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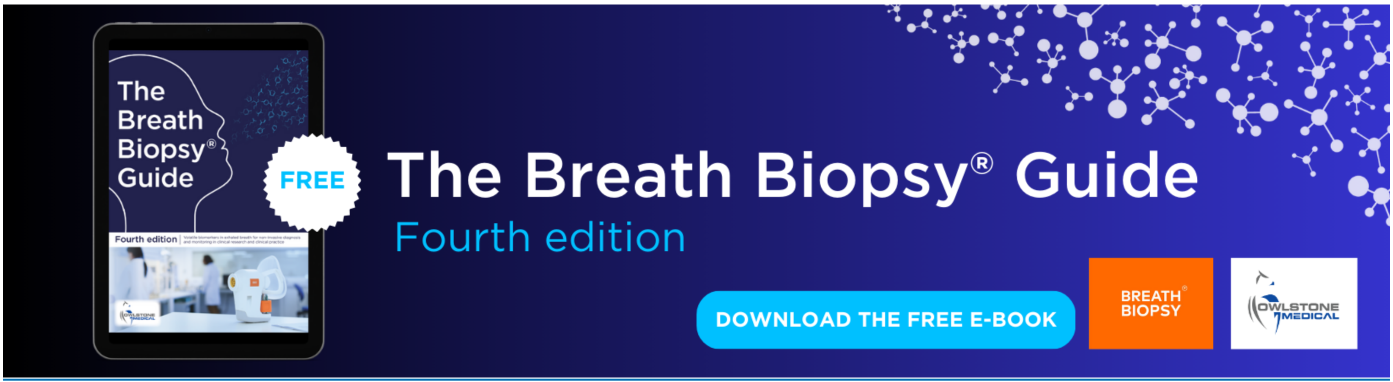

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Global methane pledge versus carbon dioxide emission reduction

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Abstract

Methane (CH_4) is a potent greenhouse gas whose contribution to anthropogenic radiative forcing of the climate system is second only to carbon dioxide (CO_2). CH_4 emission reduction has become critical to global climate mitigation policy, resulting most notably in the global methane pledge (GMP), pledging a 30% reduction of CH_4 emissions by 2030. Methane is, however, much shorter-lived in the atmosphere than CO_2, so emissions reductions may have different impacts on global warming over time. We quantify the difference over time in global annual mean surface temperature of the GMP versus the equivalent amount of CO_2 emission reduction. The avoidance of CH_4 emissions in the 2020s due to the GMP initially results in greater relative cooling than the avoidance of the equivalent amount of CO_2 emissions over the same period, but less relative cooling after ∼2060, when almost all CH_4 emitted during the 2020s has been removed from the atmosphere but much of the CO_2 emitted during the 2020s remains. However, if the GMP places the world on a lower CH_4 emissions trajectory after 2030, this results in a persistently and substantially greater reduction to global warming than the equivalent change in the CO_2 emissions trajectory, with a maximum difference of 0.22 ± 0.06 °C in 2055 and relative cooling for well over a century. This equates to a large difference in avoided climate change damages if momentum in CH_4 emission reduction from the GMP can be sustained after the 2020s. While the greatest reduction in warming is obtained by reducing both CH_4 and CO_2 emissions, our results underscore the striking global societal benefits of sustained reduction in CH_4 emissions.

1. Introduction

Mitigation of climate change is principally achievable by reducing emissions of greenhouse gases. The two greenhouse gases primarily responsible for anthropogenic radiative forcing of the climate system to date are carbon dioxide (CO_2) and methane (CH_4) [1]. In recent years there has been an increased focus on methane emission reduction. This is because of methane's large greenhouse effect per molecule, because an appreciable fraction of this emission reduction can be achieved revenue-neutrally, e.g. by sealing holes in gas pipelines which reduces emissions independently of how much methane is utilized, and because reduction in methane emissions may help offset anticipated decreases in short-lived cooling aerosol emissions as the world transitions to a zero-carbon economy. Methane emission reductions have been shown to have the potential to slow down the rate of warming and sea level rise [2, 3]. This relatedly would result in lower mid-century warming [4, 5]. They have also been shown to permit a higher carbon dioxide budget for a given temperature target [6]. It is generally thought that methane mitigation is necessary for meeting long-term temperature targets [7]. The focus on methane emission reduction has most notably resulted in the global methane pledge (GMP), whereby over 100 countries committed at COP26 to reduce global methane emissions 30% by 2030, from 2020 levels [8]. By COP27 the number of countries committed to the GMP increased to over 150.

While the GMP is a laudable global climate policy commitment, the relative benefits of CH_4 versus CO_2 emission reduction, along with how to compare emissions of greenhouse gases with different atmospheric lifetimes, are debated [3, 9, 10]. Given that methane has an atmospheric lifetime of <12 years whereas CO_2 is much longer-lived in the atmosphere [1], the global temperature reduction benefits over time of emissions reductions of these two greenhouse gases may be quite different, with implications for e.g. the social cost of CH_4 compared to CO_2 [11]. It is thus critical to understand the relative impacts of the emissions reductions in each over time. Greater attention has been paid to the climate impacts of CO_2-related emission reduction commitments, e.g. [12], while uncertainty in non-CO_2 mitigation contributes to whether climate policy is sufficient to meet international targets [13].

