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Climate trade-off between black carbon and carbon dioxide emissions

O. Boucher*, M.S. Reddy

Met Office Hadley Centre, Fitzroy Road, Exeter EX1 3PB, UK

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Abstract

There are various difficulties involved with comparing the effects of short-lived and long-lived atmospheric species on climate. Global warming potentials (GWPs) can be computed for pulse emissions of short-lived species. However, if the focus is on the long-term effect of a pulse emission occurring today, GWPs do not factor in the fact that if a radiative forcing is applied for a short period, the climate system has time to relax back to equilibrium. The concept of global temperature change potential (GTP) at a time horizon for an emission pulse has been proposed to circumvent this problem. Here we show how GTPs can be used to compare black carbon (BC) and CO_2 emissions and the methodology is illustrated with two concrete examples. In particular we discuss a trade-off situation where a decrease in BC emissions is associated with a fuel penalty and therefore an additional CO_2 emission. A parameter—which depends on the BC radiative effects, the BC emission reduction and the additional CO_2 emission—is defined and can be compared to a critical parameter to assess whether or not the BC emission reduction wins over the fuel penalty for various time horizons. We show how this concept can be generalised to compare the climate effects of carbon dioxide against a set of short-lived species and to account for differences in climate efficacy. Finally, the need for additional research is discussed in the light of current uncertainties.

Keywords: Climate metric; GWP; GTP

1. Introduction

There is a pressing need for devising a metric that allows comparing the climate effects of short- and long-lived atmospheric chemical species. Such a metric would allow one to develop more efficient climate mitigation policies as well as to achieve better trade-offs between air quality and climate policies. For instance, Hansen et al. (2000) proposed that in order to reduce the risk of dangerous climate change the emphasis on emission reduction could be put on methane, black carbon (BC) and ozone precursors over the next 50 years, although they too argue that a reduction in CO_2 emissions is also needed. Streets and Aunan (2005) highlight the potential of BC emission reduction in the household sector in China. Although they raise the possibility of including BC emission reduction as a post-Kyoto option for China and other developing countries, they do not propose any climate metric or framework to deal with BC emission reduction in a post-Kyoto protocol. Jacobson (2002, 2005) suggested that, despite their lower fuel efficiency, gasoline cars were better for climate than BC-emitting diesel cars. However, Jacobson's analysis relied on radiative forcing (RF) and climate equilibrium calculations, which is artificial and possibly misleading because any policy or technology will only be implemented for a finite period of time.

Global warming potentials (GWPs) have been introduced to compare the cumulative radiative efficiency of different long-lived greenhouse gases over a time horizon (see Section 2.1 for a definition). GWPs are used to weigh the emissions of different long-lived greenhouse gases and a basket of them can be traded against each other under the Kyoto protocol. Although GWPs can technically be defined for short-lived species as well, their usage is not well established and there is little literature on GWPs for short-lived species. Recently Bond and Sun (2005) estimated that, despite its very short lifetime as compared with CO_2, the 100-year GWP for BC is 680. Bond and Sun

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*Corresponding author.

E-mail addresses: olivier.boucher@metoffice.gov.uk (O. Boucher), shekar.reddy@metoffice.gov.uk (M.S. Reddy).

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suggested that there would be a climate benefit to cut BC emissions for a range of super-emitters even with a fuel penalty of 10%. Forster et al. (2007b) estimated a direct GWP for BC of 510 in reasonable agreement with Bond and Sun (2005). Reddy and Boucher (2007) further investigated how the direct GWP for BC depends on the region of emission. They found that the 100-year GWP for BC ranges from 374 for BC emitted in Europe to 677 for BC emitted in Africa. The regional differences in BC GWP mainly reflect differences in the BC atmospheric lifetime, which themselves are mostly due to differences in the regional efficacy of wet deposition. Reddy and Boucher (2007) also pointed out that the snow-albedo effect of BC is associated with an indirect GWP that would present even larger regional differences. In particular, it was argued that the total (direct and indirect) GWP for European BC could be as large as 1600 for a time horizon of 100 years. This argues for BC emission reduction as part of a portfolio of climate mitigation policies. However, it should be kept in mind that (i) the RF and GWP by BC are still fairly uncertain and therefore climate policies should rely on a conservative estimate if a trade-off with CO_2 is involved and (ii) GWPs do not factor in the fact that a RF concentrated at the beginning of a time period is less effective in inducing climate change at the end of the time period as compared with a RF that decays more slowly over time such as that of a CO_2 pulse (see e.g. Fig. 1 in O'Neill (2000)). Rypdal et al. (2004) also acknowledged that GWPs are not well suited for short-lived species and suggested that, because of the regional nature of the forcings, aerosol emissions could be best regulated as part of regional climate agreements linked to a global climate agreement. There are also co-benefits to further regulate aerosols and other short-lived species because of their impact on air quality, human health and ecosystems.

