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2015 Environ. Res. Lett. 10 075001

(http://iopscience.iop.org/1748-9326/10/7/075001)

Environmental Research Letters

OPEN ACCESS

RECEIVED
1 April 2015

REVISED
4 June 2015

ACCEPTED FOR PUBLICATION
5 June 2015

PUBLISHED
10 July 2015

LETTER

Impact of short-lived non-CO_2 mitigation on carbon budgets for stabilizing global warming

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Keywords: climate change, carbon budget, cumulative carbon, short-lived climate pollutants, global warming, carbon dioxide

Supplementary material for this article is available online

Abstract

Limiting global warming to any level requires limiting the total amount of CO_2 emissions, or staying within a CO_2 budget. Here we assess how emissions from short-lived non-CO_2 species like methane, hydrofluorocarbons (HFCs), black-carbon, and sulphates influence these CO_2 budgets. Our default case, which assumes mitigation in all sectors and of all gases, results in a CO_2 budget between 2011–2100 of 340 PgC for a >66% chance of staying below 2°C, consistent with the assessment of the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Extreme variations of air-pollutant emissions from black-carbon and sulphates influence this budget by about ±5%. In the hypothetical case of no methane or HFCs mitigation—which is unlikely when CO_2 is stringently reduced—the budgets would be much smaller (40% or up to 60%, respectively). However, assuming very stringent CH_4 mitigation as a sensitivity case, CO_2 budgets could be 25% higher. A limit on cumulative CO_2 emissions remains critical for temperature targets. Even a 25% higher CO_2 budget still means peaking global emissions in the next two decades, and achieving net zero CO_2 emissions during the third quarter of the 21st century. The leverage we have to affect the CO_2 budget by targeting non-CO_2 diminishes strongly along with CO_2 mitigation, because these are partly linked through economic and technological factors.

1. Introduction

A near-linear relationship between cumulative emissions of carbon dioxide (CO_2) and peak global-mean temperature increase is seen in many climate models, and the ratio between these two quantities is referred to as the transient climate response to cumulative emissions of carbon (TCRE). TCRE is defined as the global-mean surface temperature increase for an emission of 1000 PgC to the atmosphere, and applies for cumulative emissions up to about 2000 PgC until the time temperatures peak (Collins *et al* 2013). The Working Group I (WGI) contribution to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) assesses TCRE to fall with greater than 66% probability—'likely' in the calibrated uncertainty language of the IPCC (Mastrandrea *et al* 2010)—within the range of 0.8–2.5 °C (Collins *et al* 2013, Technical Summary in IPCC 2013).

As a consequence of the near-linear relationship between cumulative carbon emissions and peak temperature, a CO_2 budget can be computed that defines the emissions compatible with limiting peak warming to below a given temperature limit with a given probability. IPCC AR5 WGI computed that to limit CO_2-

induced warming to below 2°C with at least 33, 50, and 66% probability, the corresponding compatible carbon budgets would be 1570, 1210 and 1000 PgC, respectively[8] (Summary for Policymakers in IPCC 2013). With historical CO_2 emissions amounting to about 515 PgC ('likely' range 445–585 PgC) by 2011 (Friedlingstein *et al* 2014, Summary for Policymakers in IPCC 2013), this suggests that we have already emitted about half of the CO_2 emissions compatible with limiting warming to below 2°C with a greater than 66% chance. This interpretation would only be correct for the hypothetical case that all the warming is caused only by CO_2.

Many other, both cooling and warming, species influence the radiative balance of the Earth (Myhre *et al* 2013). As their resulting effect at the time of zero CO_2 emissions is projected to be net positive (i.e. to be a net warming effect), compatible CO_2 emissions budgets are smaller when taking into account all radiatively active species (Collins *et al* 2013, Clarke *et al* 2014, Knutti and Rogelj 2015, Technical Summary in IPCC 2013). For instance, IPCC AR5 WGI estimates that compatible CO_2 emissions from 2011 onward to limit peak global-mean temperature increase to below 2°C would be reduced to about 410, 355, and 275 PgC for having at least 33, 50, and 66% chance, respectively. Likewise, based on the Working Group III (WGIII) contribution to the IPCC AR5 (Clarke *et al* 2014, Summary for Policymakers in IPCC 2014), scenarios that have a 'likely' chance of limiting warming to below 2°C have a range of about 170–320 PgC for CO_2 emissions from 2011 to 2100. This is much lower than what would be estimated for a world in which only CO_2-induced warming would play a role. In other words, half of the CO_2 emissions compatible with limiting warming to below 2°C (with a greater than 66% chance) have been emitted if we consider only CO_2—taking also the influence of non-CO_2 species into account, however, about two thirds of 2°C-compatible CO_2 emissions have been emitted to date.

The level of non-CO_2 emissions could thus play an important role in determining the size of the CO_2 budget. Here we explore if, and by how much, the targeted mitigation of various, both cooling and warming, non-CO_2 species would influence CO_2 emissions budgets during the 21st century consistent with limiting warming to below specific temperature thresholds. We explore the potential impact of methane (CH_4), soot (or black carbon—BC), sulphate (SO_2), and hydrofluorocarbons (HFCs), and do so by accounting for possible linkages between sources of emissions of CO_2 and non-CO_2 species (see section 2).

