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Can Reducing Black Carbon Emissions Counteract Global Warming?

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Field measurements and model results have recently shown that aerosols may have important climatic impacts. One line of inquiry has investigated whether reducing climate-warming soot or black carbon aerosol emissions can form a viable component of mitigating global warming. We review and acknowledge scientific arguments against considering aerosols and greenhouse gases in a common framework, including the differences in the physical mechanisms of climate change and relevant time scales. We argue that such a joint consideration is consistent with the language of the United Nations Framework Convention on Climate Change. We synthesize results from published climate-modeling studies to obtain a global warming potential for black carbon relative to that of CO_2 (680 on a 100 year basis). This calculation enables a discussion of cost-effectiveness for mitigating the largest sources of black carbon. We find that many emission reductions are either expensive or difficult to enact when compared with greenhouse gases, particularly in Annex I countries. Finally, we propose a role for black carbon in climate mitigation strategies that is consistent with the apparently conflicting arguments raised during our discussion. Addressing these emissions is a promising way to reduce climatic interference primarily for nations that have not yet agreed to address greenhouse gas emissions and provides the potential for a parallel climate agreement.

Introduction: The Challenger

Imagine that carbon dioxide, which plays a role in climate warming, had an accomplice, a different substance that behaved similarly. Now imagine that this companion was not intimately related with comfort and productivity as is CO_2, but rather an unnecessary byproduct. Some might be tempted to target the new offender and perhaps to slow the uncomfortable task of reducing CO_2 emissions. Black carbon (BC), which is commonly called soot, is such a substance. While all carbon-based fuels produce CO_2, only poor combustion produces BC, which absorbs visible light, transfers the energy to the atmosphere, and prevents sunlight from reaching the ground. Climatic effects are typically compared in terms of top-of-atmosphere (TOA), globally averaged changes in the radiative balance, otherwise known as radiative forcing. On that basis, BC is the second or third largest individual warming agent, following carbon dioxide and perhaps methane (*1*, *2*). Reducing its emissions is also attractive because BC and other aerosols have adverse impacts on health and regional air quality.

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The climatic impacts of BC are not recent discoveries. It has been known for over 30 years that aerosols affect the Earth's radiative balance: reflective particles (such as sulfates) have a cooling effect, and light-absorbing particles (such as BC) warm the system (*3*). However, the role of BC in the Earth–atmosphere system has recently been emphasized by field measurements (*4*) and model results (e.g., ref *5*). Recent literature suggests that BC may have a place in climate-change mitigation (*6*, *7*) or in choosing technologies to minimize climatic impacts (*8*).

Once both BC and greenhouse gases (GHGs) are considered agents of positive climate forcing, an obvious question arises: could mitigation costs be limited by using BC reductions in place of some GHG reductions? Lessening emissions of all species that have climatic effects is the best way to reduce human impacts and can be the only long-term solution. Here, we discuss the possibility of including BC reductions in preliminary climate-mitigation measures.

Science: Disparity or Partnership?

Scientific arguments against considering BC as part of a climate-mitigation strategy can be condensed into three issues: (i) the effects of BC are uncertain, (ii) they are unlike those of GHGs, and (iii) many impacts are unquantifiable with the current metric of TOA, globally averaged forcing.

(i) Uncertain: While a consensus exists about GHG impacts on the Earth's radiative balance, a distressing number of uncertainties lingers in quantifying similar effects of BC. Source strength estimates must account for inefficient combustion sources, for which measurements are rare (*9*). Because aerosol concentrations vary widely across both time and space, comparisons between models and measurements must be interpreted with care, and it is difficult to corroborate models and their emission inputs. Processes that remove BC from the atmosphere are not well understood, so its lifetime is uncertain. Estimates of BC mass in identical samples differ depending on the measurement method (*10*). Further, direct measurements of light absorption—the quantity most affecting climate warming—often disagree with predictions based on BC mass. The lack of knowledge limits satisfactory answers to several important questions: what is the current, past, and future source strength of BC? How does it compare to forcing by other gases and aerosols? Could many sources of BC be identified and controlled? If so, what would be the effect of those actions?

