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Increased importance of methane reduction for a 1.5 degree target

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Abstract

To understand the importance of methane on the levels of carbon emission reductions required to achieve temperature goals, a processed-based approach is necessary rather than reliance on the transient climate response to emissions. We show that plausible levels of methane (CH_4) mitigation can make a substantial difference to the feasibility of achieving the Paris climate targets through increasing the allowable carbon emissions. This benefit is enhanced by the indirect effects of CH_4 on ozone (O_3). Here the differing effects of CH_4 and CO_2 on land carbon storage, including the effects of surface O_3, lead to an additional increase in the allowable carbon emissions with CH_4 mitigation. We find a simple robust relationship between the change in the 2100 CH_4 concentration and the extra allowable cumulative carbon emissions between now and 2100 (0.27 ± 0.05 GtC per ppb CH_4). This relationship is independent of modelled climate sensitivity and precise temperature target, although later mitigation of CH_4 reduces its value and thus methane reduction effectiveness. Up to 12% of this increase in allowable emissions is due to the effect of surface ozone. We conclude early mitigation of CH_4 emissions would significantly increase the feasibility of stabilising global warming below 1.5 °C, alongside having co-benefits for human and ecosystem health.

1. Introduction

Meeting the Paris temperature targets by reducing CO_2 emissions alone represents a huge challenge, even for the more optimistic assessments of the allowable carbon budgets (Millar *et al* 2017). Most existing scenarios that avoid 2 °C of global warming, and almost all of those that avoid 1.5 °C, assume periods of negative global CO_2 emissions in order to stay within the implied cumulative carbon budgets (Rogelj *et al* 2015a). This is via the widespread deployment of carbon dioxide removal (CDR) (Smith 2016) which might not be as effective as assumed (Harper *et al* 2018). Any additional options for mitigating greenhouse gases can therefore increase the feasibility of this challenge.

The transient climate response to emissions (TCRE) has proved useful in illustrating the dependence of temperature on the cumulative emissions of CO_2. However care needs to be taken as the scenarios used in the IPCC 5th Assessment Report (AR5) (Pachauri *et al* 2014) assumed specific changes in non-CO_2 agents such as aerosols and CH_4. These calculations also did not include biogeochemical feedbacks that might affect the concentrations of the greenhouse gases such as changes in permafrost and wetlands (Comyn-Platt *et al* 2018). The relationship between cumulative carbon emissions and global temperature target will therefore depend crucially on the future mix of CO_2 and non-CO_2 agents which may differ significantly from that assumed in AR5. As a consequence cumulative carbon budgets are very sensitive to assumptions in scenarios for non-CO_2 greenhouse gases (Rogelj *et al* 2015b).

Mitigation of anthropogenic CH_4 emissions leads to rapid decreases in its concentration, with an approximately 12 year response time. CH_4 mitigation therefore offers potential for rapidly reducing climate warming, either in the near-term to prevent a temporary exceedance of the 1.5 or 2.0 °C peak warming threshold, or later in the century to bring down temperatures after an overshoot of temperature to higher levels. A recent study (Stohl *et al* 2015) found that inexpensive or even cost negative CH_4 mitigation options could reduce 2050 temperatures by 0.25 °C.

Methane has a direct radiative forcing of climate. It is the second largest contributor to anthropogenic forcing over the historical period, and its atmospheric chemistry leads to O_3 and water vapour, themselves GHGs, adding to the forcing (Myhre *et al* 2013). Changes to atmospheric CH_4, O_3 and CO_2 will also affect the ocean and land carbon cycles, through direct warming effects (climate-carbon feedbacks), increasing the rates of plant respiration and decomposition of soil organic carbon. There are also indirect physiological effects of O_3, decreasing, and CO_2, increasing, plant productivity and hence carbon uptake (Sitch *et al* 2007, Collins *et al* 2010, Sitch *et al* 2008). These carbon-cycle effects are typically included in calculations of the effects of CO_2 emissions, but are currently ignored when calculating the CO_2-equivalence of non-CO_2 gases such as CH_4 (MacDougall *et al* 2013). Recent studies (Collins *et al* 2013, Gasser *et al* 2017) estimated that the climate-carbon cycle feedbacks increase the temperature impacts of CH_4 by around 20% on 100 year timescales

As a result of these typically-neglected effects, it has been argued that the total carbon budget for stabilization of the climate at about 2 °C might be much more sensitive to the atmospheric concentration of CH_4 than hereto expected (Cox and Jeffery 2010). This is likely to be even more so for a 1.5 °C target. This is because the impact on land carbon storage arising from a change in radiative forcing due to mitigation of CO_2 differs significantly from the impact of a similar non-CO_2 radiative forcing mitigation (Huntingford *et al* 2011). When including the damaging effects of surface O_3, reductions in the emissions of CH_4 have the potential to significantly increase land carbon storage.

