Black carbon emission metric values reduced and constrained by observations

Gunnar Myhre¹, Bjørn H. Samset¹, Øivind Hodnebrog¹

¹Center for International Climate and Environmental Research—Oslo (CICERO), Oslo, Norway

The present day climate impact of black carbon (BC) remains poorly constrained. For climate mitigation, however, its net climate effect per emission unit – or BC climate metrics – are more relevant. Recent advances, mainly observationally constrained estimates of the atmospheric lifetime of BC and the inclusion of semi-direct aerosol effects, act to reduce, and better constrain, BC metric values. While reductions in BC emissions will have health benefits, a lowered, more certain climate impact per emission unit makes BC less attractive as a climate policy option.

Mitigation of black carbon (BC) is a frequently discussed policy option, in the research community¹-³, beyond scientists⁴,⁵, and among policymakers. The debate has been driven by high global mean estimates of industrial era climate effect of BC¹, large estimated mitigation potential⁶, and high metric values relative to other compounds¹,⁷.

Metric values such as Global Warming Potential (GWP) and Global Temperature change Potential (GTP)⁷ are derived from calculations of radiative forcing (RF) (a measure of the Earth’s radiation perturbation), combined with lifecycle modelling of the compound in question. GWP, which was adopted in the Kyoto protocol for several well-mixed greenhouse gases, depends on RF per unit emission, the lifetime of the compound, the time horizon, and the reference gas. Several of these factors are associated with value-related judgements⁷. We focus here on the radiative efficiency (RE) – defined as the RF per emitted compound - of BC, which is essential for all metric discussions related to this compound.

Based on recently published literature, we find that, emission metric dependent RE values of BC are in remarkably good agreement. The values are then substantially constrained, through accounting for recent observational evidence. Based on multi-model information and available scientific results, we derive new best estimates and updated uncertainty ranges. The RE values we derive here are directly applicable to discussion of BC mitigation policy.

Estimates for BC
BC impacts the global energy balance most strongly through the direct aerosol effect, often quantified through aerosol life cycle modelling combined with atmospheric radiative transfer simulations\(^1\,^8\). However, estimates for emissions of BC from fossil fuel and biofuel differ substantially, leading to a poorly constrained direct radiative effect. The latest multi-model experiment within AeroCom\(^8\) reports a central value of 0.23 W m\(^{-2}\) over the industrial era, while a recent estimate from a larger BC community\(^1\) reported 0.51 W m\(^{-2}\). The latter study is also based on multi-model, industrial era simulations, from an earlier set of AeroCom simulations\(^9\), but with results strongly modified based on observations.

Nevertheless, the BC RE differs by only around 10% between these studies, demonstrating that their main difference comes from BC emissions (see Supplementary Information). Several recent studies indicate underestimated BC emissions or missing sources\(^{10-12}\), and new emission data in general point towards higher emissions\(^{13}\). Also, the general model underestimation of surface BC concentrations may be partly explained by coarse model and emission resolution\(^{14}\).

Emissions of BC are, hence, one of the major uncertainties in the RF due to BC. RE avoids this uncertainty, to a large extent. Its residual dependency on emissions is because of some degree of sensitivity to BC emission location, due to its short lifetime\(^{15}\).

**All black carbon climate effects must be considered**

The direct aerosol effect of BC is mainly absorbing, combined with a minor degree of scattering of solar radiation. In addition, BC may also change the albedo of snow and ice, change the stability of the atmosphere and thus alter clouds (semi-direct effect), and alter the internal properties of water and ice clouds (indirect effect)\(^{1,16,17}\). The uncertainties associated with these effects are poorly quantified, and the number of studies investigating each effect varies\(^{17}\). They also act quite differently on the climate, and are all dependent on the geographical and altitudinal distribution of BC. This can be exemplified by the direct effect of BC which is strongly dependent on the vertical profile of BC\(^{18,19}\), with an order of magnitude stronger RF in the upper troposphere relative to BC close to the surface\(^{18}\).

**Recent improvements in understanding of BC**

Aircraft measurements over the last few years have revealed that models tend to overestimate BC at high altitudes\(^{20}\). This has been found to place strong constraints on the BC lifetime\(^{21,22}\). While this overestimation of modelled BC in the upper troposphere is mainly quantified over the remote Pacific, a strong vertical gradient of BC is also observed over urban areas\(^{23}\). Overestimation of the total aerosol abundance is further seen in global aerosol models relative to CALIPSO satellite data, in the
middle and upper troposphere\textsuperscript{24}. Observations further indicate that BC decreases more with altitude than the total aerosol abundance\textsuperscript{25-27}.