Given the recent progress in modelling the climate effects of BC and other short-lived species and the growing political interest to regulate these species, it is timely to assess how to compare emissions of CO_2 and BC. It is the purpose of this paper to do so using the framework of the global temperature change potential (GTP) climate metric introduced by Shine et al. (2005, 2007). Section 2 summarises and discusses the concepts of GWP and GTP. We then illustrate in Section 3 how the concept can be applied to concrete policy-relevant issues. Section 4 shows how the methodology developed in Section 3 can be generalised to account for several short-lives species and different climate efficacies.

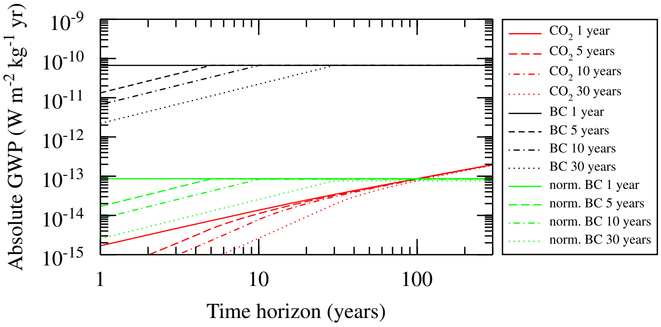

Fig. 1. Absolute generalised GWP (in $W\,m^{-2}\,kg^{-1}$ year) for CO_2, BC and normalised BC as a function of the time horizon. By definition, the normalised BC absolute GWP is equal to that of CO_2 for a time horizon of 100 years.

2. Climate metrics

2.1. *Global warming potentials*

The absolute GWP is defined as the integral of the radiative forcing caused by the pulse emission of 1 kg of a chemical species over a time horizon *T*, which results in a unit of $W\,m^{-2}\,kg^{-1}$ year. It depends both on the atmospheric decay time and on the radiative efficiency of the chemical species. Instead of a pulse emission, we define our GWPs for emission sustained during a period of 1, 5, 10 or 30 years. In any case, the total emission is kept the same and equals 1 kg as for the usual definition of GWP. Different policy questions involve different emission periods. For instance, a sustained emission period of a year should be used to assess the benefit of subsidising the phasing out of old cars that would have been withdrawn from the fleet in a short time anyway. A sustained emission period of 5 years would correspond to the lifetime of a diesel trap that would be retrofitted on an old vehicle. A sustained emission period of 10 years corresponds to the lifetime of a new vehicle and would be used to assess the relative benefits of different engine technologies. Finally, a sustained emission period of 30 years would be used for infrastructure with a longer lifetime, such as an aeroplane. We briefly discuss below the impact of considering variable emission periods instead of a pulse emission.

Rather than focusing on a particular time horizon, we first estimate and show in Fig. 1 the absolute GWP for both CO_2 and BC as a function of the time horizon *T*. The calculation of the absolute GWP for CO_2 is described in Appendix A. The absolute GWP for CO_2 shows a steep increase over the first 50 years followed by a less steep increase. The effects of lengthening the emission period are limited to the first 20–50 years and become negligible after 100 years. The absolute GWP for BC increases linearly during the emission period and is then constant as the residence time of BC in the atmosphere is very short. The absolute GWP for a 1-year sustained emission of CO_2 and for a 100-year time horizon comes out at $8.6 \times 10^{-14}\,W\,m^{-2}\,kg^{-1}$ year, in close agreement with more detailed studies for a pulse emission. The absolute GWP for BC has been somewhat arbitrarily set at $6.6 \times 10^{-11}\,W\,m^{-2}\,kg^{-1}$ year—which corresponds to a present-day RF of $+0.4\,W\,m^{-2}$ for a global emission rate of 6×10^{9} kg year^{-1} or a 100-year GWP of about 770. Fig. 1 also shows the absolute GWP of a hypothetical very short-lived species that has the 100-year absolute GWP of CO_2. This clearly shows that different species with the same

100-year absolute GWPs can exhibit very different time profiles of their absolute GWP. Such a species is thereafter referred to as "normalised BC". We show in Fig. 2 the GWP for the three species discussed in Fig. 1.