2. Methods

2.1. IMOGEN-JULES

To understand the potential additional benefits of CH_4 reductions on allowable cumulative carbon emissions consistent with the Paris targets, we use the Joint UK Land-Environment Simulator (JULES) (Clark *et al* 2011) coupled with the intermediate complexity climate model IMOGEN 'Integrated Model Of Global Effects of climatic aNomalies' (Huntingford *et al* 2010). The combined IMOGEN-JULES framework thus provides an intermediate complexity climate-carbon modelling system. IMOGEN utilises 'pattern-scaling' to capture the main features of expected local and monthly meteorological changes interpolated to alternative future levels of global warming. This is connected to a gridded version of the land surface model JULES (version 4.8) (Clark *et al* 2011) to understand the impacts of any transition to different stable warming levels.

IMOGEN comprises a global energy balance model (EBM) whose global climate response characteristics (climate sensitivity for land and ocean, ocean diffusivity etc.) can be chosen to represent any global climate model (GCM). It is driven by time-series of CO_2 concentrations and non-CO_2 radiative forcing. IMOGEN generates gridded outputs of monthly anomaly fields of surface temperature, precipitation, humidity, windspeed, surface shortwave and longwave radiation and pressure. These anomalies are derived by scaling the patterns from the output from each GCM, assuming these are linear in global surface temperature change. Here the data from the 34 CMIP5 GCMs running the RCP8.5 scenario (Taylor *et al* 2013) are used to derive both the global climate characteristics and climate patterns. Although the greenhouse gas forcings used in this study will be closer to the RCP2.6 scenario, the RCP8.5 scenario was used to get the clearest signal to determine the climate patterns.

The JULES configuration also includes modelled O_3 damage to photosynthesis, affecting land-atmosphere CO_2 exchange (Sitch *et al* 2007). This O_3 damage parameterisation can be set to 'low' or 'high' sensitivity to span the uncertainty in our knowledge of the sensitivity of plants globally. We also include a 'no' sensitivity to allow the separation of the ozone effect. In this study we use the low sensitivity parameterisation as the standard configuration, with separate tests of the effects of using the 'no' and 'high' sensitivities. Surface O_3 concentrations are parameterised as two-dimensional fields as a function of the global average CH_4 concentration. These are previously derived from global chemistry-climate simulations using the HadGEM3 model for global mean atmospheric CH_4 mixing ratios of 1285 ppb and 2062 ppb (Stohl *et al* 2015). Within IMOGEN-JULES, the O_3 concentration is calculated at each grid point as a function of CH_4 using a linear interpolation between O_3 concentrations at the above mixing ratios.

To set the initial (2015) conditions for the land carbon stores, the IMOGEN-JULES model is spun up for 1000 years at 1850 conditions and then run to 2015 with prescribed historical CO_2 mixing ratios, land use, and global surface temperatures from Morice *et al* (2012) (reaching 0.89 °C by 2015). The spin up and historical simulation are carried out for each climate model realisation. For this study we invert the IMOGEN-JULES configuration, running forward from 2015 with specified global temperature profiles,