The overestimation of upper tropospheric BC abundance is in a region with the strongest direct radiative effect by abundance of BC, as mentioned above. A recent study shows that shorter lifetime of BC reduces the RF of BC, partly due to the high radiative effect of BC aloft, but mainly due to much lower total BC abundance\textsuperscript{28}.

The positive RE of the direct aerosol effect of BC strengthens with altitude. The semi-direct aerosol effect is also found to have this behaviour, but with opposite sign, yielding a more negative RE with increasing altitude\textsuperscript{28}. This has been shown by various modelling tools\textsuperscript{29} and across different climate models\textsuperscript{30,31}. Therefore, the direct effect and the semi-direct effect are individually strongly dependent on the BC vertical profile, but the net of these two effects has a weaker altitudinal dependency.

**Updated metric values for BC**

To gauge the impact of an observationally constrained reduced BC lifetime, and the addition of the semi-direct effect, on the total BC forcing metric, we summarize and combine estimates from recent literature. Figure 1a shows BC RE values and 5-95\% uncertainty ranges for the direct aerosol effect (DAE), the semi-direct aerosol effect (SDAE), the albedo effect, BC impact on ice/mixed phase clouds, and their total. Supplementary Tables 1 and 2 show the numbers and references, together with updated estimates based on observational constraints presented in this study. The separate BC climate effects were combined assuming uncorrelated errors. Figure 1b shows the BC RE range relative to the DAE metric alone, unadjusted and when combined with the other effects and a reduced lifetime.

The new, observationally driven estimate for total BC RE, differs from previous estimates in two main ways; a reduced best estimate, as well as a narrower uncertainty range. The absolute reduction in the 5-95\% range based on the total PDF is close to 50\% between the two estimates, whereas the best estimate is 30-35\% lower. The reduction in the best estimate comes mainly from the direct aerosol effect, which we estimate to be 50\% lower than in previous multi-model studies when constrained to the observed BC vertical profile. Note that the new estimate for the direct aerosol effect has a narrower range both in absolute and relative terms. Together with changes to the semi-direct effect, this contributes strongly to the reduced uncertainty range. Smaller observed BC abundance in upper troposphere than in models leads to our slightly reduced impact of BC on mixed and ice clouds.
Although Figure 1a shows that the total BC metric and that solely from direct aerosol effect are relatively similar for the best estimate, albeit with the former having larger uncertainty, it is important to deal with comprehensive and consistent BC metrics. Figure 1b shows that including a comprehensive set of BC effects, and constraining BC lifetime to observations, yields a 40% lower best estimate than only the direct aerosol effect in earlier standard values. Further, a strong reduction can also been seen for the uncertainty range in Figure 1b for the observationally constrained BC metric. It is important to note that climate model simulations of BC will explicitly include the semi-direct effect, thus it should clearly be taken into account in RE of BC for mitigation purposes, whereas it has mostly been neglected in previous BC mitigation studies. The best estimate BC RE value of around 30 W m\(^{-2}\) (Pg yr\(^{-1}\))\(^1\) presented here is around half of the value presented in Bond et al.\(^1\).

**Policy implication**

Previous BC estimates applicable to emission metrics have been highly uncertain, substantially more so than equivalent metrics for well-mixed greenhouse gases. The new estimate provided here has a substantially reduced uncertainty range. At the same time, the reduced magnitude of the best estimate makes BC somewhat less relevant in mitigation efforts. Further reduction in the uncertainty range for BC can be achieved by further observations of BC vertical profiles and multi-model experiments. We note that emissions of BC often co-occur with other species that mainly have a cooling effect. This must be taken into account when using BC in mitigation purposes \(^1\). In the overall judgement of BC for mitigation purposes, time horizons and the type of metric also need to be carefully chosen \(^7,32,33\). Also, mitigation of BC emissions definitely carries a health benefit in terms of improved air quality, regardless of its climate metric value.
Figure 1: BC forcing metrics (a) given for direct aerosol effect (DAE), semi-direct aerosol effect (SDAE), albedo effect, impact on ice/mixed phase clouds and total of these effect. Hatched bars show estimates from publications assuming standard BC lifetime, open bars show values derived from assuming a reduced lifetime. Best estimates, uncertainty ranges and underlying references are shown in the Supplementary Material. The relative BC forcing metric (b) shows values and ranges of the unadjusted DAE metric, and when combined with the other effects and a reduced lifetime (adjusted), relative to the metric for standard DAE alone.