2.2. Global temperature potentials

Shine et al. (2005) introduced the GTP concept, which is further discussed in Shine et al. (2007). The absolute GTP is defined as the global change in surface temperature at a time horizon induced by a pulse emission and has a unit of K kg^{-1}. We compute the absolute GTP as a convolution of an impulse temperature response function with the time profile of the RF (see Appendix A for details of our calculations). We calculate the absolute GTP for our four emission periods using the methodology described above and present the results in Fig. 3. The absolute GTP for CO_2 increases rapidly with the time horizon before peaking in years 20, 22, 25 and 40 for our four cases, and decreasing slowly thereafter. The absolute GTP for BC shows a quite different behaviour with a shorter and less pronounced increase up to a maximum, which is reached in the same year as when the sustained emission stops. The absolute GTP then falls down by several orders of magnitude in line with the short timescale of our temperature change impulse response function (IRF). This sharp decrease is then followed by a slower decrease for time horizons longer than 50 years. The normalised GTP is shown in Fig. 4 and shows a similar pattern to the absolute GTP as long as BC is concerned.

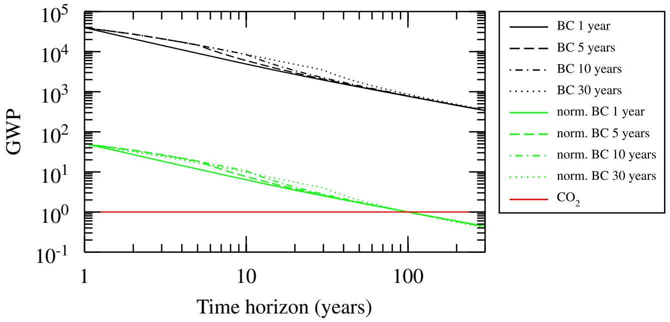

Fig. 2. Generalised GWP (dimensionless) for CO_2, BC and normalised BC as a function of the time horizon. By definition, the GWP of normalised BC for a time horizon of 100 years is equal to 1.

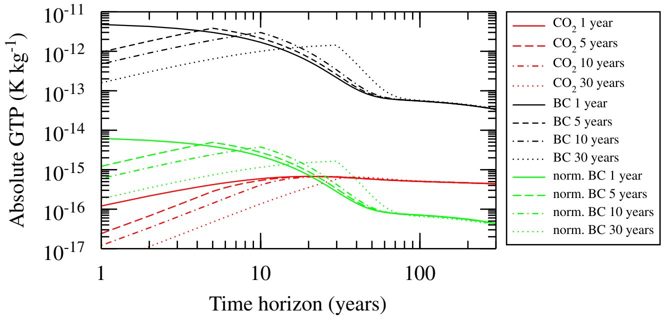

Fig. 3. Absolute generalised GTP (in K kg^{-1}) for CO_2, BC and normalised BC as a function of the time horizon.

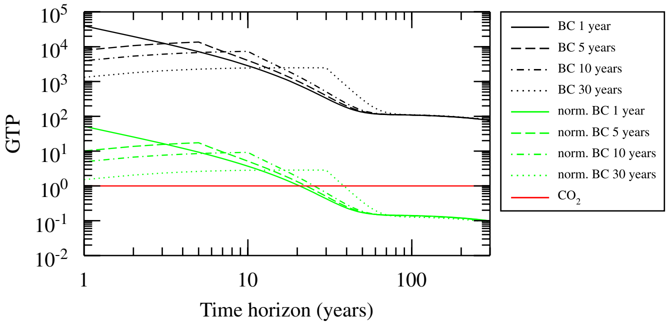

Fig. 4. Generalised GTP (dimensionless) for BC and normalised BC as a function of the time horizon.

2.3. Discussion of GWP versus GTP

Unlike GWP, GTP is an end-point rather than a cumulative measure of climate change. The time profile of the RF matters for the GTP but not for the GWP. The GTP therefore gives more weight to RF that comes later in the time period. The shorter the lifetime of the considered species, the larger the difference between GWP and GTP. For a very short-lived species like BC, the GTP for a time horizon of 100 years is about 7 times less than the corresponding GWP. This means that using a GWP to trade a short-lived species against a long-lived species will significantly overestimate the importance of the short-lived species for mitigating climate change. A similar conclusion was reached by Shine et al. (2005) although the most short-lived species they considered is HFC152a with a lifetime of 1.4 years.

