Can reducing black carbon and methane below RCP2.6 levels keep global warming below 1.5 ^{o}C ?

Short title: Reducing black carbon and methane to attain the 1.5 ^{o}C target

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Abstract

Methane and black carbon aerosols have been identified as exerting the two strongest positive radiative forcings after carbon dioxide and therefore drastic reductions in these atmospheric constituents could potentially offer strong leverage in reducing global warming. Using the HadGEM2-ES model we reduce concentrations of methane and black carbon while holding all other emissions at representative concentration pathway RCP2.6 levels to examine whether we can achieve the target of keeping global-mean temperature rise below 1.5 °C relative to the pre-industrial level during the remainder of the 21st century. We find that even total cessation of black carbon aerosol emissions is ineffective in attaining this goal. Reducing methane concentrations at four times the rate assumed in RCP2.6 is able to return warming levels to below 1.5 °C by the 2070s but overshoots the target level prior to that. As RCP2.6 represents an optimistic scenario relative to the Intended Nationally Determined Contributions our results highlight the importance of deep and rapid reductions in both CO_2 and methane emissions if humanity is serious about attaining the 1.5 °C target.

1. Introduction

A key outcome of the 21st Conference of Parties to the UN Framework Convention on Climate Change held in Paris in 2016 was a commitment to limiting global-mean warming since the pre-industrial era to below 2 °C and to pursue efforts to limit the warming to 1.5 °C. Climate model simulations for the Coupled Model Intercomparison Project Phase 5 (CMIP5; Taylor *et al.*, 2012) suggest that warming exceeds 1.5 °C during the 21st century in the majority of climate model simulations even in the most optimistic representative concentration pathway (RCP) scenario, RCP2.6 (Van Vuuren *et al.*, 2011). Along with other scenarios which aim to achieve 1.5 °C or 2 °C targets, RCP2.6 includes strong reductions in greenhouse gas emissions and even includes so-called "negative CO_2 emissions" via bio-energy with carbon capture and storage (BECCS), even though the technology required is not yet viable on the scales required (Fuss *et al.*, 2014).

Because RCP2.6 already includes CO_2 emissions reductions significantly below the Intended Nationally Determined Contributions (INDCs; Sanderson *et al.*, 2016), we focus here on the possible contribution of reducing non-CO_2 warming agents to keeping warming below 1.5 °C. Controlling black carbon (BC) aerosol emissions has been suggested as a means of slowing global warming, although questions have been raised as to how effective reducing BC emissions would be in reducing warming (Baker *et al.*, 2015; Boucher *et al.*, 2016a). Another suggestion for mitigating climate change is the direct air-capture of methane (Boucher and Folberth, 2010), although methods for achieving this on a large scale are still largely theoretical (*e.g.*, Yoon *et al.*, 2009).

Previous studies (*e.g.*, Rogelj *et al*., 2014) have examined the effects of reducing BC and methane but have not done so in the context of attempting to achieve the 1.5 ^{o}C target. We do so here using the HadGEM2-ES Earth-system model (Appendix S1) to examine the potential effectiveness of further reductions in these two short-lived climate pollutants in idealised scenarios which otherwise follow RCP2.6.

2. Experiment Design

We use the standard HadGEM2-ES four-member ensembles of CMIP5 RCP2.6 and RCP8.5 scenario simulations as a basis, denoted “rcp26” and “rcp85” (Jones *et al.*, 2011). The members of a given ensemble have identical forcings applied but start from different initial conditions. Four 4-member ensembles were constructed based on rcp26 and initialised from it at the end of 2020:

1.	bc0	No fossil-fuel or biofuel BC aerosol emissions.
2.	bc2020	Fossil-fuel and biofuel BC aerosol emissions held at 2020 levels.
3.	meth1pc	Surface methane concentrations reduced at a compound rate of 1% per annum.
4.	meth2pc	Same as meth1pc but at a rate of 2 % per annum.

The lifetime of tropospheric aerosols is only a few weeks so the instantaneous removal of BC aerosols in bc0 is a good approximation to the effect of a global cessation of BC emissions. No change is made to any aerosol emissions that might be co-emitted with BC (*e.g.* organic carbon and inorganics) or to any carbonaceous aerosol emissions from open agricultural or wildfire biomass burning. Keeping BC emissions levels at the 2020 level in bc2020 allows us to examine the impact of the emission reductions already implicit within RCP2.6.