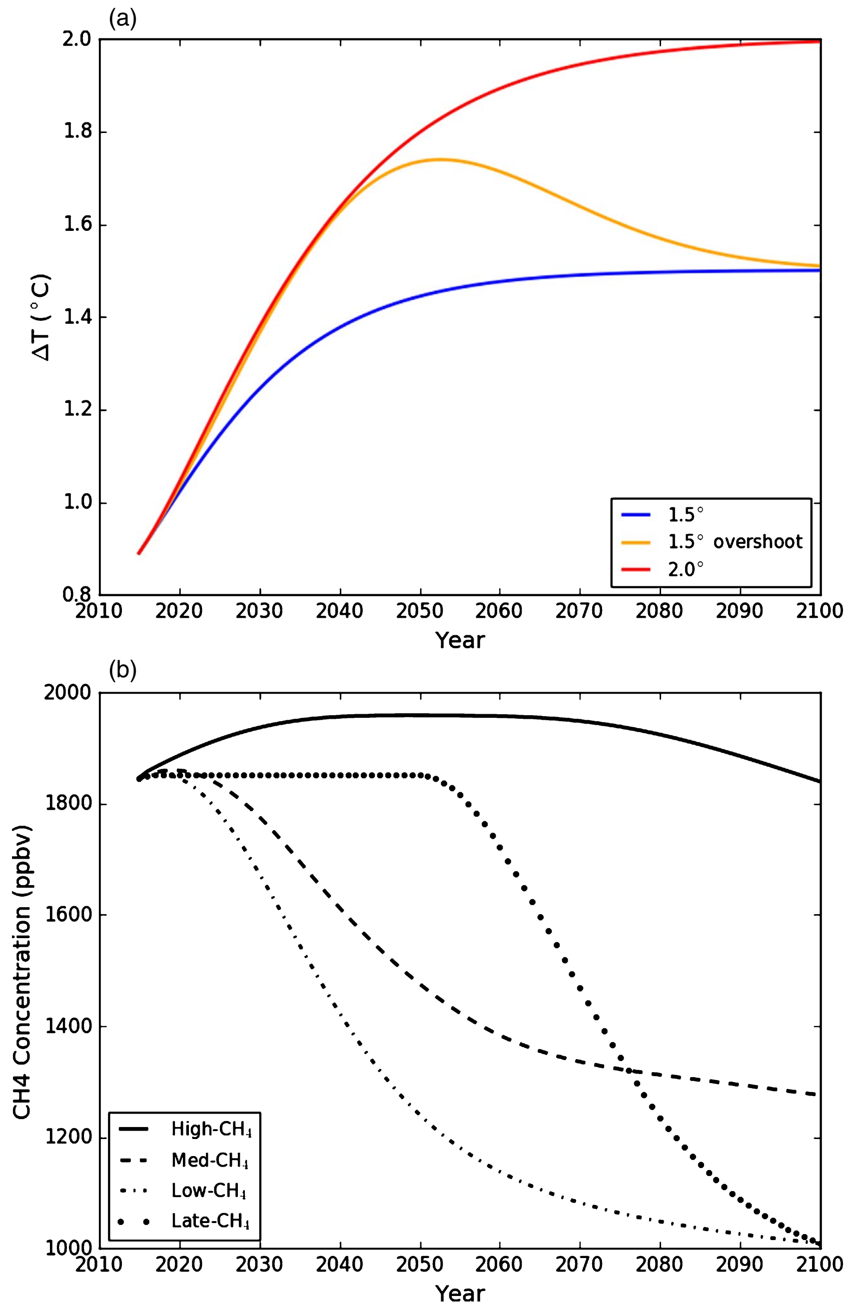

Figure 1. (*a*) The three temperature pathways used (surface temperature increases with respect to 1850). (*b*) Global mean atmospheric concentrations of CH_4 for the four scenarios.

and specified non-CO_2 radiative forcing changes from 2015. IMOGEN-JULES derives the CO_2 concentrations in each year from the EBM calculations and thence the uptake by the land biosphere; the global carbon cycle is closed with a simple description of global oceanic draw-down of CO_2 (Joos *et al* 1996). A control simulation is also run maintaining 1850 forcings and temperatures until 2100. Further details of the IMOGEN-JULES setup and the inversion procedure can be found in Comyn-Platt *et al* (2018).

2.2. Temperature and methane scenarios

We determine the carbon budgets consistent with three specified temperature trajectories that stabilise at 1.5 °C (with and without overshoot) and 2.0 °C above pre-industrial levels as shown in figure 1(*a*). These profiles are generated according to the algorithm in Huntingford *et al* (2017) as in Comyn-Platt *et al* (2018). The results are found not to be sensitive to the exact form of the temperature trajectories.

The future non-CO_2, non-CH_4 radiative forcings are taken from one of the Shared Socio-economic Pathways (SSPs) SSP2–2.6 (O'Neill *et al* 2017, Riahi *et al* 2017) by subtracting the CO_2 and CH_4 (and associated O_3 and stratospheric water vapour) contributions from the total SSP2–2.6 radiative forcing. We follow the prescription of these terms in the MAGICC climate model (Meinshausen *et al* 2011). After 2015, land-use is fixed at 2015 levels. Here, the IMOGEN physical parameters are varied to represent the climate characteristics, such as the different climate sensitivities, of 34 CMIP5 models.

There is a wide range in the CH_4 emissions in the SSPs that achieve a forcing of 2.6 W m^{-2} in 2100, suggesting that the options for mitigation are not exhausted (Gernaat *et al* 2015). We construct four different anthropogenic CH_4 mitigation scenarios (figure 1 (*b*)). The first three are 'High' CH_4 and 'Medium' CH_4 which span the highest and lowest of the SSP2–2.6, and 'Low' CH_4 which we parameterise as following the Medium scenario to 2020 then decaying faster to 62 Tg CH_4 yr^{-1} by 2100. For the High CH_4 scenario, CH_4 concentrations increase following the an upper bound of SSP4-2.6 and SSP5-2.6 CH_4 concentration projections from the GCAM integrated assessment model (IAM) (Calvin *et al* 2017). For the Medium CH_4 scenario, concentrations follow SSP2–2.6 as generated by the IMAGE 3.0 IAM (van Vuuren *et al* 2017). For the Low CH_4 scenario, we assume extra reductions are possible by removing the restriction on cost minimisation. To generate a smooth curve we parameterise emissions (in Tg CH_4 yr^{-1}) as $55 + \frac{337.25}{x^{1.337}}$, where x is the number of years after 2020. This projects a lower CH_4 projection curve than the strongest mitigation SSP storyline (SSP1–2.6 variants). The High, Medium and Low scenarios lead to year 2100 atmospheric CH_4 concentrations of 1839, 1275 and 1008 ppb, respectively. We also consider a fourth scenario 'Late', to test whether the timing of the CH_4 mitigation matters, where emissions are maintained at current (2015) levels until 2050 and then apply the same rate of mitigation for the Low CH_4 profile post-2015, but extended to ensure that the 2100 concentration matches Low CH_4. Note that we are not assuming specific methane mitigation measures in these scenarios, or possible effects on co-emitted species such as N_2O.