3. Applications

A change in technology or in fuel can reduce BC emissions while either increasing or decreasing fuel efficiency. If fuel efficiency is increased, an air quality benefit is associated with a climate benefit. This is a win–win situation, where the cumulated air quality and climate benefits may justify a higher implementation cost. An example is provided in Section 3.1. If, in contrast, fuel efficiency is decreased, an air quality benefit is tarnished by a climate loss. This is a trade-off situation where decision-making will be more difficult. Trade-off situations are common. NO_x and particle traps on diesel cars are usually associated with a fuel penalty. Cleaner fuels can help to limit emissions of short-lived species, but may necessitate more energy to manufacture. Aviation is known to have several non-CO_2 climate effects such as contrails (Forster et al., 2006, 2007a). The warming effect due to contrail formation could possibly be limited by rerouting aircraft according to meteorological conditions, but this is expected to cost some fuel as current routes are more or less optimised for fuel consumption. A methodology to address trade-off situations is presented in Section 3.2.1 and an application is discussed in Section 3.2.2.

3.1. A win–win situation

Various measurements suggest that a fuel shift from raw coal into coal briquettes for use in domestic cooking stoves could reduce both the emissions of BC and CO_2 per unit of energy delivered (see Table 1 for details of the emission factors). This can be of particular interest given the fact that residential coal combustion accounts for half of the BC emissions in China (Streets et al., 2001; Streets and Aunan, 2005) and about 10% of global BC emissions (Bond et al., 2004). We estimate the absolute GTP for 1 MJ of delivered energy separately from CO_2 and BC emissions. Fig. 5 shows the absolute GTP as a function of the time horizon for both the raw coal and the coal briquette options. It can be seen that, beyond 50 years, most of the climate benefit comes from the CO_2 reduction. However, over the first 20–30 years the temperature change from the BC reduction is much larger than that from CO_2, thus bringing a significant climate benefit over the short term.

3.2. Trade-off situations

3.2.1. Theoretical framework

Let us now assume that one wants to mitigate against global warming by decreasing BC emissions, but this BC emission reduction has to be traded against a "fuel penalty" that leads to an increase in CO_2 emissions. We note Δx_{CO_2} the average additional CO_2 emissions (in kg CO_2) for a BC emission reduction of Δx_{BC} (in kg BC). We define a parameter X as

$$X = \mathrm{GWP}_{BC}(T = 100\mathrm{years})\Delta x_{BC}/\Delta x_{CO_2}. \qquad (1)$$

If BC is radiatively very efficient (large GWP_{BC}) or if a large reduction in BC emissions is achievable (large Δx_{BC}) at a small fuel penalty (small Δx_{CO_2}), then X is large and it is more likely that a trade-off between BC and CO_2 emissions will be beneficial to climate. It can be shown that the critical X value for which the trade-off is climate neutral at a time horizon T can be expressed as

$$X_{\mathrm{limit}}(T) = \mathrm{AGTP}_{CO_2}(T)/\mathrm{AGTP}_{\mathrm{nBC}}(T) = 1/\mathrm{GTP}_{\mathrm{nBC}}(T), \qquad (2)$$

where $\mathrm{AGTP}_{\mathrm{nBC}}(T)$ and $\mathrm{GTP}_{\mathrm{nBC}}(T)$ are the absolute and normalised GTP for our "normalised BC" species defined above. The dependence of X_{limit} on the time horizon T is shown in Fig. 6. For short time horizons, climate mitigation can be effectively achieved through BC emission reduction over a large range of the X parameter. This is less so for longer time horizons. It is usual that a particular trade-off can be beneficial over a short time horizon from

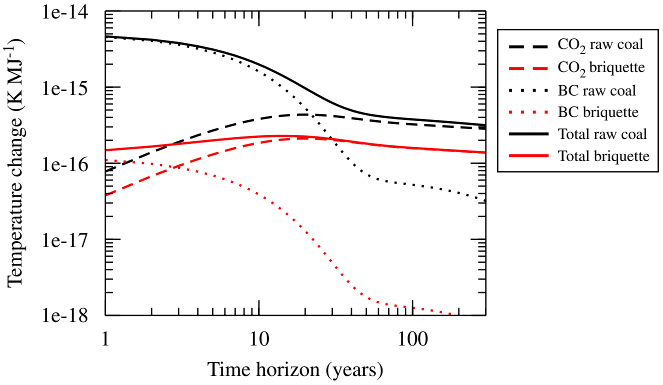

Fig. 5. Absolute GTP for a delivered energy of 1 MJ in a domestic cooking stove from CO_2, BC and their combined effects for raw coal and coal briquettes.