Emission mitigation actions discussed in the framework of the United Nations Framework Convention on Climate Change (UNFCCC) focus on the so-called Kyoto-basket of greenhouse gases (GHGs). This basket contains CO_2, as well as CH_4, N_2O, HFCs, perfluorocarbons, sulphur-hexafluoride (SF_6), and nitrogen trifluoride (NF_3) (UNFCCC 1998, 2012). Actions to reduce BC and sulphates are thus not explicitly pledged under the UNFCCC. Recently, however, initiatives have been launched by other forums that focus on limiting so-called short-lived climate pollutants (SLCPs). These SLCPs consist of CH_4 and HFCs, (both controlled under the UNFCCC), the tropospheric ozone arising from CH_4, NMVOC, CO and NO_x emissions, and BC (UNEP 2011). The cooling sulphates, although also being air and climate pollutants, are not considered under the group of SLCPs.

It is well-established that, unlike for CO_2, the annual rate rather than the cumulative emissions of SLCPs have the strongest effect on peak warming (Smith *et al* 2012, Bowerman *et al* 2013, Pierrehumbert 2014, Rogelj *et al* 2014c). Moreover, despite not being directly covered by actions undertaken under the UNFCCC, also some SLCPs (including BC) will be strongly reduced by mitigation measures to limit cumulative CO_2 emissions (figure 1; Rogelj *et al* 2014b, Rogelj *et al* 2014c). This is because CO_2 and some SLCPs are emitted by common sources. For example, many combustion processes, like diesel engines, release both CO_2 and BC. If diesel engines are phased out because CO_2 emissions are limited, the BC emissions that originally originated from these engines disappear.

2. Methods

Based on an initial scenario set of almost 200 scenarios (Rogelj *et al* 2011), we construct a set of cases that allow an assessment of the influence of SLCP mitigation on CO_2 budgets. Each of the original scenarios contains an internally consistent set of both CO_2 and non-CO_2 emission trajectories over the 21st century. We here use a set of earlier published methods (Rogelj *et al* 2014b, Rogelj *et al* 2014c) to recalculate new, internally consistent baseline emissions for CH_4, BC, co-emitted species like organic carbon (OC), and SO_2, and compare these to stringent emission mitigation pathways. These new baselines are required to allow an assessment of the maximum effect of non-CO_2 mitigation on CO_2 budgets: the difference between a mitigation path and a baseline in absence of mitigation targeting a specific non-CO_2 forcer.

CH_4, BC, and SO_2 are affected differently by CO_2 mitigation (figure 1). For BC, OC, SO_2 and other co-emitted pollutant emissions, we use a tool provided by Rogelj *et al* (2014b) that allows to calculate consistent global relationships between CO_2 and these air-pollution species. Default baseline emissions for these air pollutants assume that current air-pollution

[8] This assumes the 0.8–2.5°C range to approximately correspond to the one-standard-deviation range (1 sigma or about 68%) of a normal Gaussian distribution.