2. Summary of approach

Here we quantify the difference over time in global annual mean surface temperature (T [°C]) resulting from GMP-like CH_4 emission reduction versus the equivalent reduction in CO_2 emissions. Unlike other studies focusing on the timescale over which CH_4 mitigation is deployed or its level of ambition, e.g. [14], we consider an internationally agreed level of ambition and timescale of implementation of CH_4 emission reduction. We then investigate the consequences over time to global warming of this emission reduction being imposed on CH_4 emissions versus CO_2 emissions, and the global warming mitigation benefits due to the internationally agreed CH_4 emissions reductions themselves versus the subsequent effect these emission reductions could have on future CH_4 emissions. Our analysis is based on a widely used simple climate model [15–17] with parameters calibrated to mimic the response of more complex Earth System Models (see Methods). We use a large ensemble of simulations to quantify uncertainty related to the climate system's response to different emissions trajectories. This approach thereby estimates how state-of-the-art climate models would differentiate the effects of CH_4 versus CO_2 emission reduction in the 2020s and beyond.

We superimpose a GMP-like reduction in CH_4 emissions on different emissions time-series from shared socioeconomic pathways (SSPs), using SSP2-4.5 as our baseline. We also superimpose the equivalent CO_2 emission reduction, using the conversion factor that the global warming potential (GWP) of CH_4 on a standard 20 year timescale is 82.5 times that of CO_2 [1]. This corresponds to a 21% reduction in global CO_2 emissions by 2030 from 2020 levels. (We also try different SSPs and time horizons (Methods); note that the time horizon over which CO_2 and CH_4 are compared via GWP is an important factor in their comparison [18].) For each greenhouse gas, we consider a linear decrease in emissions from 2020 levels down to a 30% reduction in CH_4 emissions, or the equivalent CO_2 reduction.

We then consider either that emissions return to what they would have otherwise been in 2031 and thereafter, in order to isolate the effect of the emissions avoided in the 2020s, or that emissions of either greenhouse gas follow the same relative emissions reductions in 2031 and thereafter as they would otherwise, in order to quantify the effect of an emissions reduction strategy changing the pathway of emissions over time (figure 1(a)). In other words, in the second case, if CH_4 emissions reduce in a given year after 2030 by a given percentage in a given SSP, we specify that CH_4 emissions decrease by the same percentage in the same year, just starting from a lower level. Both of these scenarios after 2030 are idealized and somewhat artificial, particularly the first case. However, the first case allows us to explore the temperature effects of emissions reductions in the 2020s alone, and the second case allows us to explore the longer-term benefits of altering the emissions pathway and thus the benefits of sustained CH_4 emissions reductions. Sustained emissions reductions could be achieved by building on the GMP and pledging more ambitious international CH_4 emission reduction policy from 2030, or by other strategies such as removal of atmospheric CH_4 through chlorine addition [19]. We compare these cases of CO_2, CH_4, and combined emissions reductions not because we expect or advocate that only the emissions of one greenhouse gas will or should be reduced, or that they are reduced equivalently in GWP terms, but rather because this comparison allows us to compare temporal patterns of global warming mitigation resulting from emissions reductions in each greenhouse gas.

Table 1. Summary of scenarios considered here.

Scenario	Emissions reduction in.	During 2020s	After 2030
B	Neither	N/A	N/A
C−2	CO_2	Yes	No
M−2	CH_4	Yes	No
CM−2	CO_2 & CH_4	Yes	No
C−c	CO_2	Yes	Yes
M−c	CH_4	Yes	Yes
CM−c	CO_2 & CH_4	Yes	Yes

We also consider simultaneous emission reduction in both greenhouse gases combined, i.e. the above emissions reductions in both CO_2 and CH_4 at once. For a given SSP we thus test seven scenarios: the baseline scenario B, (see table 1) and the CH_4, CO_2 and combined emissions reductions in the 2020s alone (scenarios M−2, C−2, and CM−2 respectively in table 1) as well as continuing beyond 2030 (scenarios M−c, C−c, and CM−c respectively in table 1). We compare the T trajectories resulting from the different emissions trajectories, and also translate these into climate-change-related damages to the global economy avoided by emissions reductions using standard economic formulas (Methods) [20, 21].

