed at Caltech, GFDL, Hadley center and Stanford converge around 0.55 Wm^{-2} (range is 0.53 to 0.55 Wm^{-2}) compared with the empirically constrained values of 0.75 to 0.85 Wm^{-2} (see Table 1 for clarification). The empirical values have an uncertainty of at least $\pm 50\%$ (Ramanathan and Carmichael, 2008). The Ramanathan and Carmichael's value is based on the Chung et al (2005) top-down observational assimilation study.

Most, if not all, of the models shown in Figure 1 use the BC emission inventory of Bond et al (2007). The uncertainty in the emission inventory (for fossil-fuel and bio-fuel emission) has also been quantified by Bond et al (2007) and reproduced in Figure 2. For the year 2000, the uncertainty range is 1000 to 14000 Gg/Yr (for just the fossil fuel and bio fuel emissions of BC) and their recommended central (see solid curve in Figure 2) value (which is the value used by GCMs) is about 4000 Gg/Yr (rounded off). It is tempting to claim that such a large uncertainty is not possible. But the model simulated surface concentration differs from the observations substantially (Koch et al, 2009). For example, a recent GFDL study (Ganguly et al, 2009) which compares observations at the surface with their model simulations reveal that the model BC concentrations are lower by factors ranging from 2 to 10 over S Asia. Large negative biases in simulated BC concentrations in other regions of Asia have also been shown by Koch et al (2009), for a group of GCMs referred to as AEROCOM GCMs. Errors in the emission should translate into errors in the forcing values. It is likely that the central value of emission in Bond et al (2007) as well as the simulated BC forcing in B2010 may be a severe underestimate, at least over Asia (source of about 50% of the BC emission).

Given this 14-fold uncertainty in the emission, it is surprising (and somewhat reassuring) that the forcing obtained from the empirical approaches (Figure 1) is within a

C6229

factor of 2 of the B2010 value, with the B2010 value a factor of two smaller. Similar factor of two lower bias appears (Lawrence and Lelieveld, 2010) in the simulation of other pollutants (such as CO) between the bottom-up approaches of GCMs and the top-down approach of empirically based studies. Hence, instead of treating the empirical approach as unsuitable for evaluating BC forcing as suggested by B2010, it may be prudent to bracket the unacceptably large uncertainties in the emission inventory, by using the empirical values. Accordingly, we propose that the value of 0.55 Wm^{-2} (for BCA_Atmospheric Solar absorption) adopted from the GFDL/Hadley/Caltech/Stanford models be adopted as the central value for the anthropogenic atmospheric solar forcing for BC with a 90% range of 0.2 to 0.9 Wm^{-2} . In summary we have,

BCA direct forcing by atmosphere solar absorption [BCA_DF_A(S)] = 0.55 (90% interval of 0.2 to 0.9) Wm^{-2} .

BC direct forcing due to increased absorption by the cryosphere [BC_DF_A(C)] = 0.05 (90% interval of 0.01 to 0.1) Wm^{-2} .

With respect to issue #2, the B2010 study ignored the following well understood warming effects of BC and OC.

Greenhouse Effect [BC+OC_DF_A(GH)]: BC as well as other aerosols, absorb and emit in the infrared and thus has a greenhouse effect (Lubin and Simpson, 1994; Satheesh and Lubin, 2003; Jacobson, 2001). The global mean value has been estimated by at least only one study (Jacobson, 2001) to be around 0.01 Wm^{-2} for just BC and that for BC+OC is $\leq 0.04 \text{ Wm}^{-2}$.

Inclusion in Cloud drops and crystals [BC_DF_A(ICD)]: BC is removed by wet removal (water and ice clouds) and inclusion of BC in cloud drops and crystals enhances absorption (Chylek et al, 1996 and Jacobson, 2006). Chylek et al arrive at a theoretical upper limit of 1 Wm^{-2} , while from Jacobson's (2010) GCM study we obtain about 0.15 Wm^{-2} (Jacobson, private communication).