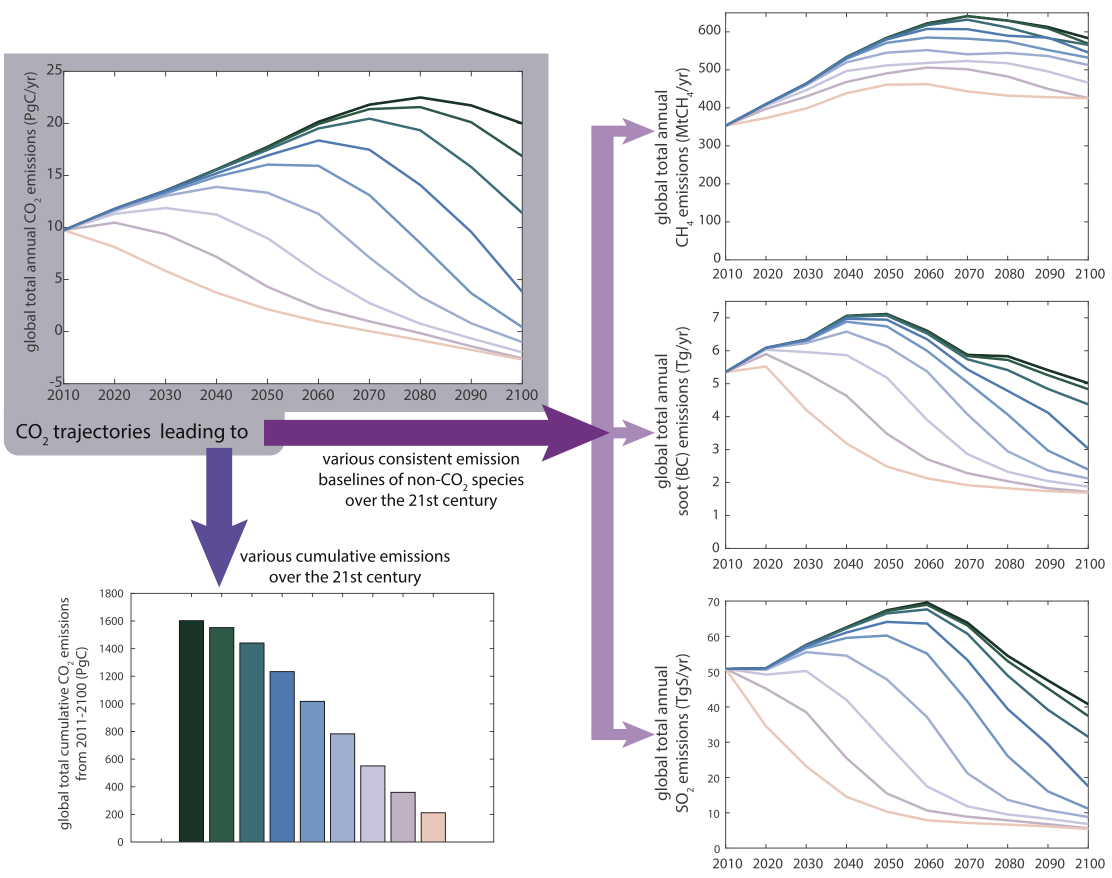

Figure 1. Schematic representation of trajectories of radiatively active non-CO_2 species consistent with various cumulative CO_2 emissions over the 21st century.

legislation is fully implemented and that global air-quality standards converge in line with regional economic development. This baseline also assumes that with increasing economic development an increasingly larger share of the population will get access to clean sources of energy (Pachauri *et al* 2012, Rogelj *et al* 2014c). The mitigation path for BC and its co-emitted species mimics the 'all measures' case developed by the UNEP SLCP report (UNEP 2011) until 2030 and is further projected throughout the century as described by Rogelj *et al* (2014c). The mitigation path for SO_2 assumes that stringent air-pollution controls are implemented over the 21st century (see Rogelj *et al* 2014b).

Also three alternative baselines are constructed for a sensitivity analysis: two with air-pollution legislation frozen at its 2005 levels throughout the 21st century for BC and SO_2/NO_x, respectively. In these two baselines, no improvements for BC or SO_2/NO_x air-pollution legislation are assumed to have occurred over the last decade and the stringency of air-pollution control is frozen at its 2005 levels throughout the 21st century for BC and SO_2/NO_x, respectively. These assumptions represent a counterfactual evolution of air-pollution control over the past decade, and a failure to effectively implement any additional air-pollution measures in the future. A third alternative baseline includes no targeted energy access policies (see table 1 and Rogelj *et al* 2014b for details). Under the latter assumption, large shares of the global population remain without access to clean energy until the end of the century. The use of traditional biomass for cooking and heating is currently a major source of anthropogenic BC emissions globally (Pachauri *et al* 2012).

For CH_4, we follow the method presented in Rogelj *et al* (2014c) to create CH_4 baselines consistent with each respective CO_2 emission trajectory. This method applies no common carbon price to CO_2 and CH_4, but only to CO_2. Because CO_2 and CH_4 have few common sources, CH_4 baseline emissions do not vary much across a wide range of CO_2 emission pathways (figure 1). These CH_4 baseline emissions are then compared to a very stringent CH_4 mitigation path, derived from a model with particularly strong CH_4 reduction response to, for example, increasing carbon prices (van Vuuren *et al* 2011). Also a case assuming a 20-year delay of these stringent CH_4 measures is constructed.

For HFCs, we use updated HFC baseline estimates (Velders *et al* 2009) and assess their influence relative to earlier estimates (Nakicenovic and Swart 2000) as described in Rogelj *et al* (2014c). These estimates are the high end of the literature (Gschrey *et al* 2011).

Table 1. Overview and description of cases and sensitivity cases assessed in this study. Accompanying references can be found in the main text.

Case	Description
Reference case	Case with internally consistent evolutions of air pollutants at the level of current legislation. This implies that global air-pollution control converges, along with regional economic development, to current best levels of air-pollution control. Also along with regional economic development, rural populations gradually gain access to clean forms of energy. Reductions in CH_4 are driven by the same carbon price as reductions in CO_2.
No CH_4 mitigation	As reference case, but no carbon-price-induced reductions of CH_4. CH_4 emissions are only reduced to a small degree as a result of technical linkages to CO_2 mitigation (see figure 1).
Stringent CH_4 mitigation	As reference case, but CH_4 emissions follow a very stringent mitigation path (from RCP2.6) which is situated at the very low end of the CH_4 mitigation literature range.
Delayed stringent CH_4 mitigation	As stringent CH_4 mitigation case, but with a 20-year delay of reduction.
BC measures	As reference case, but with BC and co-emitted species reduced very stringently, in line with the 'all measures' case of UNEP/WMO (2011). This impacts emissions from BC, OC, NMVOC, and CO.
Frozen BC baseline	As reference case, but instead of assuming the level of current legislation, BC and co-emitted species are subject to air-pollution controls frozen at their 2005 levels throughout the entire 21st century.
No energy access policies	As reference case, but instead of assuming no specific energy access policies at all during the entire 21st century, resulting in large populations still lacking access to clean sources of energy by the end of the century.
SO_2 measures	As reference case, but SO_2 is subjected to stringent air-pollution controls in the future.
Frozen SO_2 and NO_x baseline	As reference case, but instead of assuming the level of current legislation, SO_2 and NO_x are subject to air-pollution controls frozen at their 2005 levels throughout the entire 21st century.
Updated HFC projections	As reference case, but with updated HFC projections for the 21st century which represent the high-end of the literature.