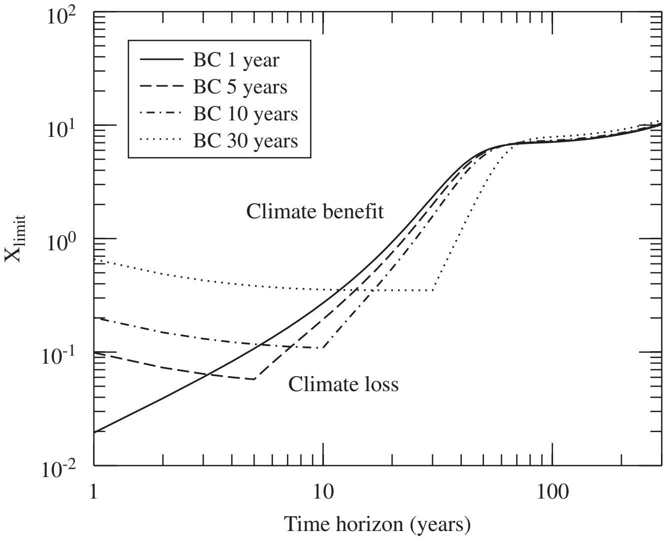

Fig. 6. Critical X_{limit} parameter as a function of the time horizon. If X is larger than X_{limit}, there is a climate benefit for this time horizon to reduce BC emissions despite the associated CO_2 penalty.

Table 1

BC and CO_2 emission factors (in g kg^{-1} and g (1 MJ)$^{-1}$ delivered energy) for two different coal fuels for domestic combustion in a cooking stove

Coal type	Energy content (MJ kg^{-1})	Stove efficiency (%)	BC (g kg^{-1})	BC (g MJ^{-1})	CO_2 (g kg^{-1})	CO_2 (g MJ^{-1})
Raw coal	27.3^a	14.3^a	3.7^b	0.96	2510^a	432^a
Coal briquette	13.9^a	37.1^a	0.12^b	0.023	1600^a	312^a

The energy content and the stove efficiency are also given.

[a] Zhang et al. (2000).

[b] Streets et al. (2001).

a climatic point of view but detrimental over a longer time horizon. The critical values for X are 7.1, 8.3 and 10.1 for time horizons of 100, 200 and 300 years, respectively. As expected, these critical values are insensitive to uncertainties in the short climate timescale d_1 (Table 2; see also Appendix A where the climate parameters are defined). They are more sensitive to uncertainties in the longer climate timescale d_2, with opposite effects for a reduction or an increase in d_2 on the critical values for time horizons of 100 and 200 years and an increase in both cases for a time horizon of 300 years. There is also some sensitivity to changes in the components of the climate sensitivity (the c_1 and c_2 parameters). These sensitivity studies are somewhat arbitrary but represent a lower and an upper bound for each parameter. One can for instance conservatively assume that an X value larger than 15 always brings a climate benefit up to a time horizon of 200 years.

We also present the results in a different way to facilitate their interpretation and their use by policymakers. Fig. 7 shows the threshold $\Delta x_{BC}/\Delta x_{CO_2}$ ratio as a function of the time horizon and GWP_{BC} ($T = 100$ years). It can be seen again for instance that with a GWP_{BC} of 700 at 100 years, the climate neutral $\Delta x_{BC}/\Delta x_{CO_2}$ ratio is slightly larger than 0.01 for a time horizon of 100 years.

Table 2
Critical X values for time horizons of 100, 200 and 300 years for our baseline case and for eight sensitivity experiments where the parameters of the climate impulse response function are arbitrarily varied by ±50%

Scenario	$T = 100$ years	$T = 200$ years	$T = 300$ years
Baseline case	7.1	8.3	10.1
d_1 reduced by 50%	7.0	8.3	10.1
d_1 increased by 50%	7.0	8.4	10.2
d_2 reduced by 50%	5.1	7.7	11.9
d_2 increased by 50%	9.4	9.9	11.0
c_1 reduced by 50%	4.1	5.2	6.6
c_1 increased by 50%	10.1	11.4	13.6
c_2 reduced by 50%	13.1	14.5	17.1
c_2 increased by 50%	5.1	6.2	7.8