In contrast to BC, methane has an atmospheric lifetime of the order of a decade so it is not appropriate to reduce it instantaneously. Surface concentrations were therefore reduced at a constant compound rate; the rates of 1% and 2% per annum used here are approximately twice and four times the rate of reduction in the RCP2.6 scenario, respectively.

3. Results

Figure 1 shows the evolution of ensemble-mean anomalies in global-mean near-surface temperature for rcp85, rcp26 and bc0 with respect to the long-term mean from HadGEM2-ES’s CMIP5 pre-industrial simulation. The results for rcp26 are similar to the ensemble-mean of 32 CMIP5 model simulations in Collins *et al.* (2013) suggesting that HadGEM2-ES results are consistent with those obtained by the wider scientific community. The considerable benefits of the mitigation efforts included in RCP2.6 are evident when rcp26 is compared with rcp85; nevertheless, rcp26 still exceeds the 1.5 ^{o}C target from around 2030. In bc0 the mean warming over 2030-2100 is only slightly less than rcp26 (Table 1). Comparing bc2020 with bc0 we get a total cooling of 0.13 °C for 2030-2100, with over 50% coming from the reduction in BC emissions assumed in RCP2.6. The radiative forcing (RF) by BC in HadGEM2-ES for 2011 (compared with pre-industrial) of +0.31 Wm^{-2} is in reasonable agreement with the mean RF of +0.40 (+0.05 to +0.80) Wm^{-2} quoted by the Intergovernmental Panel on Climate Change (IPCC; Myhre *et al.*, 2013) for the same period. Our simulations do not include the impacts of BC deposition on snow/ice surfaces, but these have been assessed at only around +0.04 Wm^{-2} (Myhre *et al*., 2013). However, the effective RF (ERF) for BC in our study (+0.15 Wm^{-2}) is lower than the RF due to a fast feedback/response to BC within HadGEM2-ES which reduces medium-high altitude clouds (Jones *et al*., 2007).

Although temperature in meth1pc has almost returned to 1.5 °C above pre-industrial by 2100 (Figure 2) it still exceeds this level for the whole of the 21st century from 2030. In contrast, although it overshoots the target initially, warming in meth2pc drops below 1.5 °C in the 2070s and continues to fall thereafter (see Appendix S2 for some impacts of this overshoot). The RF by methane includes both direct effects due to changes in atmospheric concentration and indirect impacts such as where methane oxidation affects ozone, aerosols and stratospheric water vapour. The IPCC suggests methane has a direct RF of +0.48 Wm^{-2} for 2011 and an indirect RF of similar magnitude (Myhre *et al*., 2013). We calculate only an ERF owing to the difficulties in separating the direct and indirect forcings and obtain an ERF for meth2pc of +0.76 Wm^{-2} for the same period. Our simulations do not include any impacts on stratospheric water vapour (assessed at around +0.07Wm^{-2}; Myhre *et al*., 2013). The resulting changes in surface ozone are given in Table 1.

4. Discussion

There have been many studies that have examined the response of the climate to mitigation of short-lived climate forcers such as aerosols, BC and methane. While early studies examined the generic climate response to emissions (*e.g*., Jones *et al*., 2007), as climate model capability has improved, more sophisticated treatment of mitigation pathways have recently been developed (Rogelj *et al*., 2014; Stohl *et al*., 2015). However, these more sophisticated studies pre-date the ambitious 1.5 °C target and do not address such a low-warming scenario. In these studies, the strongest emission reduction scenario for BC was a reduction of around 80% from current emissions while for methane emissions the stringent emission scenarios RCP3-PD were followed. However, in an attempt to meet the 1.5 °C target, our more idealised simulations are more extreme with BC emissions reduced to zero and methane reduced at four times the rate in RCP2.6.