The 'reference case' of our study includes internally consistent baseline evolutions for air pollutants that all follow an extrapolation of current policies, as well as the original CH_4 and HFC pathways from Rogelj *et al* (2011). Note that carbon-price or policy effects *are* typically included in the CH_4 and HFC 'reference case' pathways which are found in the literature. To explore the maximum range, these carbon-price effects are excluded in our CH_4 and HFC baselines. However, CH_4 baselines still change as a function of CO_2 mitigation, not due to a carbon price but because some sources of CH_4 are phased out together with CO_2 mitigation (figure 1).

Comparing the various baseline, sensitivity and reference cases will provide us with an estimate of the potential effects of a set of policy interventions, which are, however, rarely fully independent from CO_2 mitigation. While BC and SO_2 emissions are coupled to CO_2 mitigation by co-emission from economic activities and technologies, CH_4 and HFCs are coupled to CO_2 mitigation by multi-gas carbon-price/policy effects, resulting from multilateral agreements under the UNFCCC and/or national policies.

The temperature outcome of each scenario variation is assessed with the reduced-complexity carbon-cycle and climate model MAGICC, version 6 (Meinshausen *et al* 2011a), in a probabilistic setup that is consistent with the IPCC AR5 WGI climate sensitivity assessment (Meinshausen *et al* 2009, Rogelj *et al* 2012, Rogelj *et al* 2014a). Temperature increase is computed relative to preindustrial levels (1850–1875). Global-mean temperature projections and assessing associated uncertainties are a key application for which MAGICC has been extensively vetted (Meinshausen *et al* 2011b). For each scenario, the 50%, 66% or other percentiles are computed out of a sample of 600 climate model runs; a cubic smoothing spline (smoothing parameter: 5×10^{-9}) is computed to show the general dependence of maximal target temperature versus cumulative CO_2 emissions (figure 2(A)). Alternative appropriate values for either smoothing parameter or fit type do not change our main conclusions.

3. Results

We here look at how CO_2 budgets consistent with limiting warming to below a specific temperature limit by 2100 are influenced by the mitigation of short-lived non-CO_2 species. As introduced earlier, to first order, annual emissions of short-lived non-CO_2 species leading up to the time of the peak play the most important role for peak warming (Smith *et al* 2012). Therefore mitigation actions on these species are only important insofar as they effectively reduce the annual emission burden of short-lived non-CO_2 species around the time of peak (or maximum) warming during the 21st century. In most temperature stabilisation scenarios, peak warming is reached by the last quarter of the 21st century. Scenarios with little CO_2 mitigation reach their maximum warming during the 21st century only by 2100, and are still increasing afterwards. Any scenario that does not reach zero or lower annual CO_2 emissions by 2100, will exhibit further warming after the 21st century.

Results are reported as relative changes to the 'reference case' (tables 1 and 2). Absolute values are reported in table S1.

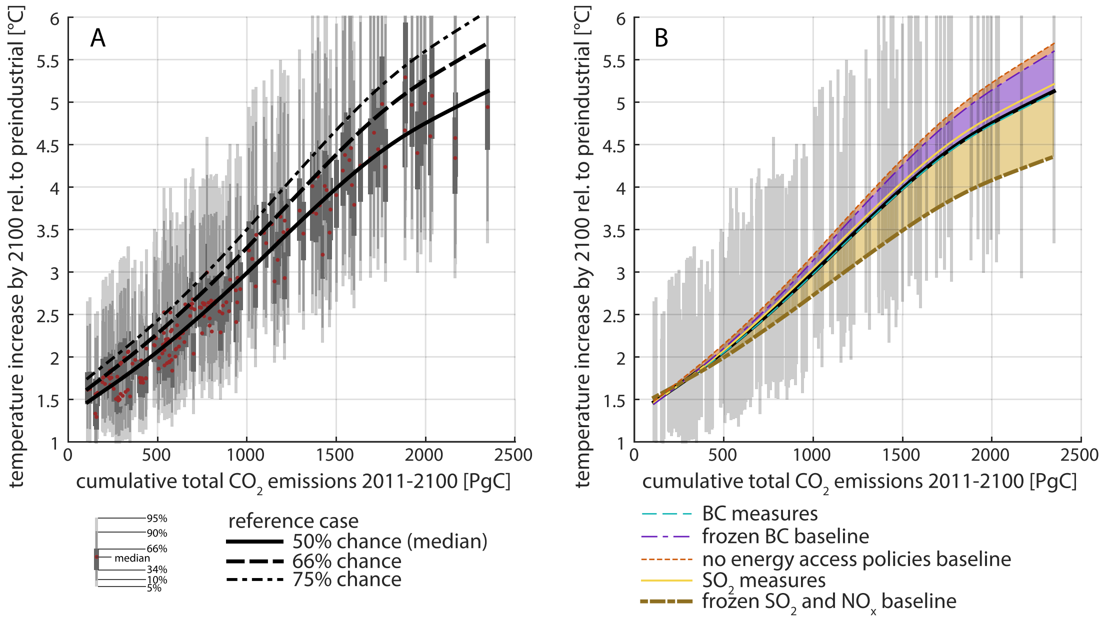

Figure 2. Dependence of carbon budgets consistent with a particular temperature limit during the 21st century. Panel A shows the distribution of global-mean temperature outcomes per scenario and smoothing splines for the outcomes at the 50, 66 and 75% probability level. Panel B shows how the median outcome would change when assuming alternative mitigation of non-CO_2 air-pollutant species. Panel B shows smoothing splines for the medium temperature outcome for each case, respectively. The shaded ranges are visual guides. Note that the full range is to be considered highly hypothetical (see section 4 in main text). Moreover, only scenarios with a temperature increase in 2100 of about 2°C and less are stabilizing temperatures by 2100. When year-2100 temperatures are higher, temperatures continue to increase past 2100 and the provided carbon budgets are thus not holding warming to below the here reported year-2100 warming in the long term.