Emissions are converted into concentrations using the formulation of the MAGICC model (which includes natural emissions of 250 Tg CH_4 yr^{-1}). Radiative forcings for the CH_4 scenarios are calculated using formulae including the short-wave absorption (Etminan *et al* 2016), and the overlap with N_2O using the N_2O concentrations in SSP2–2.6. The contributions from O_3 and stratospheric water vapour are added in as linear functions of CH_4 mixing ratio. From IPCC AR5 (Myhre *et al* 2013) these amount to $2.36 \times 10^{-4} \pm 1.09 \times 10^{-4}$ Wm^{-2} per ppb CH_4 (0.65 ± 0.3 times the CH_4 radiative efficiency).

This spread in possible CH_4 trajectories is wider than typically projected in integrated assessment models (IAMs) (Rogelj *et al* 2015a). However, the IAM outputs are unlikely to span the full range of CH_4 measures that are available. This is partly due to their cost minimisation approaches which exclude the more expensive measures and neglect the social costs of methane (Shindell *et al* 2017), and their lack of diversity in treatment of non-CO_2 mitigation measures. These IAMs also have limited representation of the specific processes responsible for methane production and of the technologies available for methane mitigation. It is therefore difficult to estimate how deep (or not) reductions can go. Achieving our most stringent scenario would be expected to draw on specific sectoral measures to address CH_4. These could include increasing agricultural efficiency, decreased food waste and decreased beef consumption (van Vuuren *et al* 2017). The Low and Late scenarios should therefore be seen as illustrative examples.

3. Results

3.1. Carbon budgets

For the High CH_4 scenario (no CH_4 mitigation) the allowable carbon emissions from 2015–2100 span from 149 ± 51 GtC for 1.5 °C (no overshoot), 143 ± 56 GtC for 1.5° with overshoot, to 403 ± 94 GtC for the 2° temperature pathway. The uncertainty is due to the range of climate sensitivities of the CMIP5 models emulated by the IMOGEN framework. Rather than these absolute budgets we focus on the differences in the cumulative carbon emissions from the inversions for the different CH_4 scenarios. These show almost no dependence on the climate model realisation and little dependence on the temperature profile. The benefit of the Medium vs the High CH_4 scenario is approximately 155 GtC over the period 2015–2100 (figure 2(*a*)). Stronger CH_4 mitigation down to the Low scenario gains another 80 GtC if it is done early. The loss in benefit from delaying CH_4 mitigation according to the Late CH_4 scenario is 40 GtC. These values are similar to a study comparing no mitigation with stringent mitigation (Rogelj *et al* 2015b) which calculated an increase of 130 GtC in the carbon budget, with a 30 GtC penalty for late mitigation.

The relationship between the allowable carbon emissions from 2015–2100 and CH_4 concentrations at 2100 is almost linear (excluding the Late CH_4 scenario) with very little difference between the climate model realisations (figure 2(b)). The slopes are −0.269 ± 0.001 GtC ppb^{-1} for the 1.5° and 1.5° overshoot profile and −0.277 ± 0.002 GtC ppb^{-1} for the 2 °C profile. Compared to the CH_4 forcing at 2100 (including the O_3 and stratospheric water vapour effects), this is equivalent to 350 or 360 GtC $(Wm^{-2})^{-1}$. There are uncertainties in these relationships due to the uncertainty in the total radiative efficiency of methane. As these relationships are based on the methane concentrations, rather than emissions, uncertainties in the methane lifetime do not affect the result. The uncertainty in the direct methane radiative efficiency is taken to be 9% of the total (Etminan *et al* 2016). When combined with the 16% uncertainty from the ozone and water vapour contributions this leads to an overall uncertainty of 18%, (0.048 GtC ppb^{-1}). This uncertainty includes within its span the relationship (−0.236 GtC ppb^{-1}) expected using the Myhre *et al* (1998) forcing instead of Etminan *et al* (2016).