(ii) Unlike: The spatial distribution of forcing by BC and GHGs is quite different. Because most BC remains in the atmosphere for a short time as compared to gases, radiative impacts are concentrated around source regions. Compared with the global-average forcing of +2.5 W/m^2 by GHGs, regional forcing by aerosols (including BC) can be 2–3 times greater at TOA and an order of magnitude greater at the surface (*4*). Aerosols are suspected of having other important regional effects: changes in the hydrologic cycle when sunlight cannot reach the surface to evaporate water (*11*), changes in cloud reflectivity (*12*), and persistence (*13, 14*) and shifts in circulation and rainfall due to the patchy distribution of absorbed or reflected energy (*5*, *15*).

(iii) Unquantifiable: TOA-average forcing alone is insufficient for predicting climatic impacts of BC. Adverse impacts of climate change have been listed by the Intergovernmental Panel on Climate Change (IPCC, ref *16*). While some of these effects are linked to TOA-average forcing, other changes such as altered precipitation patterns may occur regardless of the sign or magnitude of TOA forcing and are associated with aerosols. Further, BC is inevitably coemitted with other

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cooling substances such as nonabsorbing carbon, sulfate precursors, or fly ash. The net effect on TOA forcing could be small or even negative, and modeling studies disagree on the sign (*8*, *17*). Even the brown cloud near India, said to absorb more light than expected, had a net negative forcing (*18*). One study estimates that recent changes in China's energy structure decreased emissions of both BC and sulfur; the net result was climate warming (*19*). A scorecard based on reducing positive TOA forcing would have given demerits for these actions.

The United Nations Framework Convention on Climate Change (UNFCCC) is the basis for international climate accords. Unlike the Kyoto Protocol of 1997, the UNFCCC has been ratified by many nations, including the largest greenhouse gas emitters. Although its ultimate objective is to stabilize greenhouse gases, aerosols fall under its definition of sources; their effects may be considered under its definition of climate change; and its guiding principles indicate that measures to mitigate climate change should include aerosol sources for comprehensiveness. All parties to that Convention have committed to mitigating climate change; countries listed in the document's Annex I have made specific commitments to reduce greenhouse gases. (Annex I countries include many of those considered industrialized; that term will be used in the following discussion without intent to judge particular countries' development level.)

The UNFCCC's guidelines call into question the scientific reasons for excluding BC from the climate framework. The effects of BC are uncertain, but within bounded limits, there is no question that BC alters the Earth's radiative balance and participates in the climate change targeted by the UNFCCC. The impacts of aerosols are unlike those of GHGs, but they may qualify as adverse effects of climate change. The effects are as yet unquantifiable by TOA-averaged forcing, but that metric's failure to gauge climate change is not a reason to disregard the species. In fact, because both aerosols and GHGs adversely affect the climate system, the principles outlined in the UNFCCC suggest that both should be addressed. This concept may be controversial and uncomfortable. In communities ranging from atmospheric monitoring to emission reporting to political negotiation, GHGs and aerosols have rarely been considered together. Each is a stranger to the culture of the other, and treating them as partners will require innovation.

Comparability: Time and TOA

Continued GHG emissions represent a commitment to a warmer climate in the future; continued BC emissions entail immediate climatic impacts. Can a common framework assess these dissimilar species? The Kyoto Protocol sets a precedent for equivalence by allowing trading of GHGs based on the global-warming potential (GWP). GWP is defined as the total amount of TOA forcing that is attributable to a given mass of emitted pollutant during a specified time after emission (currently 100 years), relative to the forcing of the same mass of CO_2. Lower-cost mitigation of a climate change may result from this basket treatment of climate-active species (*20*); a scenario that adds BC to the basket might be attractive for this reason.