Earlier literature has shown that mitigation measures of BC and its co-emitted species only have a limited effect on maximum 21st century temperatures (≪0.1°C) when compared to a baseline which already includes current and planned legislation (Rogelj *et al* 2014c). In the context of this study, this limited effect on maximum 21st century temperatures translates into virtually no effect (<2.5%) of 'BC measures' on CO_2 budgets (figure 2(B) and table 2, relative shifts of CO_2 budgets are rounded to the nearest 5%). This limited impact is robust across all temperature levels assessed here.

These findings are sensitive to the air-pollutant baseline evolution. Therefore sensitivity cases were created (table 1). First, when assuming a baseline without explicit energy access policies, CO_2 budgets decrease by about 5% for 2°C-compatible budgets (table 2). For higher temperature levels, this relative effect becomes smaller. Second, we assume a frozen BC baseline, representing a roll-back of future air-pollution controls over the 21st century from today's levels. In this case, maximum 21st century temperature is affected by 0–0.4°C, depending on the concurrent CO_2 mitigation. This translates in a 0–5% smaller CO_2 budget compatible with 2°C and 3°C, and 5–10% smaller CO_2 budgets compatible with 4°C by 2100 (figure 2(B)). The lower end of these ranges corresponds to higher probabilities of limiting warming to below these temperature levels. This is a logical result as to achieve higher probabilities of staying below a given temperature limit, increasingly lower CO_2 pathways are required. A discussion of the robustness and adequacy of these values is provided in the following section.

The 'BC measures' assumed in the previous paragraph only tackle sources of air pollutants that have a net warming effect. However, other air pollutants (like SO_2) exist which have a net cooling effect. SO_2 emissions are strongly linked to emissions of CO_2, and in addition, technology shifts lead to a projected steady phase-out of these emissions over the 21st century. Therefore, stringent emission reductions of SO_2 are projected to influence maximum 21st century warming to a very limited degree compared to our reference case which includes a 'current legislation' baseline, and their influence on CO_2 budgets consistent with particular temperature limits is therefore assessed to be virtually zero. Assuming that SO_2 controls are frozen at their 2005 levels, however, would increase the CO_2 budget for limiting median global-mean temperature to below 2, 3, and 4°C, by 10, 15, and 25%, respectively. For higher probabilities, this effect is smaller (table 2).

In the CH_4 pathways of our 'reference case' typically a multi-gas mitigation approach was pursued (e.g., Clarke *et al* 2009). This means that CH_4, and other gases of the Kyoto-GHG basket, are targeted together with CO_2 by means of a common carbon price and a metric translating non-CO_2 emissions into CO_2-equivalent emissions (for example, 100-year

Table 2. Carbon budgets between 2011 and 2100 in line with limiting warming to specific temperature limits with a particular probability level during the 21st century, and their relative changes (rounded to the nearest 5 PgC and nearest 5%). Note that all cases are not equally plausible across the various temperature levels (see section 4 in main text). Absolute emission values are in PgC (=GtC). Corresponding values in $GtCO_2$ are obtained by multiplying the reported values by a factor of 3.66. Note that only for the 1.5°C and 2°C temperature limits the results reflect the change in peak warming budgets. For both the 3°C and 4°C limit, CO_2 emissions are not at or below zero by 2100 and temperatures are thus not yet stabilized. In the latter case, the budget shifts are driven by changes in transient warming in 2100 rather than peak warming during the 21st century.

Carbon budgets between 2011–2100				
Temperature (*T*) limit relative to preindustrial levels	1.5°C	2°C	3°C	4°C
50% chance of staying below T limit in 2100				
Reference case	130 PgC	460 PgC	1005 PgC	1510 PgC
Relative changes:				
No CH_4 mitigation	*ND*	−35%	−15%	−5%
Stringent CH_4 mitigation	+75%	+20%	+20%	+25%
Delayed stringent CH_4 mitigation	+55%	+15%	+15%	+25%
BC measures	+5%	0%	0%	0%
Frozen BC baseline	+10%	−5%	−5%	−10%
No energy access policies	−20%	−5%	−5%	0%
SO_2 measures	5%	0%	−5%	−5%
Frozen SO_2 and NO_x baseline	*ND*	10%	15%	25%
Updated HFC projections	*ND*	−20% to −45%	−10% to −15%	−5% to −10%
66% chance of staying below T limit in 2100				
Reference case	*ND*	340 PgC	870 PgC	1325 PgC
Relative changes:				
No CH_4 mitigation	*ND*	−40%	−20%	−5%
Stringent CH_4 mitigation	*ND*	+25%	+20%	+25%
Delayed stringent CH_4 mitigation	*ND*	+20%	+15%	+20%
BC measures	*ND*	0%	0%	0%
Frozen BC baseline	*ND*	0%	−5%	−10%
No energy access policies	*ND*	−5%	0%	0%
SO_2 measures	*ND*	0%	−5%	−5%
Frozen SO_2 and NO_x baseline	*ND*	5%	15%	20%
Updated HFC projections	*ND*	−30% to −60%	−10% to −20%	−5% to −15%
75% chance of staying below T limit in 2100				
Reference case	*ND*	260 PgC	780 PgC	1210 PgC
Relative changes:				
No CH_4 mitigation	*ND*	−50%	−20%	−10%
Stringent CH_4 mitigation	*ND*	+35%	+15%	+20%
Delayed stringent CH_4 mitigation	*ND*	+25%	+10%	+20%
BC measures	*ND*	+5%	0%	0%
Frozen BC baseline	*ND*	0%	−5%	−5%
No energy access policies	*ND*	−5%	0%	0%
SO_2 measures	*ND*	0%	−5%	−5%
Frozen SO_2 and NO_x baseline	*ND*	−5%	15%	20%
Updated HFC projections	*ND*	*ND* to −40%	−10% to −25%	−5% to −15%
COMPARISON				
IPCC AR5 WGIII table SPM.1				
(Summary for Policymakers and chapter 6 in IPCC 2014)				
'likely' (>66%) probability	*ND*	170–320 PgC	170–665 PgC	170–1360 PgC
'more likely than not' (>50%) probability	*ND*	260–390 PgC	700–910 PgC	*ND*
'about as likely as not' (33–66%) probability	*ND*	270–420 PgC	*ND*	*ND*