Reducing BC emissions to zero in bc0 only reduces global-mean temperature by 0.06 °C over 2030-2100 compared with rcp26. However, substantial BC reductions are already incorporated into the RCP2.6 scenario, although it is acknowledged that it would in principle be possible to reduce BC emissions further (Van Vuuren *et al*., 2011) as done here. The difference between bc2020 and bc0 (emissions reduction of ~6 Tg year^{-1}) produces a cooling of ~0.13 ^{o}C. This suggests that reducing BC emissions has a limited potential for reducing global-mean temperature, and if co-emitted species (such as sulphate aerosol) are considered, the actual cooling from reducing BC emissions could be even less. The lack of a sizeable climate response from additional BC mitigation has also been found by Rogelj *et al.* (2014) but a consistent model response to BC mitigation remains elusive (Samset *et al.*, 2016).

Reducing methane concentrations had much more of an impact on near-surface temperature, especially when reduced rapidly in meth2pc. Our results suggest that a 2% per annum reduction rate from 2020 could provide a significant contribution to returning warming to below 1.5 ^{o}C before the end of the 21st century in a scenario which otherwise follows RCP2.6. However, this rate of reduction would require methane concentrations to fall below pre-industrial levels from ~2055-2060, *i.e.* net removal of methane from the atmosphere or 'negative methane emissions'. Assuming methane is well-mixed and using a lifetime of approximately 10 years, a simple analysis (Appendix S3) suggests that to achieve the concentrations reductions used in meth2pc would require reducing net anthropogenic emissions from their 2020 level of ~250 Tg yr^{-1} to zero by the 2050s and then further to a net negative rate of approximately -103 Tg yr^{-1} by 2100 (Figure 3). Suggested methods for methane removal include filtration systems containing methanotrophic bacteria sited at locations with high atmospheric methane such as landfill and factory farms (Yoon *et al.*, 2009). Although no technology currently exists to reduce methane concentrations at the relatively dramatic rates investigated here, the same argument applies to CO_2, even though large-scale negative carbon emissions are commonly assumed in scenarios.

Whilst warming is closely related to the cumulative emissions of CO_2 due to its long lifetime (Allen *et al.*, 2009; Matthews *et al.*, 2009), the shorter lifetime of methane means that warming is more closely linked to its rate of emission (Smith *et al.*, 2012). This means that although methane reductions can realise near-term benefits, for longer-lasting benefits the emissions reductions have to be maintained over many decades. In other words, whereas a pause in CO_2 emissions in the near future (followed by a return to previous emissions rates) would still show an impact on global temperature by the end of the century, a similar pause in much shorter-lived methane would show little trace. As discussed by Hallegatte *et al.* (2016), methane reduction should therefore be seen not as an alternative to reducing CO_2 emissions but as an additional mitigation measure.

5. Conclusions

We have used the HadGEM2-ES Earth-system model to examine whether further reductions in certain short-lived climate pollutants beyond those specified in RCP2.6 can keep global-mean temperature below 1.5 ^{o}C above pre-industrial levels. Specifically, we have assessed the potential of reducing concentrations of the two atmospheric constituents which exert the strongest positive present-day radiative forcing after CO_2, namely BC and methane (Myhre *et al.*, 2013).

Mitigation by the removal of all fossil-fuel and biofuel BC emissions yielded a temperature decrease of 0.13 °C compared with the present day with the contribution from RCP2.6 contributing over 50% of this temperature change. This was insufficient to avoid exceeding the 1.5 °C target over most of the 21st century in our model. Reducing methane concentrations at approximately four times the rate assumed in RCP2.6 did achieve the 1.5 °C target level but only after overshooting it for several decades. It must be emphasised that this result is dependent on the aggressive mitigation efforts - including active CO_2 removal via BECCS - already encapsulated in the RCP2.6 scenario. Without these, further methane reductions will have far less impact. Given the continued increases in greenhouse gas concentrations, simply achieving RCP2.6 is likely to be a major task in itself. It is also worth noting that while the benefits of reductions in BC and methane appear relatively modest in terms of reducing global mean temperature, there are considerable benefits in terms of air-quality and human health (Anenberg *et al.*, 2012). Reducing BC emissions would also reduce melt from absorbing aerosol on snow/ice (Hadley and Kirchstetter, 2012).