As a preliminary basis for equivalence, we use the direct GWP of BC, ignoring coemitted species and cloud effects. We choose to exclude the valid concerns of coemitted species, such as organic matter, and effects on cloud droplet size or persistence for several pragmatic reasons, which are discussed next. This analysis is not intended to disregard these issues from future consideration but to identify conclusions that can be supported despite the present scientific uncertainties.

First, a physical meaning can be ascribed to TOA forcing by BC. It is the maximum contribution of the emitted aerosols to global-average warming; the net effect of additional considerations is probably negative forcing. If CO_2-equivalent reductions are not cost-effective for BC alone, then reducing warming will be even more expensive when cooling species and other effects are considered.

Second, some biases offset each other even though they do not cancel: counting only BC overestimates the magnitude of positive TOA forcing by all emitted particles, while TOA forcing underestimates total climate impacts by neglecting changes in cloud properties and the hydrologic cycle. Here, we use the BC-only direct GWP as a preliminary metric that takes advantage of this compensation.

Third, TOA forcing is already accepted for comparing species with different lifetimes. Although TOA forcing does not reflect many of the impacts of interest, neither does the global average temperature. While more comprehensive measures are being considered (*21*), climate simulations need to mature before they agree on the nature and magnitude of impacts other than temperature increase. Again, our goal is to conduct a preliminary assessment with information that is available now.

Fourth, only the lifetime and forcing by a specific mass of BC are required to estimate the GWP. These values contain fewer uncertainties than estimates of total BC emissions and are sufficient to quantify the results of individual actions.

Fifth, although the UNFCCC and other literature recommend constraining the rate of climate change, no currently accepted method allows valuation of that rate. However, the GWP time horizon can be adjusted to reflect the shorter term focus suggested by some studies (*6*, *22*), including an emphasis on near-term rapid climate change, if desired.

Finally, although analyses comparing forcing (*7*) or temperature change (*8*) with emission rates constitute useful thought experiments, the benefit of an individual mitigation measure is the total emission avoided by that action. Costs to reduce emissions in perpetuity cannot be estimated and thus cannot be compared with benefits.

An estimate of the direct GWP for BC alone, ignoring coemitted species and cloud effects, can be derived by examining the published results of global transport models and using these values in the calculation method recommended by IPCC (*23*). Although the uncertainties in these models should not be forgotten, these results represent the scientific community's best current estimate of BC lifetime and direct radiative impact. While models disagree with regard to simulated temperature changes, differing values of TOA forcing per mass (normalized forcing) can largely be explained by assumptions in particle transport and optical properties. We have accounted for most of the differences in results from seven independent modeling groups, deriving a central estimate of 1800 W/g and an uncertainty range of 900−3200 W/g for normalized direct radiative forcing. BC lifetimes estimated from the same studies, as well as the corresponding parameters for CO_2 and the full calculation of GWP, are described in the Supporting Information and used in the following discussion.

Figure 1 shows the forcing by BC and CO_2 integrated over the time since emission, highlighting the short-term and long-term nature of BC and CO_2 forcing, respectively. The ratio of integrated BC and CO_2 forcing, also shown in Figure 1, gives the GWP over different periods. The central value of $GWP_{BC,100}$ is about 680; that is, during 100 years after emission, 1 kg of BC produces as much forcing as 680 kg of CO_2. For a 20 year time period, the GWP is about 2200. BC is an impressive warmer because it absorbs most of the intercepted visible light, whereas the impact of CO_2 occurs over a limited range of infrared wavelengths. The estimates of global warming potential have large uncertainties. $GWP_{BC,100}$ ranges from 210 to 1500, and $GWP_{BC,20}$ ranges from 690 to 4700. (These values are not comparable to those in Jacobson (ref