ND: no data

Global-Warming-Potentials, as currently under the UNFCCC). By contrast, in our baselines for CH_4, we decoupled CH_4 from CO_2 mitigation by assuming that the carbon price is only applied to CO_2. When switching CH_4 pathways in all scenarios to this hypothetical baseline, CO_2 budgets for limiting warming to specific temperature levels during the 21st century are reduced across all scenarios, but with important variations. For limiting warming to below 2°C, CO_2 budgets consistent with a 50, 66, and 75% chance of success are reduced by 35, 40, and 50% respectively (table 2). For higher temperature limits, this change is smaller (figure 3(A), table 2), because for higher CO_2 budgets the 'reference case' includes higher *reference* CH_4 emissions due to a lower (implied) common carbon-price pressure in the original scenarios.

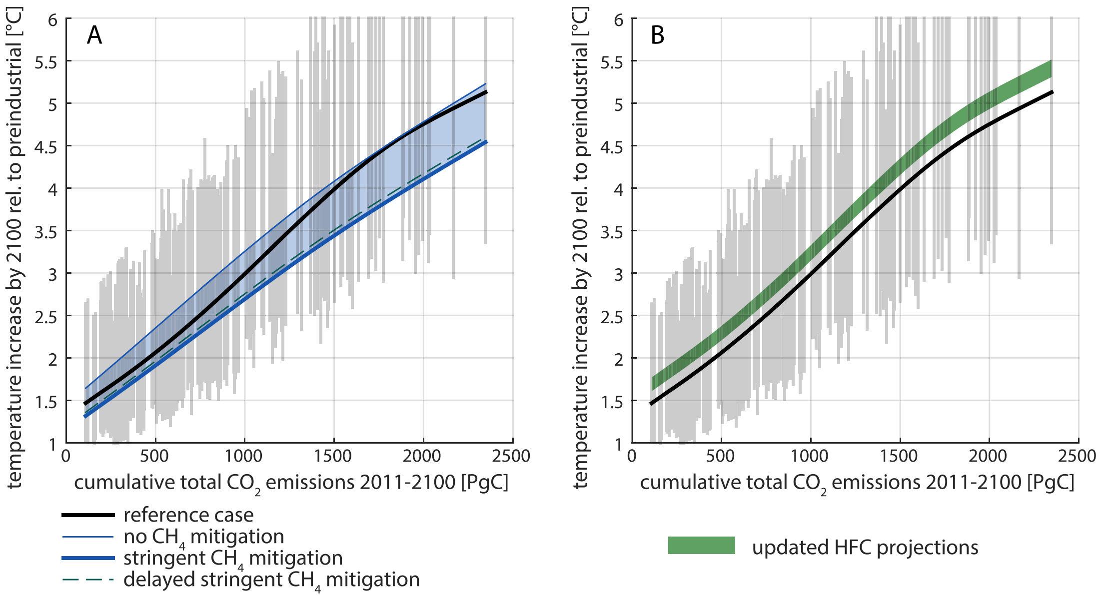

Figure 3. Dependence of carbon budgets consistent with a particular temperature limit during the 21st century. Vertical lines represent the 5th to 95th percentile range around the 'reference case' (see text). Panel A shows how the median outcome would change when assuming alternative levels of CH_4 mitigation. Panel B shows how the median outcome would change when taking into account updated baseline projections for HFCs. Note that accounting for common carbon-price signals already brings our 'reference case' at low CO_2 budgets down towards the stringent CH_4 reduction case (panel A), while at high carbon budgets the opposite is true. Not all cases are equally plausible across the various temperature levels (see section 4 in main text). Only scenarios with a temperature increase in 2100 of about 2°C and less are stabilizing temperatures by 2100. When year-2100 temperatures are higher, temperatures continue to increase past 2100 and the provided carbon budgets are thus not holding warming to below the here reported year-2100 warming in the long term.