It is a subject of debate as to exactly what is meant by the 1.5 °C target. While some take it to mean non-exceedance of 1.5 °C even as a peak warming, others have argued that an overshoot of this level is allowable with the target referring to the end-of-century (Schleussner *et al.*, 2016). Either way, Boucher *et al.* (2016b) argue that it is too early to give up hope – future technology is highly uncertain and we do not know what opportunities may emerge. Nonetheless, it is clear that a number of measures will be needed to meet the 1.5 °C target, including further emissions reductions which hitherto have not been investigated. Commentators have suggested both the need to consider all forms of climate policy in an open debate (Parker and Geden, 2016) and to consider how each may contribute to parallel “wedges” of action (*Nature* editorial, 2016). Here we have examined and quantified the potential contribution of BC and methane reductions to such a wedge. Finding this contribution to be relatively modest we conclude that renewed efforts to curb CO_2 emissions below existing INDCs and even below RCP2.6 will be required to stand a realistic chance of achieving the 1.5 °C ambition of the Paris Agreement.

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Supporting Information

Appendix S1: HadGEM2-ES model description

Appendix S2: Effects of overshooting the 1.5 °C target

Appendix S3: Methane emissions

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Simulation (4-member ensembles)	Mean warming over 2030-2100 (^{o}C)	Maximum decadal-mean warming (^{o}C)	Mean temperature change over 2030-2100 compared with rcp26 (^{o}C)	Change in 2090s surface ozone compared with rcp26
rcp85	3.58 [n/a]	–	+1.76	–
rcp26	1.82 [1.79-1.85]	1.91 [1.84-1.99]	–	–
bc0	1.76 [1.73-1.79]	1.90 [1.83-1.97]	-0.06	-0.2 %
bc2020	1.89 [1.86-1.92]	2.00 [1.90-2.11]	+0.07	-1.0 %
meth1pc	1.71 [1.68-1.74]	1.79 [1.71-1.87]	-0.11	-6.7 %
meth2pc	1.50 [1.46-1.53]	1.64 [1.55-1.72]	-0.32	-14.7 %

Table 1. Global-mean changes in near-surface air temperature (^{o}C) for the various simulations over the time periods indicated. Values in columns 2 and 3 are given as "mean [95% confidence interval]". Also given are the changes in surface ozone concentration with respect to rcp26 averaged over the 2090s.