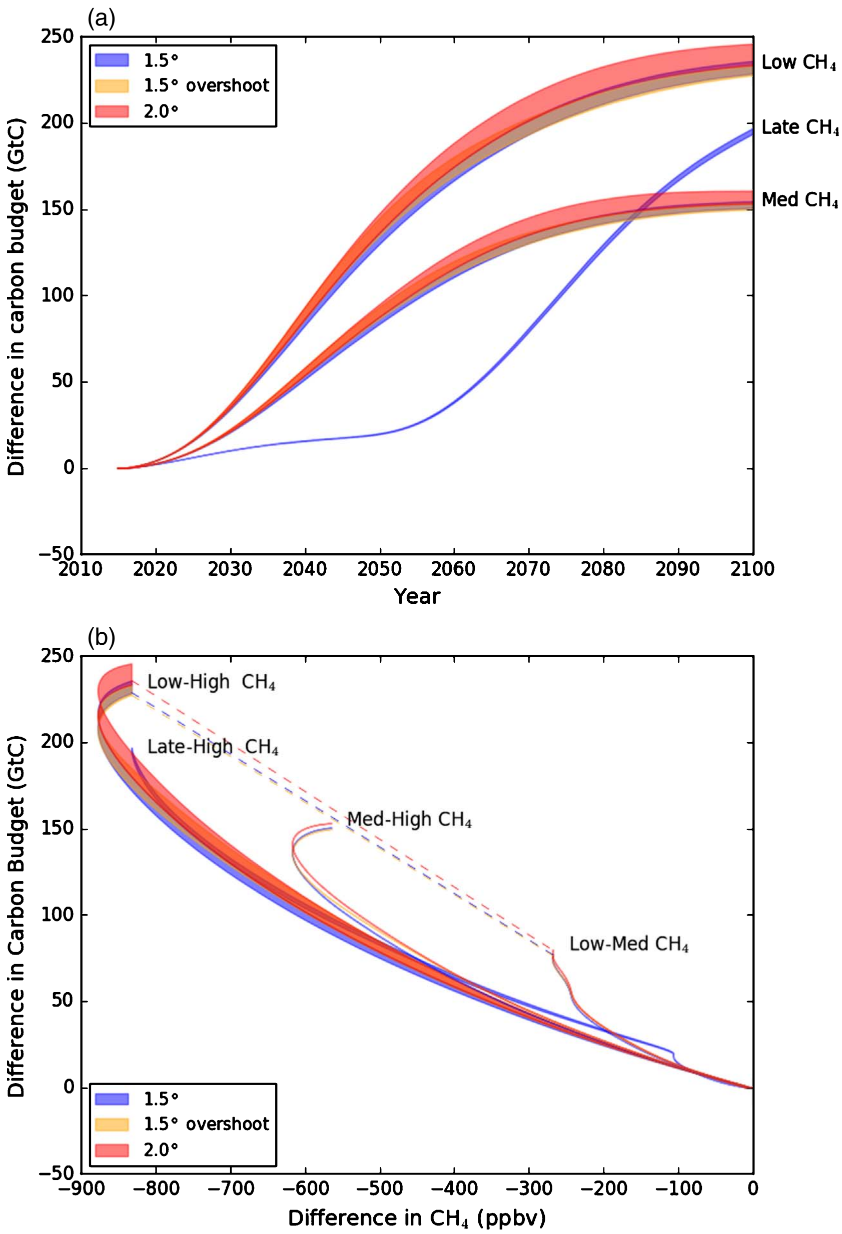

Figure 2. Impact of CH_4 mitigation on the carbon budget for the three temperature profiles. (*a*) Increase in allowable carbon emissions compared to the High CH_4 scenario. Data are shown for the three temperature profiles. The widths of the lines cover the range of the CMIP5 models. (*b*) Difference in allowable carbon emissions between pairs of CH_4 scenarios, as a function of difference in CH_4 concentration for each year 2015–2100. The widths of the lines cover the range of the CMIP5 models. The dashed lines connect the differences in 2100 carbon budget against 2100 CH_4 concentrations for the Low, Medium and High CH_4 scenarios. For the Late vs High CH_4 scenario only the 1.5° temperature profile is shown.

The change in carbon budgets (high methane vs low methane) can be broken down in to the different carbon stores: atmosphere, land (soil and vegetation) and ocean (figure 3(*a*)). We define the airborne fraction $\alpha_F = \Delta CO_2/\Delta E_{CO_2}$, where ΔCO_2 is the change in the atmospheric CO_2 burden and Δ_{ECO_2} is the change in cumulative CO_2 emissions, both in GtC. We find that the α_F of the extra carbon allowed through CH_4 mitigation is independent of the climate sensitivity of each climate model. α_F is also the same when comparing Low-High and Medium-High CH_4 mitigation (not shown). There is a slight dependence of α_F on temperature profile with the 1.5 °C profiles having an α_F of 0.44 vs 0.49 for the 2 °C profile. The Late CH_4 mitigation does not follow the same linear relationship as the Low or Medium scenarios, falling well below the line of proportionality in figure 2(*b*). With late CH_4 mitigation, the comparative increase in allowable atmospheric CO_2 concentrations (compared to High CH_4) does not occur until late in the century. The increase in the atmospheric carbon is the same as for the early mitigation, but the ocean and the land have not had time to take up this extra carbon and the α_F of the extra CO_2 is thus higher (0.53).