Alternatively, if CH_4 pathways are all switched to a very stringent mitigation path (van Vuuren *et al* 2011) CO_2 budgets for limiting warming to below 2°C are increased by 20, 25, and 35%, for achieving a probability of 50, 66, and 75%, respectively. These relative shifts are similar for higher temperature limits, yet become increasingly less plausible (see discussion). When delaying this shift towards a stringent CH_4 mitigation path by 20 years, CO_2 budgets for 2°C are increased by about 5% less.

Finally, the high end of recent projections of HFCs are significantly higher than earlier estimates. Not tackling this projected increase strongly reduces the CO_2 budgets consistent with 50% probability of keeping warming to below 2, 3, and 4°C, by 20–45%, 10–15%, and 5–10%, respectively (table 2, figure 3(B)). In some cases, the highest updated HFC projections would push the achievability of staying below low temperature levels with high probability (66 or 75%) beyond the here assessed scenario literature. Given that our HFC assumptions are based on the highest available literature estimates and also lower—equally plausible—estimates are available, our results should also be read as upper-limit estimates.

4. Discussion

4.1. Comparison to IPCC AR5 ranges

To situate our analysis within the wider literature, we compare our results with the transformation pathway assessment of the IPCC AR5 (table 6.3 in Clarke *et al* 2014). IPCC AR5 WGIII provides ranges of cumulative CO_2 emissions for limiting warming to specific temperature levels with a given probability (table SPM.1 in IPCC 2014). For several temperature-probability combinations, a comparison with the data of this study can be made (table 2), which shows that our results are broadly consistent with the WGIII scenario assessment of the IPCC AR5.

In our 'reference case', limiting warming to below 2°C relative to preindustrial levels with 75, 66, or 50% chance would imply cumulative carbon emissions between 2011 and 2100 to be limited to 260, 340, and 460 PgC. This compares to IPCC ranges of assessed cumulative CO_2 emissions over the same period for limiting warming to below 2°C of 170–320, 260–390, and 270–420 PgC, for a >66%, >50%, and 33–66% probability, respectively. Our 2011–2100 CO_2 budget estimates for the higher probabilities (for instance, 340 and 260 PgC for 66% and 75% chance, respectively), both fall well within the IPCC ranges for a >50% and >66% probability, respectively. Our estimate for a >50% probability is slightly larger than the IPCC's 33–66% range. This is consistent with the understanding that the IPCC AR5 WGIII assessment of transformation pathways does not just use the direct model output of the MAGICC model but also further accounts for uncertainties of the temperature projections which are not covered by climate models (and which were assessed by WGI). In other words, the

IPCC conservatively interpreted the raw output numbers of their probabilistic model setup when translating them into the calibrated IPCC uncertainty language. This results in budget estimates that tend to be lower than what would be derived directly from model output. Finally, also 2011–2100 CO_2 budgets consistent with limiting warming to higher temperature levels over the 21st century, for example a 3 or 4°C warming, are found to be consistent with the IPCC—again, taking into account that the results and numbers in this paper reflect the direct probabilistic output of the MAGICC model simulations, while the IPCC further assessed these probabilities in light of possible limitations in our current understanding of the climate response.

4.2. Applicability and limitations

The magnitude of the effect of non-CO_2 mitigation on CO_2 emission budgets across 2°C and 4°C scenarios is strongly affected by the expected baseline range of the non-CO_2 emissions in these scenarios. These emissions may vary to a much larger extent in a 4°C scenario where CO_2 emissions are relatively high by the end of the century (figures 2 and 3). This is because even when not specifically targeted, non-CO_2 emissions can still be reduced by CO_2 mitigation. Emissions of air pollutants like BC can be emitted by the same sources as CO_2. Hence, in a world with stringent CO_2 mitigation, air-pollution baseline emissions (in absence of any targeted air-pollution control) will already be much lower than in a world with high CO_2 emissions (Rogelj *et al* 2014b). Therefore, measures that target air-pollution species would allow a larger absolute amount of air pollution to be removed in a 4°C world compared to a 2°C world, where the baseline air pollution levels are much lower because sources common with CO_2 have been phased out.

Likewise, emissions of CH_4 by 2100 would be much higher in scenarios that reach high end-of-century warming, and the effect of policies targeting CH_4 specifically would be larger. This is because of two reasons. First, CH_4 emissions are to a limited degree coupled to technologies that also emit CO_2, and are thus slightly reduced through mitigation targeting CO_2 only. Second, price signals like carbon prices lead to CH_4 emissions being reduced along with CO_2. It is important to note that the inclusion of this price signal linkage in our 'reference case' pushes CH_4 emissions at low CO_2 budgets down towards the stringent CH_4 reduction case, while at high carbon budgets a lack of price signals results in CH_4 emissions towards the high no-mitigation baseline (figure 3(B)).

Emission (reductions) of CO_2 and other species are often coupled because of physical/technological links (a certain technology emits both CO_2 and a host of other species), or an economic and policy link (an entire basket of gases is made subject to a single carbon price, e.g. in the UNFCCC). Taking into account these links, we find that the effectiveness of targeting non-CO_2 species individually is reduced in stringent CO_2 mitigation scenarios. In other words, initiatives that target individual species provide less additional benefits (or have a decreased '*additionality*') when CO_2 emissions are stringently reduced. Furthermore, our results also provide an indication of how much displacement (in terms of cumulative CO_2) can be tolerated without exhausting the CO_2 budget benefits of, for example, stringent early CH_4 abatement (supplementary table 1).