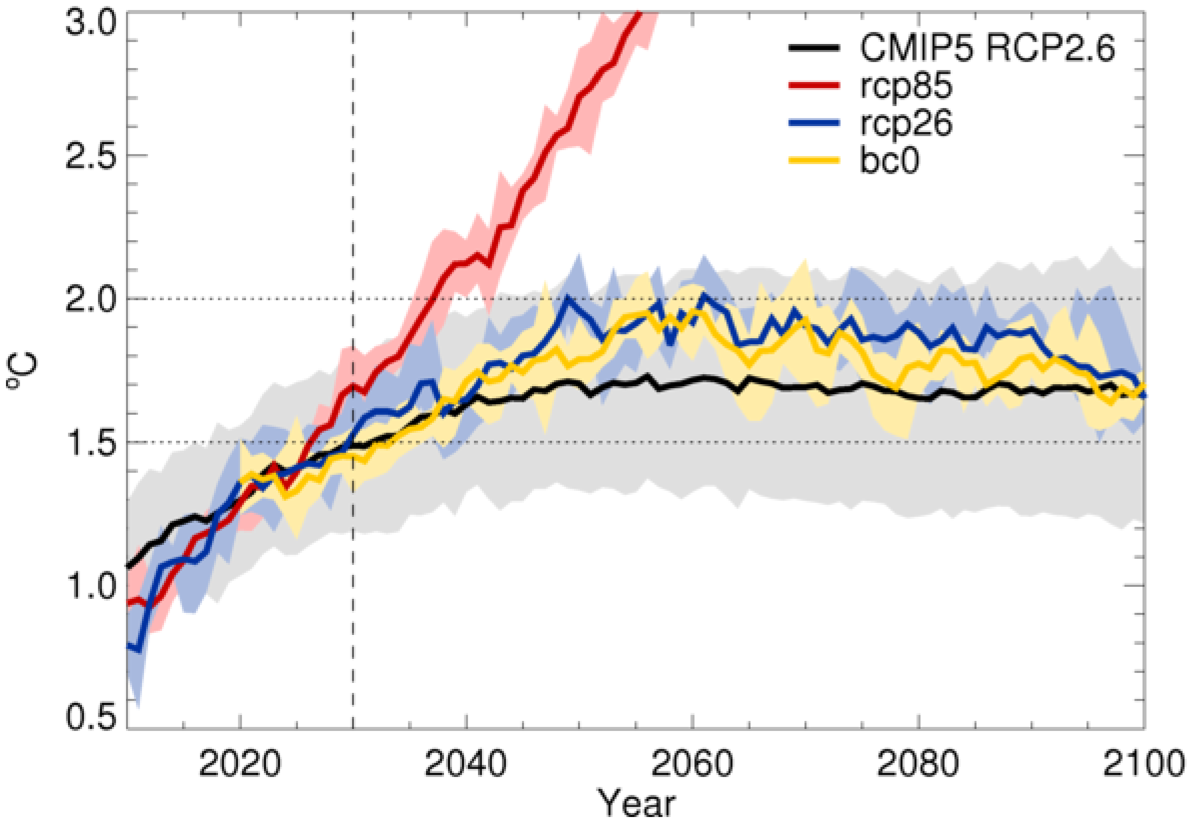

Figure 1. Evolution of annual global-mean near-surface temperature anomaly (°C) with respect to the long-term mean of the pre-industrial control simulation for ensembles rcp85, rcp26 and bc0. The mean and min-max spread of each ensemble is shown. Also shown is the multi-model mean (±1 standard deviation) of the CMIP5 RCP2.6 ensemble. The dashed line at 2030 indicates approximately when warming in rcp26 exceeds 1.5 °C.