Since surface O_3 decreases vegetation productivity, mitigation of CH_4 leads to additional climate benefits than might be expected simply through the radiative forcing. Decreasing atmospheric CH_4 concentrations

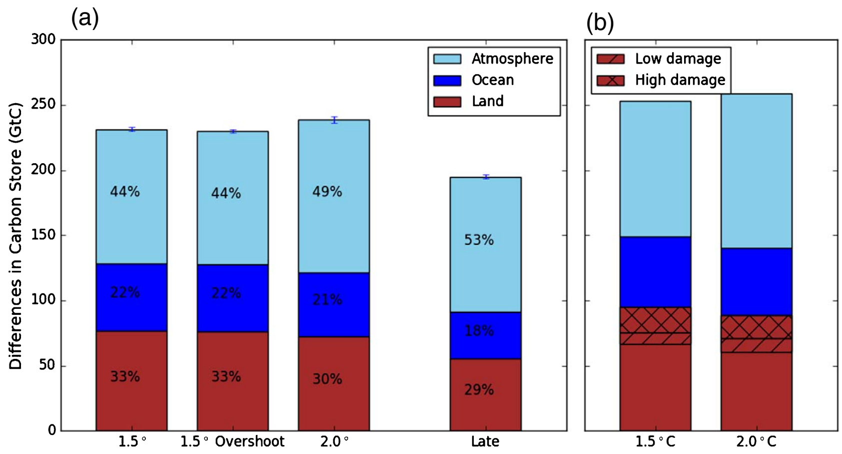

Figure 3. Difference in carbon stores in the atmosphere, ocean and land at 2100 compared to the High CH_4 scenario. (*a*) Low CH_4 scenario for the three temperature profiles, and the Late CH_4 scenario for the 1.5° temperature profile. Values shown are percentages of the total carbon stores (equal to allowable carbon emissions). Error bars are very small and show the inter-model standard deviation. (*b*) As (*a*), but for high O_3 sensitivity, showing the contributions of low and high O_3 sensitivity to the increased soil carbon. Diagonal hatch is low damage, total hatch is high damage, cross hatch is extra effect of high vs low damage.

reduces O_3 levels and increases the uptake of carbon into vegetation and soils. In terms of equation (1), reducing O_3 reduces α_F. We test this through further inversions assuming no and high sensitivity of vegetation to O_3, compared with the baseline parameterisation in the previous results of lower plant-O_3 sensitivity. We find that by increasing the impacts on the land carbon uptake, O_3 damage adds 9–28 GtC (4%–12%) to the benefit of the Low vs High CH_4 scenarios depending on the assumed sensitivity of vegetation to O_3 (figure 3(b)).

3.2. Linearity of carbon budgets

To maintain the radiative balance in the inverse model the change in atmospheric CO_2 is entirely determined by the change in the non-CO_2 forcing. Since we invert IMOGEN to derive the radiation balance consistent with the specified temperature profiles, the greenhouse gas forcing must be the same at any given time, such as at 2100, (assuming the climate sensitivities to radiative forcing from CH_4 and CO_2 are equal). So

$$\Delta F_{CO_2} + \Delta F_{CH_4} = 0, \text{ or}$$
$$\Delta CO_2 \times A_{CO_2} + \Delta CH_4 \times \overline{A}_{CH_4} = 0;$$

where ΔCO_2 and ΔCH_4 are the CO_2 and CH_4 burdens in GtC and $GtCH_4$, and $\bar{A}_{CH_4}$ and $\bar{A}_{CO_2}$ are the average radiative efficiencies for increases in CH_4 (including its indirect effects) and CO_2 in $Wm^{-2}\,GtCH_4{}^{-1}$ or $Wm^{-2}GtC^{-1}$. So combining these with the airborne fraction α_F defined previously gives the ratio of extra cumulative carbon emissions (ΔE_{CO_2}) to change in CH_4 abundance:

$$\frac{\Delta E_{CO_2}}{\Delta CH_4} = -\frac{\overline{A}_{CH_4}}{\alpha_F \overline{A}_{CO_2}} \tag{1}$$

This equation is exact and simply follows from the way we have defined $\bar{A}_{CH_4}$, $\bar{A}_{CO_2}$ and α_F. The linear relationship between the change in the allowable emissions and the change in 2100 forcing therefore implies a constant ratio between the cumulative emissions to 2100 and the 2100 atmospheric CO_2 burden, i.e. a constant airborne fraction for the extra allowable emissions as found in figure 3(*a*). Although $\bar{A}_{CH_4}$ and $\bar{A}_{CO_2}$ are not constant, but functions of the atmospheric CO_2 levels and the magnitudes of the changes ΔCO_2 and ΔCH_4, the deviations from linearity are small for the methane mitigation scenarios used here. The slightly higher α_F for the 2.0° temperature profile is due to the lower radiative efficiency ($\bar{A}_{CO_2}$) at higher absolute CO_2 levels.