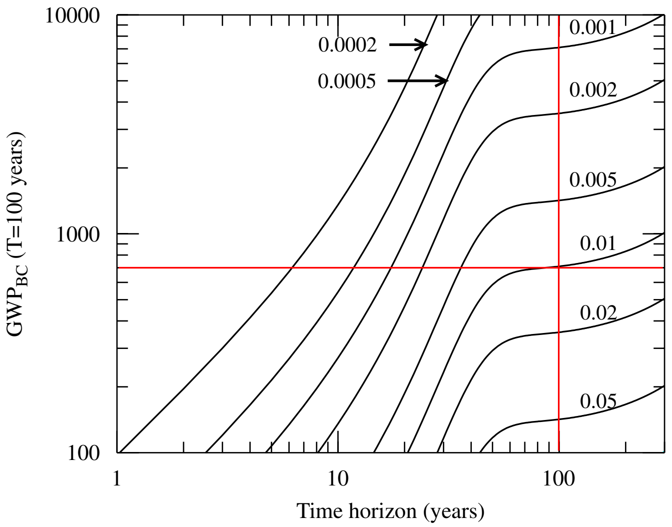

Fig. 7. Threshold $\Delta x_{BC}/\Delta x_{CO_2}$ ratio as a function of $GWP_{BC}(T = 100$ years) and the time horizon.

3.2.2. Diesel particulate filters

The possibility of fitting a particulate filter on new (or old) diesel vehicles offers a case study that is particularly relevant to policy-makers. Some off-road and heavy-duty vehicles can have very large BC emission factors. So-called "super-emitter" diesel vehicles have BC emission factors as high as 10 g BC $(\text{kg fuel})^{-1}$ (Bond et al., 2004). Euro-4 sets a standard of 0.025 g PM km^{-1} for passenger cars, most of it being BC. The Euro-5 norm is likely to further tighten PM emission standards, which will require particulate filters for diesel cars. It is usually considered that fitting a particulate filter induces a fuel penalty. While measurements show that diesel particulate filters are very efficient to cut down BC emissions, it proved difficult to find quantitative estimates of the associated fuel penalty in the published literature. The fuel penalty is a function of the type of particulate filter (active or passive technology), the vehicle and the driving test cycle. A particulate filter may also require a change in the fuel properties (low sulphur content in particular), which also impacts on fuel efficiency (LeTavec et al., 2002; Lev-on et al., 2003). In many cases, the fuel penalty is not even measured and the performance of the diesel particulate filter is just assessed against the emission standards (e.g. Verbeek et al., 2001). This said, a fuel penalty of about 2–3% is usually quoted in the literature and we will be using this figure here for a range of heavy-duty vehicles (Chandler et al., 2003; LeTavec et al., 2002; Lev-on et al., 2003). Combined with a reduction in BC emission of 0.15–0.30 g mile^{-1}, CO_2 emissions of 1500–2000 g mile^{-1}, a 100-year GWP of 680 for BC, this results in an X parameter in the range of 1.7–6.8. Retrofitting a diesel particulate filter on these heavy-duty vehicles would therefore lead to less climate warming up to a period of 28–68 years. Over longer time horizons, the CO_2 warming effect due to the fuel penalty would dominate.

4. Extension of the concept

Our methodology and our parameter X in Section 3.2.1 can easily be extended to include the climate effects of all other emitted very short-lived species, such as other aerosol types (Reddy et al., 2005). As long as the net effect of all short-lived species is a warming, they can be lumped together and the parameter X can be defined as

$$X = (\Sigma_i \text{GWP}_i(T = 100\text{years})\Delta x_i)/\Delta x_{CO_2}, \tag{3}$$

where $\text{GWP}_i(T = 100\text{years})$ is the 100-year GWP for species i and Δx_i is the emission reduction of species i (in kg). For instance, organic matter (OM) is often emitted as the same time as BC, with a ratio that is source- and sector-dependent. The negative GWP for OM can be combined with the positive GWP for BC in Eq. (3) to estimate an X parameter for the mixture. Eq. (3) and our methodology are valid as long as the atmospheric lifetimes of all species are short in comparison to the time horizon and the CO_2 lifetime. The methodology, based on the ratio between emissions of short-lived species and carbon dioxide, would break if three distinct lifetimes were involved, such as would be the case for very short-lived species—such as aerosols, methane and carbon dioxide.

We have so far ignored the potential differences in climate sensitivity among the different climate agents. Some forcing agents may be responsible for a smaller or a larger global temperature response than expected from equal forcing by CO_2. The climate efficacy is defined as the equilibrium global temperature change relative to that of CO_2 for a unit radiative forcing. There is quite some uncertainty on the climate efficacy of BC with some studies indicating an efficacy larger than 1 (Hansen et al., 2005) and other studies pointing to an efficacy lower than 1 (Roberts and Jones, 2004; Jones et al., 2007). The climate efficacy of the snow-albedo effect of BC is also uncertain but is suggested to be about 2 (Hansen and Nazarenko, 2004) or 3 (Flanner et al., 2007). Eq. (3) can be corrected to account for the climate efficacies:

$$X = (\Sigma_i \mathrm{GWP}_i(T = 100\mathrm{years})\mathrm{EF}_i \Delta x_i)/\Delta x_{\mathrm{CO}_2}, \quad (4)$$

where EF_i is the climate efficacy of the radiative forcing of species i.