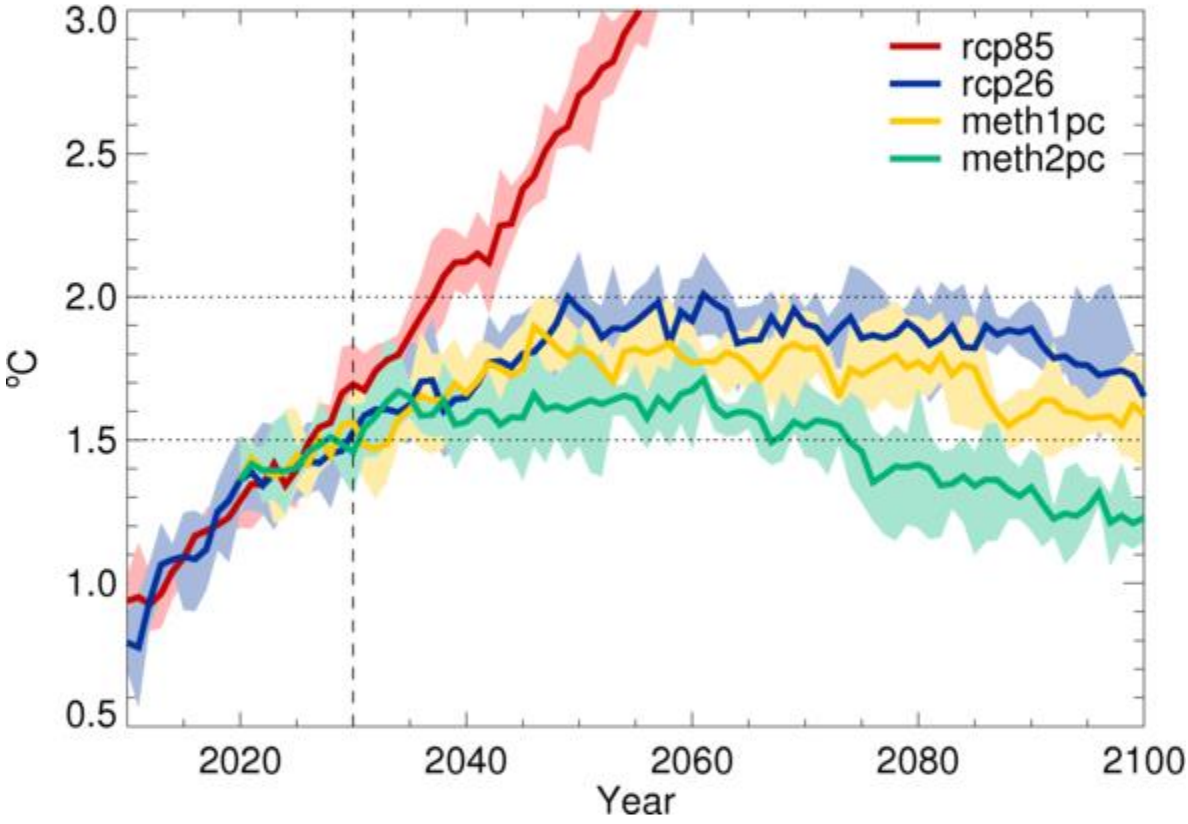

Figure 2. As Figure 1 but for ensembles rcp85, rcp26, meth1pc and meth2pc.

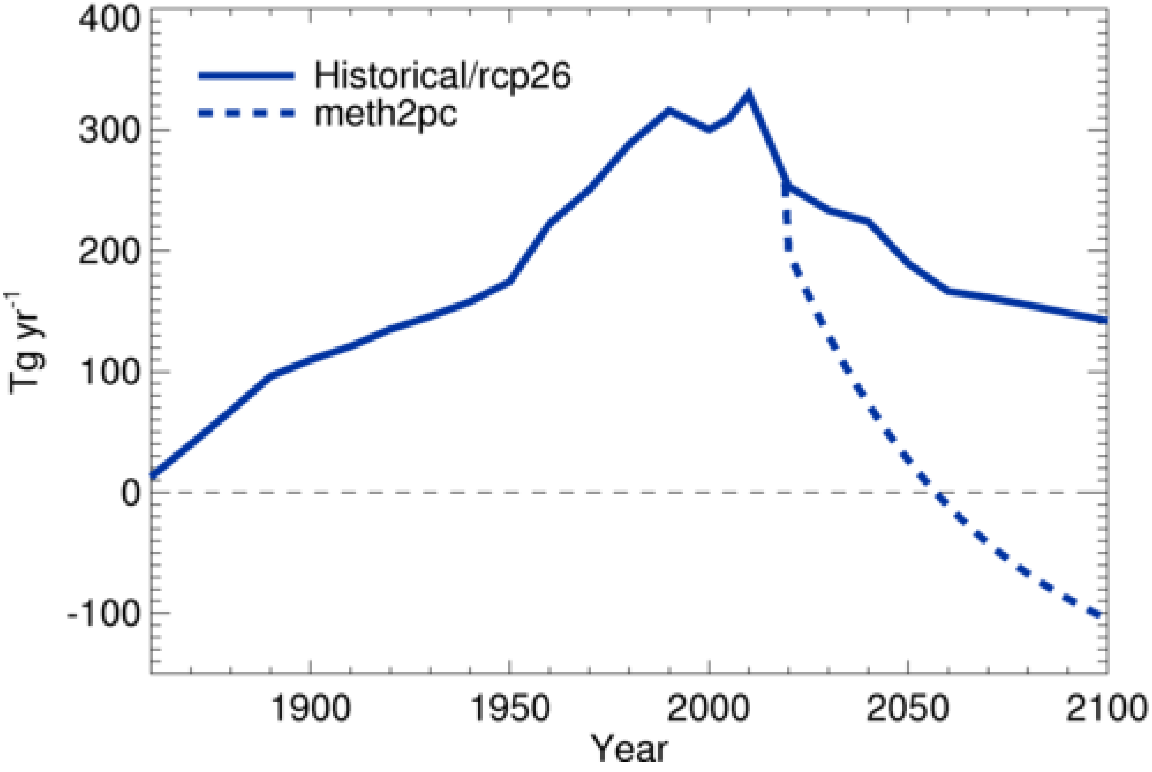

Figure 3. Anthropogenic methane emissions (Tg yr^{-1}) inferred from concentrations prescribed in HadGEM2-ES simulations.