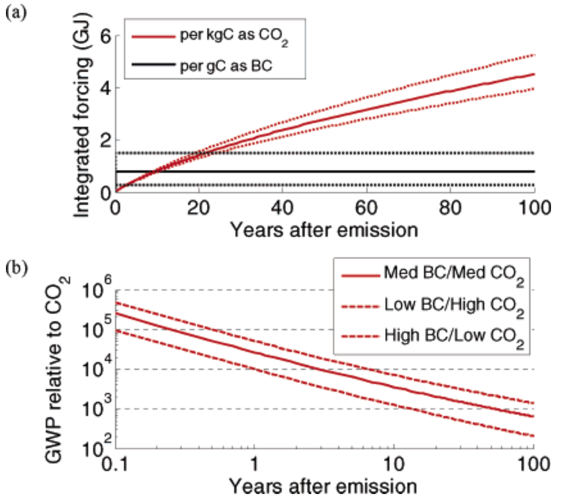

FIGURE 1. (a) Integrated forcing of C emitted as CO_2 and as BC over 100 years. (b) Direct-forcing GWP of BC, relative to CO_2 mass. Atmospheric concentrations of CO_2 were assumed to decay according to the Bern carbon-cycle model, while those for BC were assumed to decay exponentially. Model results summarized in the Supporting Information provided forcing per kg of BC. The forcing by BC takes place within the first few days of emission. The ratio between BC forcing and CO_2 forcing decreases as time progresses because CO_2 remains in the atmosphere and continues to warm it.

8, Figure 14), which were instantaneous temperature responses instead of integrated climate forcing and which assumed equilibrium between current CO_2 emissions and concentration.)

Feasibility: Cost and Control

In part due to the scientific arguments against equivalence, BC reductions have not yet been assessed within a framework similar to that of CO_2. Introducing a GWP for aerosols may be controversial, but it is useful for this preliminary inquiry. Within the limitations of current uncertainty, we can inquire whether these reductions might be cost-effective for climate purposes. If BC reductions are clearly expensive in such a framework, then they are not viable alternatives to GHG mitigation and should be discussed mainly for their ancillary benefits. If they are obviously economical, they should be considered immediately, especially when additional benefits make them more attractive. While a full analysis that combines climate, air-quality, and health benefits is warranted, we address simpler questions here: are BC reductions economically feasible for climate purposes only? If not, how prominently can climate considerations figure in advocating for reductions?

While BC has many sources, a few types dominate global BC emissions. Figure 2 shows the division of BC emissions between Annex I and other countries. A more detailed analysis would address a succession of marginal abatement costs. Here, we examine only the most promising actions: those that are relatively inexpensive and that can reduce large fractions of the emissions in each sector. We address only emissions from energy use, which constitute about half of the global emissions. Open burning of vegetation provides the remainder of global BC; this source should be considered, but alternatives other than outright prohibition are scarce.

Emissions are highly dependent on combustion processes, varying by orders of magnitude when identical fuels are burned differently. Figure 3 demonstrates this variability within the major sectors shown in Figure 2. The highest emission rates suggest the largest contributors to global emissions; these technologies are comprised of numerous small sources because larger devices often have better

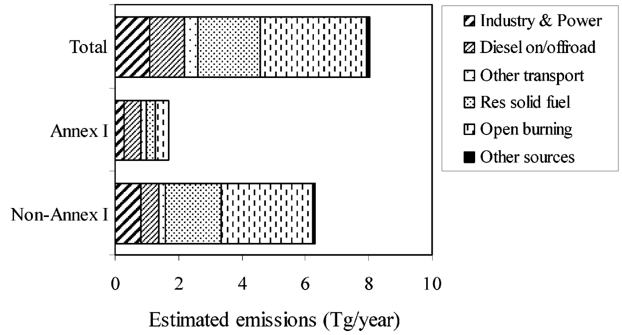

FIGURE 2. Estimated sources of global BC, from ref *9*; uncertainty in global totals is estimated as a factor of 2, and totals of individual sectors are even more uncertain. Here, Annex I countries include those in transition to market economies.