The equation also holds in the more realistic case where the extra allowed CO_2 is not emitted with the time profile required to precisely follow the prescribed temperature curve, although in this case the α_F may be slightly different from found in this study. The energy balance has little dependence on the shape of the temperature curve before 2100 (or any specific time), and is dominated by the absolute temperature and its time derivative at 2100. This relationship has no dependence on climate sensitivity. However the α_F will be affected by the sensitivity of the carbon cycle to changes in atmospheric CO_2, surface temperature and precipitation (Arora *et al* 2013).

Allen *et al* (2016) have derived a variant of the Global Warming Potential metric (GWP*) that relates the change in *cumulative* emissions of CO_2 to the change in *instantaneous* emissions of a short-lived species (here CH_4).

$$GWP^* = \frac{\Delta E_{CO_2}}{\Delta e_{CH_4}} = \frac{AGWP^H_{CH_4}}{AGWP^H_{CO_2}/H},$$

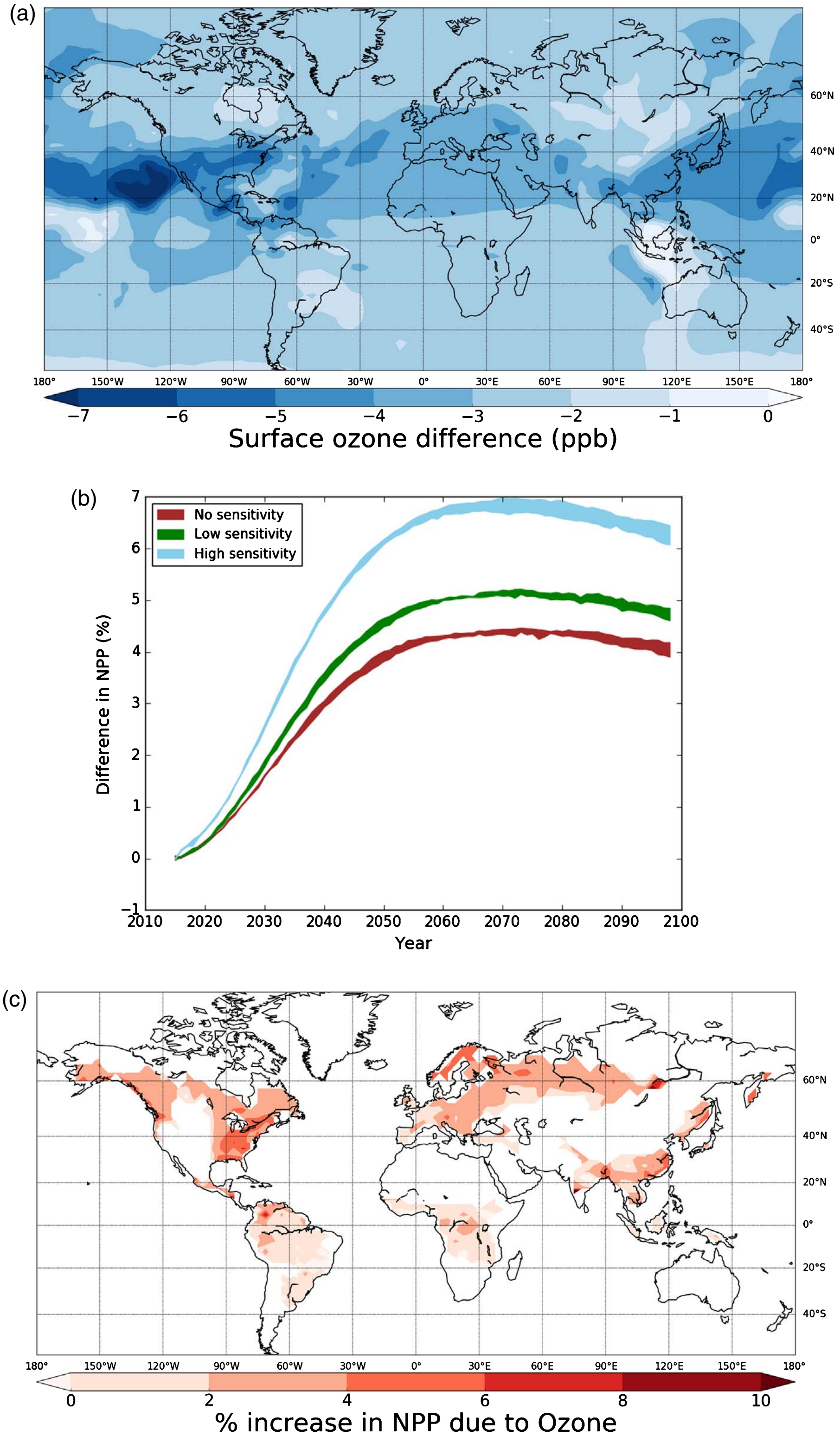

Figure 4. (*a*) Effect of CH_4 mitigation (Low-High) on surface ozone levels. (*b*) Effect of CH_4 mitigation (Low-High) on global NPP where vegetation has no sensitivity to O_3, low sensitivity (as standard setup) and high sensitivity to ozone. The widths of the lines cover the range of the CMIP5 models. (*c*) Map of the regions of increased NPP attributable to reducing surface O_3 (Low CH_4 vs High CH_4 scenarios) using the high sensitivity to O_3, as a percentage of the total NPP.

where Δe_{CH_4} is the change in the instantaneous CH_4 emission rate (in $GtCH_4\,yr^{-1}$), H is a chosen time-frame, and $AGWP^H{}_X$ are the absolute GWPs for CH_4 and CO_2. The absolute GWPs can be expanded to give:

$$\frac{\Delta E_{CO_2}}{\Delta e_{CH_4}} = \frac{\overline{A}_{CH_4}\tau_{CH_4}(1-e^{-H/\tau_{CH_4}})}{\overline{A}_{CO_2}\times\alpha_F(H)}$$

where α_F(H) is the airborne fraction of a pulse of CO_2 averaged over H years. This is similar to equation (1), but only equal to it if the CH_4 has reached equilibrium (i.e. ΔCH_4 can be replaced by $\Delta e_{CH_4} \times \tau_{CH_4}$) and the airborne fraction of CO_2 in the $AGWP^H_{CO_2}$ (α_F(H)) is equal to the α_F of the extra allowed CO_2.

In terms of GWP*, the results from our experiments give a ratio $\frac{\Delta E_{CO_2}}{\Delta e_{CH_4}}$ at the end of the century of 2900 (low-medium mitigation) to 3300 (low-high mitigation) in $GtCO_2\ GtCH_4{}^{-1}\ yr^{-1}$, which compares well with a GWP∗ (100 years) of 2800 yr, given that implicit in the GWP* approximation are the assumptions that the CH_4 concentrations have equilibrated and that the CO_2 airborne fraction is constant.