The GWP in Eq. (4) can be made region-dependent. Reddy and Boucher (2007) have shown that BC emitted in different regions has different residence times and radiative efficiencies, leading to regional differences in GWP. Moreover, Reddy and Boucher (2007) suggested that the snow-albedo effect of BC was caused preferentially by European emissions, resulting in an indirect 100-year GWP of 1200 for European BC. If we retain a direct 100-year GWP of 400 for European BC (Reddy and Boucher, 2007) and a conservative value of 2 for the climate efficacy of the snow-albedo forcing, we end up with an X factor that is 4 times larger than that discussed in Section 3.2.2 (i.e., a range from 6.8 to 27). This favours the BC emissions reduction over the fuel penalty for periods of 68 years to centuries.

5. Discussion and conclusions

The approach presented above provides a framework to analyse the relative climate values of emission reductions of short-lived and long-lived species. The concept is illustrated in the context of BC and CO_2 with both a win–win and a trade-off situation. We also showed how the approach can be generalised to handle multiple short-lived species and differences in climate efficacies. While we believe that this work is relevant to policy-making, it should be used with caution and the following caveats ought to be stressed:

1. There are other uncertainties involved in the calculations presented here. In particular, the IRF for the climate response used here has been derived from an experiment featuring a step change in a homogeneous radiative forcing. We need to investigate the climate responses to pulse homogeneous and inhomogeneous radiative forcings.
2. We have followed Shine et al. (2005) and expressed the climate effect in terms of the change in global surface temperature. However, the climate metric to be used depends on the policy question. In some instances, a climate metric based on a physical climate parameter may not be appropriate. A trade-off policy that accounts for both the air quality and climate benefit of emissions reductions may eventually require an analysis in some monetary unit.
3. There might be other dimensions to the trade-off. For instance, some particulate diesel filters require ultra-low sulphur fuel. Manufacturing this fuel may also be associated with a fuel penalty (Beer et al., year not specified). It is therefore important to have a lifecycle approach in these cases. Lifecycle approaches will be critically needed to compare biofuels and fossil fuels.
4. The choice of an appropriate time horizon to evaluate the benefit of a climate policy is difficult and to a large extent this depends on the policy question that needs to be answered. Obviously, the longer the time horizon, the more importance is given to CO_2 as compared with BC. However, the longer the time horizon, the smaller the residual climate effect, especially if the trade-off is close to compensation. The picture should therefore not just be "black and white" and a negative climate effect for a very long-time horizon has to be balanced against a positive climate effect occurring on shorter timescales and the magnitude of the residual climate effect.
5. The 100-year GWP by BC has been included in the X parameter above, rather than made implicit in the analysis, because it is still fairly uncertain. It is therefore essential that the uncertainties surrounding the GWP and climate efficacy of BC are reduced before firm decisions can be made in trade-off situations involving BC and CO_2.

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Appendix A. Methods

We base our analysis on simple carbon cycle and climate models that use impulse response functions (IRF)

Table A1
Parameters of the impulse response functions used in this study

	$i=0$	$i=1$	$i=2$	$i=3$
a_i (unitless)	0.217	0.259	0.338	0.186
b_i (years)		172.9	18.51	1.186
c_i $(\mathrm{K}\,(\mathrm{W\,m^{-2}})^{-1})$		0.631	0.429	
d_i (years)		8.4	409.5	

to describe the evolution of the atmospheric CO_2 concentration and global surface temperature to CO_2 emissions (Table A1). The parameters in these simple models are derived from simulations with more complex chemistry and climate models. We appreciate that this approach is very simple and is associated with a number of caveats (Joos and Bruno, 1996). For instance, it does not account for the processes governing the CO_2 cycle on a very long-time scale (Archer et al., 1997). However, we believe that this approach is sufficient in the current context to support our conclusions. The impulse response function for CO_2 is an update from Joos and Bruno (1996), which has been used for the Fourth Assessment Report of the IPCC. It has been estimated from a 400 GtC impulse emission in the Bern carbon cycle model under conditions of stabilised CO_2 concentrations at 378 ppmv. The fraction of carbon emitted at time $t=0$, which is left in the atmosphere at time t is expressed as

$$f(t) = a_0 + \sum_{i=1}^{3} a_i \exp(-t/b_i),$$

with $\sum_{i=0}^{3} a_i = 1$ by construction.