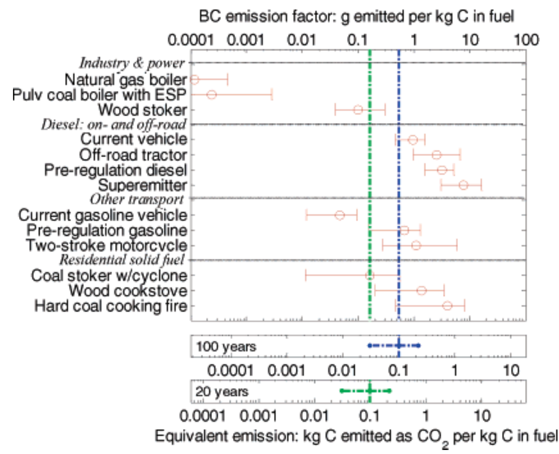

FIGURE 3. Comparison between BC elimination and improvements in efficiency for selected technologies in major emitting sectors. Central estimates and uncertainties for BC emission factors, taken from a recent literature summary (ref *9*), are shown in the top panel. The bottom panels show the emitted mass of CO_2−carbon that provides the same forcing as the emitted BC. The dashed lines show the point at which BC emissions provide the same forcing as 10% of the emitted CO_2 (blue = 100 years and green = 20 years, using the central value of GWP_{BC}). For points to the right of these lines, eliminating BC has a greater impact on radiative forcing than improving the efficiency by 10%. The horizontal lines in the lower panels show where the 10% efficiency line would fall when using the range of GWP_{BC} shown in Figure 1.

combustion and emission controls. Figure 3 also shows the CO_2 equivalent of BC emissions from each source, calculated using the GWP derived previously. For example, over 100 years, TOA forcing by BC emitted from a current diesel engine is about the same magnitude as TOA forcing by 15% of the CO_2 emitted from that engine.

Although Figure 3 shows many of the high-emitting devices that contribute most to global BC concentrations, much of the world's fuel is burned in low-emitting technologies such as pulverized coal burners and gasoline vehicles with current technology. The comparative radiative impact of BC is small for these sources, often less than 5% of the CO_2. For those sources, reducing CO_2 emissions through efficiency improvements, sequestration, or fuel-switching is a better way to reduce radiative impacts than reducing BC. For other sources, such as diesel engines that have not had to meet regulations and solid-fuel combustion in domestic applications, BC reductions might be the most immediate way to mitigate climatic impacts. These sources usually contribute only a small fraction of the global CO_2 budget. A more extensive analysis would consider emissions of all

TABLE 1. Comparison of Possible CO_2 Equivalent Reductions for Eliminating All BC from Several Technologies[a]

emitting technology	abatement technology	EF-BC (g/kg)	fuel (kg/year)	lifetime (year)	lifetime BC (kg)	CO_2 equiv (t) 100 years	CO_2 equiv (t) 20 years	cost ($/t CO_2 equiv) 100 years	cost ($/t CO_2 equiv) 20 years
Diesel engines									
current light vehicle	particle trap ($250−500)	0.9	1500	10	14	10	31	25−50	8−16
superemitting light vehicle	repair ($500−1000+); vehicle turnover (several thousand dollars)	3	1500	5	23	15	50	30−130	10−40
preregulation truck	particle trap ($5000−10000)	2	10000	10	200	140	440	36−71	11−23
Residential solid fuel									
wood cookstove	cleaner stoves, fuel switching ($3−100)	0.7	2000	3	4.2	2.9	9.2	1−34	0.3−11
coal cookstove	same as wood stove	8	1000	3	24	16	53	0.2−6	0.1−2
Other transport									
gasoline: 2-stroke engine	education, engine switching	1	300	5	1.5	1.1	3.3	not estimated	
Industry and power									
coal: low-tech brick kiln	switch kiln type[b]	5	500000	1	2500	1750	5500	18−35	5.5−11

[a] Lifetime emissions are based on the assumptions given. The analysis should be reevaluated with consensus values for technologies on the border of cost-effectiveness. Emission factors for BC are quite uncertain and vary among individual units and operating conditions. In this table, the range in cost per CO_2 equiv t includes only cost uncertainty, not uncertainties in GWP (as shown in Figure 1), emission factors (as shown in Figure 3), unit lifetime, or fuel consumption. [b] Emission factor estimated; measurements unavailable. Assume only 50% emission reduction with new kiln.

climate-active chemical species; the present comparison demonstrates only that different sources may be eligible for very different mitigation approaches.