C6230

Brown Carbon atmospheric solar absorption: Another non-controversial effect, also ignored in the B2010 study, is the absorption by the so-called brown carbon (Andreae and Glencser, 2006; Magi, 2009; Schnaiter et al, 2005; Alexander et al, 2008; Kirchstetter et al, 2004). There are numerous experimental studies that have established the importance of this absorption both in the laboratory and in the field, based on which we estimate it to be $\geq 0.1 W m^{-2}$. The empirical studies (e.g. Ramanathan and Carmichael, 2008) implicitly include this as part of BC; whereas in GCMs this should be included as part of organics. Thus inclusion of this effect in GCMs will reduce the cooling attributed to the direct and the indirect effects of OC.

B2010 should acknowledge the neglect of these non-controversial effects and point out that their study includes only two out of the five positive direct forcing components.

However, the direct forcing is only one part of the story. BC, after some aging, can also be effective nuclei for cloud drops and thus enhance low cloud albedo and cool the climate (Chen et al 2010). This is referred to as the indirect effect. At the same time, BC's atmospheric warming is so large that it can decrease the boundary layer relative humidity and evaporate low clouds. This effect, referred to as the semi-direct was modeled by Ackerman et al (2000) in cloud-scale model with INDOEX data (Ramanathan et al, 2001). Thus there are two competing effects on the forcing due to BC-Clouds interactions.

The Chen et al (2010) study, referred to by B2010, includes only one of the five direct (atmospheric solar only) forcing and shows that the indirect effect can effectively overcome the direct forcing and even make the net effect into slight cooling. The Jacobson (2010) study on the other hand, includes all of the five direct effects, the indirect effect and the semi-direct effect, and concludes BC is the second largest warmer of climate, next to CO₂.

Given the extreme complexity of the aerosol-BC-Cloud interaction issue, it is important to consider the findings of the empirical studies. Fortunately there are numerous

C6231

empirical studies using satellite and surface observations that examine the semi-direct and indirect effects.

Surface Dimming and Brightening Observations: The studies which use surface solar radiation data, exploit the fact that Europe, USA and China have witnessed drastic changes in emissions of BC, SO₂ and other pollutants during the twentieth century. These regions also maintained an excellent network of surface solar radiometers that monitored dimming and brightening. The regions examined for the indirect effects are Europe and China. Europe witnessed dimming trends from 1950s to 1980s when the emissions of BC and SO₂ increased significantly (Ruckstuhl et al, 2010). On the other hand, the period from 1980 to (the last year included in the analysis) 2005 witnessed brightening and about 50% or more decrease in both the BC and SO₂ emissions (Junker and Liousse, 2008 and Smith et al, 2010). Analyses (Ruckstuhl et al, 2010) of cloudiness data along with surface solar radiation data revealed that the large changes in surface solar radiation can be accounted for by the aerosol direct effect while for the aerosol indirect effect, they concluded (quoted from Ruckstuhl et al, 2010) *the first aerosol indirect effect makes little contribution to surface solar radiation changes over Europe*. China, where both BC and SO₂ increased by factors ranging from 5 to 10 from 1950s to early 2000s (Junker and Liousse, 2008 and Smith et al, 2010), witnessed a large solar dimming (Liang and Xia, 2005; Norris and Wild, 2007) most of which was contained in clear sky fluxes. In fact, in China, the large increases in BC and SO₂ emissions were accompanied by decrease in cloudiness (Liang and Xia; and Qian et al, 2006). Thus either the aerosol (BC and SO₂) indirect effect was over-compensated by the semi-direct effect of BCs or both effects were negligible due to other factors related to climate changes. More importantly, IPCC GCMs were unable to simulate the large trends in surface solar radiation (Ruckstuhl and Norris, 2009) in clear as well as cloudy skies.