An important limitation of our estimated effects of non-CO_2 mitigation on CO_2 budgets is that for temperature levels higher than 2°C, global-mean temperature is not yet stabilized by 2100, as annual CO_2 emissions in 2100 in such scenarios are not yet at or below zero. Only for the lowest temperature levels (<2°C), scenarios thus actually represent realistic pathways towards keeping warming to below the levels indicated in the long term. For higher temperature levels, the estimated effects of non-CO_2 mitigation are to be considered transient and impermanent. This also explains the larger effect of non-CO_2 mitigation on CO_2 budgets for higher temperature levels—in some sense an artefact of the limited time horizon of this study, which only extends until the end of the 21st century. A second aspect, which works in the opposite direction, is the simple fact that CO_2 budgets consistent with higher temperature limits are larger and absolute changes therefore translate in smaller relative changes. If the time horizon would extend beyond 2100, the relative influence of non-CO_2 mitigation on CO_2 budgets for temperature limits higher than 2°C is expected to decline.

Because assumptions of socio-economic scenarios become increasingly uncertain when going more than 100 years into the future, our analysis is limited to the 21st century and therefore provides results for maximum 21st-century warming only. This maximum 21st-century warming either occurs at peak warming in case of stringent mitigation scenarios which keep warming to below 2°C, or in 2100 for scenarios that do not stabilise temperatures during the 21st century. However, the trade-offs that were quantified between CH_4 mitigation and CO_2 budgets also have to be seen in a longer-term context. Over longer timescales and for the same global warming in 2100, cases with larger CO_2 budgets and more stringent CH_4 abatement have more committed, irreversible long-term warming, than cases with lower CO_2 budgets and higher CH_4. In the latter case, the possibility of bringing down temperature by later action on methane beyond 2100 is left open.

Most of these scenarios assume global mitigation action to start at a time point that lies in the past (2005 or 2010). Recently, many studies have provided scenarios that start mitigation at later points in time and thus explicitly delay near-term mitigation (Kriegler *et al* 2013, Luderer *et al* 2013, Rogelj *et al* 2013a, Rogelj et al 2013b, Riahi et al 2015, Tavoni et al 2015). While such delays strongly impact the technology feasibility and costs of scenarios, as well as transient temperature levels (Rogelj et al 2013a, Schaeffer et al 2013), the anticipated impact on CO_2 budgets consistent with limiting warming to below 2°C is anticipated to be small.

Our cases have been developed to span the widest range of conceivable sensitivity cases. However, not all combinations remain equally plausible. For instance, given the already existing and operational policy instruments under the UNFCCC for mitigating the entire Kyoto-GHG basket, it is already counterfactual today to assume that no CH_4 mitigation occurs when CO_2 is reduced. Also for the future, it is thus plausible that CO_2 and CH_4 mitigation will be linked. Likewise, given that our assumed CH_4 mitigation path is extremely ambitious (Smith and Mizrahi 2013, Rogelj et al 2014c, Smith et al 2014), it is highly unlikely that it can be achieved if CO_2 emissions rise to levels in line with 3°C and higher. Finally, both our sensitivity BC and SO_2 frozen legislation baselines are highly hypothetical. It is difficult to conceive a future in which local policymakers strongly target air pollution from soot, but at the same time keep sulphate controls frozen at historical levels, or vice versa. As figure 2(B) indicates, freezing air-pollution legislation across the board (both BC and SO_2) would result in an overall cooling.

5. Conclusion

In conclusion, we have quantified the possible influence of short-lived non-CO_2 mitigation on CO_2 budgets consistent with limiting warming to various levels during the 21st century. The most meaningful findings are for 2°C, as for this level temperatures are actually stabilized by 2100, and peak warming has thus been reached. Our study looked at warming during the 21st century. If 21st-century reductions of short-lived climate forcers are traded with reductions in CO_2, warming during the 21st century might be the same, but the multi-century warming commitment would still be larger due to larger cumulative CO_2 emissions.

We find that mitigation of air-pollution species (both warming and cooling) barely affects consistent CO_2 budgets. That is largely because a phase-out of CO_2 emissions would lead to reductions of co-emitted emissions as their sources disappear.

Very stringent CH_4 mitigation can markedly influence 2°C-consistent budgets, at the expense of a higher post-2100 CO_2 warming commitment. However, this influence depends strongly on the realism of the very low CH_4 scenario that was used here, or on the hypothetical case in which no CH_4 mitigation would be undertaken at all. Delaying stringent CH_4 mitigation by 20 year still yields a comparably large benefit as immediate stringent CH_4 mitigation. Similarly, updated HFC baseline projections could trigger substantial extra warming that would constrain the remaining CO_2 budget. However, for both CH_4 and HFCs, mitigation options and policy instruments are readily available.

Although our results indicate relatively large hypothetical variations of the remaining CO_2 budget, the real-world effects of more or less stringent mitigation action on CH_4 are likely much more limited. Thus, our results can be seen as an exercise to sketch the boundaries of the sensitivity. Even in case of very stringent CH_4 mitigation, the CO_2 budget's increase would not in any way change the fundamental necessity to limit the cumulative amount of CO_2 emissions and hence to phase-out unabated fossil-fuel emissions to net zero or below, likely earlier rather than later in the second half of the 21st century.

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