Table 1 evaluates cost effectiveness of emission reductions by estimating CO_2-equivalent reductions for a number of mitigation actions. The table compares short- and long-term focus by using two GWP time horizons. Where costs appear very high, BC reductions are unlikely to become cost effective even if continuing research discovers somewhat greater impacts than those assumed here. Identifying individual sources and managing mitigation programs will increase these costs, particularly when the highest emitters are sparsely distributed; on the other hand, costs will decrease with advances and prevalence in control technology.

The cost estimates in Table 1 may be compared with a currently acceptable price of about $10 per metric ton of CO_2-equivalent. Recent (October 2004) transactions at the Chicago Climate Exchange resulted in a price of about $1/ton, while purchase agreements at the World Bank's Prototype Carbon Fund averaged about $4/ton in 2003. However, these prices would increase if mitigation were mandatory. With the present costs, BC reductions appear affordable for only a few technologies when evaluated over a 100 year time frame.

For diesel engines, climate credits may not cover the cost of BC abatement. Particle traps are often successful at reducing emissions from newer vehicles (*24*) but may need additional technology and maintenance when used with the older vehicles responsible for a significant fraction of emissions. For very high emitting vehicles or superemitters, emission reductions and costs vary widely between vehicles so that BC reductions range from economical to rather costly (*25*). The costs here reflect studies in industrialized countries, and simple, inexpensive maintenance procedures may reduce more emissions when vehicle quality or maintenance tends to be lower.

In contrast to diesel engines, CO_2-equivalent credits could easily fund some improvements in solid-fuel use for cooking or heating, even when evaluated with a 100 year GWP. The apparent simplicity of these solutions is deceptive. As discovered during many years of development work, viable technology is only a prelude to clean combustion. Many improved cookstove programs have failed when they ignore market-based dissemination and the wishes of the affected populations (*26*). Current improved cookstoves do not eliminate particulate emissions, and some even increase them (*22*). Switching to cleaner fuels is another solution, but it requires sufficient local resources, distribution networks, and policy mechanisms. Despite these caveats, mitigation in this sector can be linked with substantial health benefits, well-designed programs have demonstrated success (*27*), and deficiencies in previous efforts are leading to revised approaches to dissemination and design.

An example of a small, polluting industrial source is included in the table, and the potential climate benefits are high but uncertain. For these sources, highly polluting units may reside in informal sectors, which have hardly even been quantified, a task made difficult by fear of punishment and regulation. The cost of abatement technology is high, partly because low-cost emission reductions have not been explored (*28*). Regulation is notoriously problematic for this type of source (*29*) and requires local support as well as awareness of political and socioeconomic conditions.

Of course, uncertainties in knowledge may affect these conclusions. For example, action on current diesel engines may become cost-effective ($10/ton of CO_2-equivalent) if abatement costs were reduced by factors of 2−5 or if emission factors, light absorption, or atmospheric lifetime were found to be higher than those assumed here, again by factors of 2−5. Our estimates of GWP alone do contain such uncertainties. Diesel mitigation could also be cost effective for climate purposes by shortening the time frame of interest to 20 years instead of 100 years.

On average, BC emissions in Annex I countries are dominated by road transport: diesel engines, off-road vehicles, and a few superemitters. For these sources, BC reductions appear relatively costly, even using the maximum metric of warming. While GHG mitigation actions with similar or higher costs have been reviewed, their prices usually preclude them from consideration in early rounds of reductions. Including BC in the climate basket does not appear to increase the affordability of reducing warming in Annex I countries, unless a large fraction of the value comes from health or air quality considerations. Therefore, the promise of BC reductions should not be a distraction for parties opposed to GHG mitigation for economic reasons. Further, the relatively high greenhouse-gas emissions by Annex I countries are difficult to offset with aerosol reductions. Estimated annual BC emissions from the U.S. are equivalent to only about 5% of CO_2 emissions, using the central GWP.