Satellite Studies: The satellite studies (e.g. Koren et al, 2004; Kaufman and Koren, 2006) contrast polluted regions and episodes with less polluted regions to deduce the

C6232

effect of aerosol-cloud interactions. The satellite study that focused on the Amazon (Koren et al, 2004), a huge source of biomass BC and OC, shows that the cloud fraction reduces to near zero when smoke optical depth exceeds 1.2. Many GCM studies (e.g, Koch et al 2009) report that biomass BC+OC have a net negative direct forcing. The Koren et al study also obtains a negative direct forcing, but shows that the semi-direct effect of BC and OC in the smoke is so large that the net effect (direct plus semi-direct effect) of biomass smoke is positive and large.

Clearly the issue of BC interaction with clouds is far from settled and it may be premature to suggest that the BC-cloud changes will result in a negative forcing as implied in B2010. If any, available empirical data point in the other direction, i.e, the BC-cloud interactions over land regions may be positive.

Thus far we had focused on the global mean forcing of BC. Independent of its global mean forcing, numerous studies (Ramanathan et al, 2001 and also see the references in Ramanathan and Carmichael, 2008; Flanner et al, 2009) have shown through direct observations and modeling of the radiative forcing that regionally, BC increases the radiative heating of the atmosphere by 10 to 20 Wm^{-2} (seasonally and or annually averaged values) and leads to dimming at the surface by similar amounts. The most recent example of such studies is by Panicker et al (2010). Such a drastic vertical redistribution of solar radiation will significantly perturb the convective forcing of the system. In addition BC and OC alter the land-Ocean contrast as well as north-south contrast in the absorption of solar radiation by the system (Ramanathan et al, 2001) which will perturb the general circulation of the ocean-atmosphere system and impact the monsoon and large scale precipitation in the tropics. The most recent example of tens of such studies is the one by Ming et al (2010). In addition, BC also has a large impact on the retreat of the arctic sea-ice (Shindell and Falvugi, 2009; Jacobson 2010 for recent examples of such studies) and the Himalayan snow packs and glaciers (Ramanathan et al, 2007; Flanner et al, 2009; Xu et al, 2009).

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C6233

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C6234

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C6235

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C6236

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C6237

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Interactive comment on *Atmos. Chem. Phys. Discuss.*, 10, 15713, 2010.

C6238

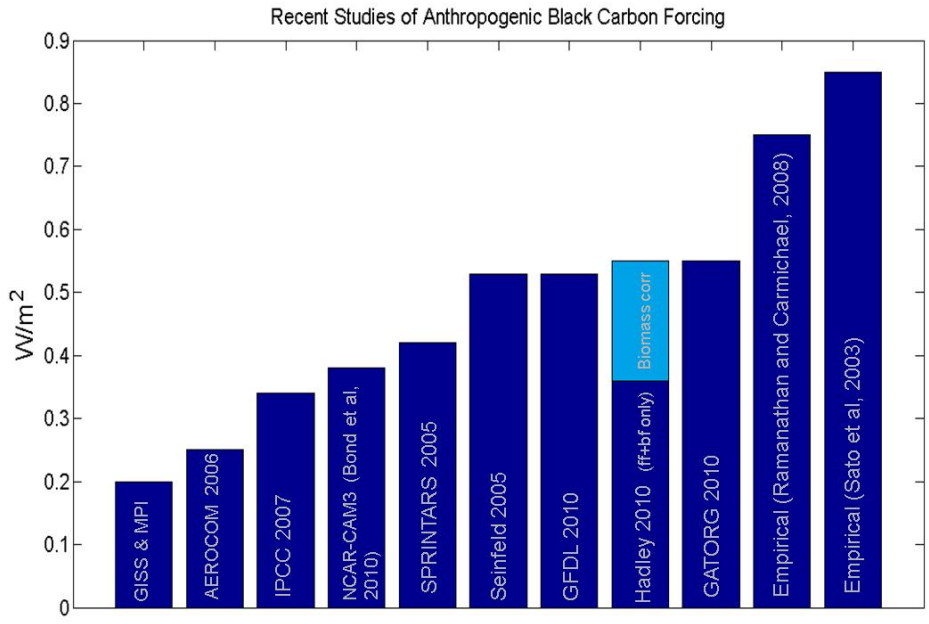


Fig. 1. Comparison of BC-Direct forcings.