3.3. Air quality and productivity benefits

We find that CH_4 mitigation has non-climate benefits in terms of air quality and vegetation productivity (by allowing greater atmospheric CO_2 levels, and by reducing the damage from O_3). West *et al* (2012) found that a strong methane mitigation scenario (emission decrease of 180 Tg $CH_4\ yr^{-1}$) resulted in a decrease in global ozone concentrations of around 2 ppb and avoided mortalities of around 90 000 per year. In this study, mitigation by 260 $TgCH_4\ yr^{-1}$ (Low vs High scenario) achieves a decrease in surface O_3 concentration of 3 ppb as a global average, with the largest impact in the tropics (see figure 4(*a*)). Therefore a rough scaling of West *et al* (2012) would suggest a benefit of around 130 000 avoided mortalities per year.

The increased allowable CO_2 levels lead to increased net primary plant productivity (NPP) in JULES by 4% as a global average (figure 4(*b*). If we assume the high sensitivity of plants to ozone the effects of O_3 reduction add up to another 2% increase in NPP globally. In places where the changes in ozone overlap with areas of high productivity (Eastern US, northern Europe) the reductions in ozone could increase total NPP by 4%–6% in the high sensitivity case (figure 4(*c*)).

4. Conclusions

We conclude that mitigating CH_4 can lead to substantial benefits in the allowable carbon emissions consistent with either a 1.5° or 2.0° temperature target. We find a robust relationship between decreased CH_4 concentrations at the end of the century and increased budget of allowable carbon emissions to 2100. This relationship is independent of climate sensitivity or temperature pathway. These changes come from the direct radiative effects of CH_4 and its atmospheric oxidation products, from the carbon uptake by the land and ocean, and from the effects of O_3 on plant productivity. Budget calculations based simply on TCRE will therefore underestimate allowed emissions. As well as making carbon targets more feasible, CH_4 mitigation leads to substantial land ecosystem benefits through increased productivity, and to improved air quality. The variation in CH_4 emissions between the IAMs in the SSP scenarios shows that there is substantial opportunity for CH_4 mitigation even using the cost optimisation assumptions in these models. Very large cuts in CO_2 emissions will certainly be needed to achieve the climate goals, but our study shows that the benefits of CH_4 mitigation could be substantially larger than the IAMs assume, making the exploration and costing of more ambitious reduction potentials and their co-benefits a priority.

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