Most of the global BC is emitted in non-Annex I countries. There, emissions appear dominated by solid-fuel combustion and many vehicle superemitters, and BC may be an affordable alternative to GHG mitigation. However, enacting such a program requires sensitivity. Many of the important sources are considered subsistence uses, necessary for survival even if the emissions are undesired. For these practices, the users clearly cannot be held to the conventional standard known as "polluter pays".

Equity: Parallel Challenges, Parallel Action

We are learning that anthropogenic climate change is rooted in both advanced and low-technology combustion. An interesting parallel between industrialized and developing nations offers the possibility for global participation in addressing global change.

Industrialized nations are responsible for most of the anthropogenic CO_2 burden, which is predicted to cause long-term climate change. For the most part, these countries have the ability and desire to contribute to long-term, global solutions. Concordantly, reducing GHGs is often a more economical method of reducing climatic impacts. BC reductions as climate mitigation are not only economically impractical but logistically unrealistic as well: the difficulty of verifying emissions and reductions belies the current cap-and-trade approach accepted by most of these nations. Further, if BC reductions are included in such a framework, BC must also be added to the baseline emissions, a formidable task that will increase both compliance costs and reduction requirements.

Developing countries, emitting much of the global BC, also affect the climate system despite their lower GHG emissions. These nations have immediate environmental problems to address before tackling the long-term issue of global atmospheric change. Reducing emissions of short-lived aerosols can be an economical way to reduce both TOA forcing and climatic impacts, with ancillary benefits enhancing appeal and affordability of these measures. Although growth in GHG emissions may be required for equitable development, many nations have already planned or achieved measures that reduce anthropogenic interference by short-lived climate forcing agents. While credits might be difficult to quantify, these nations are not yet party to agreements that demand such precision. They could propose a parallel agreement on mitigation of climate change, using the broad brushstrokes of GWP to recognize their participation.

Country-specific time scales in GWP calculations could encourage this natural dual focus. Although the 100 year GWP has been used in the Kyoto Protocol, shorter time scales and a shorter-horizon GWP better correspond to the problems faced by developing countries. Reducing the GWP horizon increases the relative value of short-lived species. For developing countries entering an agreement, short time horizons could reward aerosol reductions during an initial period. In later years, the horizon could be extended, shifting the focus to GHGs and the future. A more explicit method of weighting future impacts differently is applying a discount rate to future forcing and calculating GWP over an infinite time horizon (*30*, *31*). High discount rates would represent short-term focus, and sliding-scale discount rates might be differentiated according to development level. However, outlining a workable proposal is beyond the authority of these authors; that task more rightly belongs to the affected nations.

Should we consider black carbon, a climate-warming partner of CO_2, as a partner in discussions on mitigation? Reducing BC cannot counteract global warming because (i) it behaves differently than greenhouse gases, and decreasing aerosol emissions may not diminish warming; (ii) in countries that have already committed to reducing GHG emissions, mitigating BC appears to be a relatively costly way to reduce warming if only climate benefits are considered; and (iii) in other countries, the relevant emission sources are difficult to address. Still, there is promise in such a partnership because (i) reducing BC in some locations is an economically feasible method of reducing radiative impact; (ii) addressing aerosols will reduce climatic interference, regardless of the impact on TOA forcing; and, most importantly, (iii) the joint venture could provide a mechanism for all nations to participate in global stewardship with a more realistic definition of global change. There is no magic bullet here, only more integration required, more creativity demanded, more to the heaven and earth of climate change than were dreamt of in the TOA-average, GHG-only philosophy.

Acknowledgments

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Supporting Information Available

Formula used to calculate global warming potential and the necessary parameters: normalized direct forcing and lifetimes of black carbon and carbon dioxide; characteristics of black carbon derived from a tabulation and comparison of published climate model results. This material is available free of charge via the Internet at http://pubs.acs.org.

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