The CO_2 atmospheric concentration at time t_1 from an emission profile $e(t)$ can then be approximated as a convolution of $e(t)$ with $f(t)$:

$$[\mathrm{CO_2}](t_1) = [\mathrm{CO_2}](t_0) + \int_{t_0}^{t_1} e(t) f(t_1 - t)/c\,\mathrm{d}t,$$

where c is a constant that converts emissions in GtC to atmospheric concentrations in ppmv (1 ppmv = 2.123 GtC) and t_0 is pre-industrial time. By design, the CO_2 impulse response function does not account for the fact that both the land and ocean carbon sinks depend on the atmospheric CO_2 concentration and climate change. Accounting for the carbon-climate feedback can result in a significantly larger airborne fraction of emitted CO_2 (Jones et al., 2006). We follow Ramaswamy et al. (2001) and approximate the radiative forcing due to anthropogenic CO_2 as

$$\mathrm{RF}(t) = \alpha \ln([\mathrm{CO_2}](t)/[\mathrm{CO_2}](t_0)),$$

with $\alpha = 5.35$ and $[\mathrm{CO_2}](t_0) = 380$ ppmv.

The absolute GWP for CO_2 at a time horizon T is then calculated as

$$\mathrm{AGWP}(T) = \int_{t_0}^{t_0+T} \mathrm{RF}(t)\,\mathrm{d}t.$$

It should be noted that this definition of the GWP is based on a constant concentration baseline $[\mathrm{CO_2}](t_0)$ rather than a more realistic CO_2 increase scenario. However, the CO_2 band saturation effect is almost perfectly compensated for by the reduced ocean uptake at a higher CO_2 atmospheric concentration (Fuglestvedt et al., 2003).

The climate response (in terms of global surface temperature change) is estimated from an impulse response function to RF:

$$\delta T(t) = \Sigma_i c_i/d_i \exp(-t/d_i),$$

with the c_i and d_i coefficients given in Table A1. The climate responds with a short timescale d_1 and a longer timescale d_2. The equilibrium climate sensitivity, as the sum of the c_i coefficients, is 1.06 K $(\mathrm{W\,m^{-2}})^{-1}$ or 3.9 K for a doubling of the CO_2 concentration. The impulse response function for surface temperature has been derived from more than 1000 simulated years of an experiment with the HadCM3 climate model in which atmospheric CO_2 concentrations were quickly ramped up to 4 times the pre-industrial levels before being held constant. We believe that the experimental setup favouring the longer timescales of the climate response is responsible for the slightly larger climate sensitivity than reported elsewhere for the HadCM3 model. The IRF is shown in Fig. A1 as the temporal evolution of the global temperature change (K) in response to a normalised radiative forcing of 1 $\mathrm{Wm^{-2}}$ applied during the first year. The climate response IRF can then be used to estimate the global surface temperature change at a time horizon T from a RF profile RF(t) as

$$\Delta T(tT) = \int_{t_0}^{t_0+T} \mathrm{RF}(t)\,\delta T(t_0 + T - t)\,\mathrm{d}t.$$

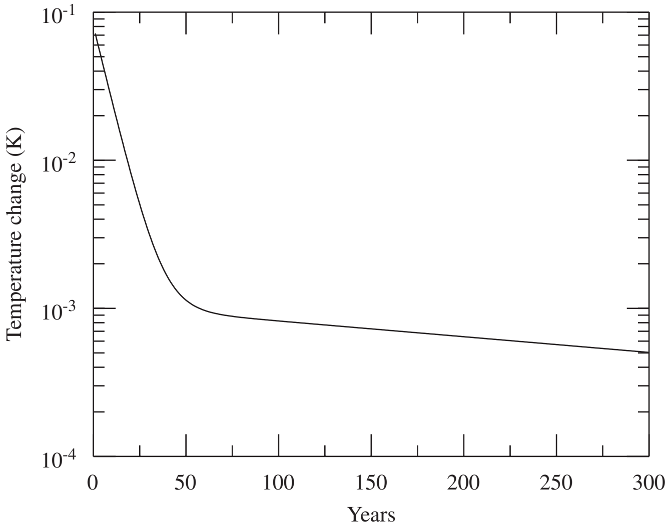

Fig. A1. Idealised temporal evolution of the global temperature change (K) in response to a normalised radiative forcing of 1 $\mathrm{W\,m^{-2}}$ applied during the first year.

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