C6239

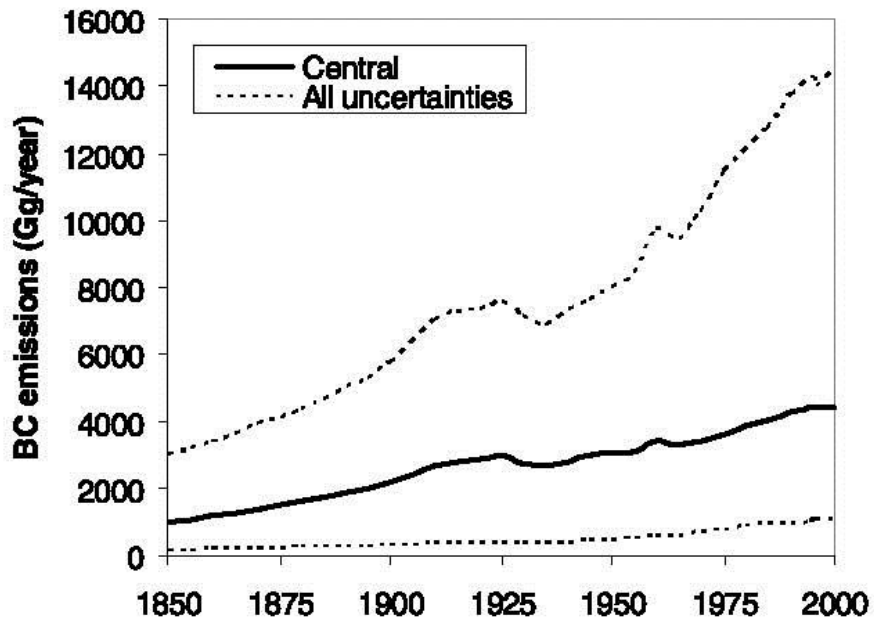


Fig. 2. Uncertainty of BC Emission Inventory. Reproduced from Bond et al (2007)

C6240

Citation in the Figure 1	Direct RF (W/m ²)	Source
GFDL, 2010	0.53	Ming et al, 2010
Hadley, 2010	0.36 (fossil+bio-fuel) 0.55 (adjusted for biomass)	Andrews et al, 2010. Biomass BC forcing is not reported in this study. Based on emissions, we added biomass BC is about 35% of total.
GATORG, 2010	0.55	Jacobson, 2010
IPCC, 2007	0.34	Forster et al, 2007
SPRINTARS 2005	0.42	Takemura 2005
Seinfeld, 2005	0.53	Liao & Seinfeld 2005
Aerocom 2006	0.25	Shultz et al, 2006
Empirical (RC) 2008	0.75	Ramanathan & Carmichael 2008*. <i>The 0.9 Wm⁻² in this paper has been reduced to 0.75 Wm⁻² to account for pre-industrial BC forcing, and Brown carbon forcing</i>
GISS & MPI	0.2 to 0.22	The GISS and MPI Hamburg values are taken from Shultz et al for these values
NCAR-CAM3-modified	0.38	Bond et al 2010
Empirical (Sato et al 2003)	0.85	Sato et al 2003. <i>The 1 Wm⁻² in this paper has been reduced to 0.85 Wm⁻² to account for pre-industrial BC forcing, and Brown carbon forcing</i>

*This differs from the published value of 0.9 Wm⁻² in Ramanathan and Carmichael (2008) because the 0.9 Wm⁻² is for BCT, whereas the model values are for pre-industrial to present. In addition, the Ramanathan and Carmichael value implicitly includes brown carbon, whereas model studies are only for BC.

Fig. 3. Supporting Table for Figure 1