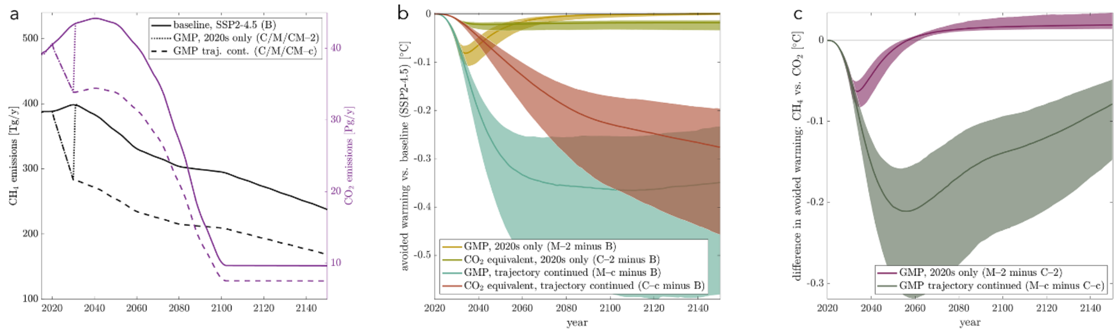

Figure 1. (a): CH_4 (black) and CO_2 (purple) emissions under the baseline case (B, solid) SSP2-4.5, the global methane pledge or equivalent CO_2 emissions reductions in the 2020's only (C/M/MC−2, dotted), or the continuation of this emissions trajectory after 2030 (C/M/MC−c, dashed). The dotted lines follow the solid lines after 2030. (b): avoided warming (i.e. temperature minus baseline case) for CO_2 and CH_4 emissions reductions in the 2020s only and continued after 2030 (i.e. yellow is M−2 minus B, green is C−2 minus B, orange is C−c minus B, and teal is M−c minus (B)). (a): the global annual mean surface temperature in the CH_4-emission-reduction scenario minus that of the equivalent CO_2-emission-reduction scenario for just the emission reductions in the 2020s (purple) and the continuation of these emissions trajectories after 2030 (green) (i.e. purple is M−2 minus C−2, and green is M−c minus C−c). For middle and bottom, solid lines correspond to the median; shaded area corresponds to the 10th–90th percentile.

3. Results: 2020s emissions reductions

As expected from the short atmospheric lifetime of methane, the benefits of global temperature reductions of methane emissions in the 2020s alone are short-lived (figures 1(b) and (c)). GMP-like CH_4 emissions reductions (M−2) result in less warming initially, with a maximum difference of 0.06 (±0.01 °C; ± herein refers to half the 66% range, corresponding approximately to ±1 standard deviation) in 2034 (±1 year). As methane is rapidly removed from the atmosphere but CO_2 persists, however, the warming in the CH_4 emission reduction scenario (M−2) equals that of the equivalent CO_2 reduction scenario (C−2) by 2057 (±3 years). By the end of the century, the CO_2 emissions reduction scenario (C−2) results in less warming by 0.016 ± 0.005 °C (figure 1(c), purple). This latter difference is because nearly all CH_4 emitted in the 2020s has been removed from the atmosphere by natural processes by 2100, regardless of the amount of those 2020s emissions; in contrast, much of the CO_2 emitted in the 2020s will persist in the atmosphere in 2100. In essence this illustrates that CH_4 emission reductions have a more powerful short-term effect, but that this effect is not as long-lasting.

4. Results: long-term emissions reductions

However, reducing emissions over a given decade benefits long-term climate mitigation if a lower-emissions trajectory is followed thereafter. If the GMP can be capitalized on such that CH_4 emissions are reduced compared to what they otherwise would be beyond 2030, this will yield persistent benefits. In contrast to the short-lived gains from methane emissions avoided in the 2020s, the benefits of altering this CH_4 emission path (M−c) are persistent and large (figure 1(c), green line and shading). Following the GMP and then afterwards following the same relative reductions in CH_4 emissions as specified in SSP2-4.5 (M−c)produces a much greater, persistent reduction in global warming than doing the same for equivalent CO_2 emissions (C−c). The maximum difference occurs in 2056 (±3 years), with 0.21 ± 0.06 °C less global warming in the CH_4 emissions reduction scenario (M−c). Notably, the CH_4 emission reduction (C−c)results in less global warming for well over a century (figure 1(c), green). This effect is similar but exacerbated when considering GWPs on longer timescales, e.g. the 100 year GWP of CH_4 is 40, roughly half of its 20 year GWP of 82.5. Even a 30% reduction in CO_2 emissions by 2030 from 2020 levels, corresponding to a 117:1 ratio of CO_2 to CH_4 emission reduction (consistent with using a 10 year GWP timescale for CH_4) reduces global warming less than the GMP-like 30% reduction in CH_4 emissions until 2129 (±5 years), with a maximum difference of 0.17 ± 0.04 °C in 2051 (±2 years). The persistent relative benefits of CH_4 emission reduction are therefore simply due to its greater short-term potency. These differences are robust across SSPs, and correspond to $10 ± 5Trn in additional climate change damages avoided using middle-of-the-road economic assumptions (i.e. a 2% discount rate and the preferred non-catastrophic damage function from the meta-analysis in [20]), varying from $3.5 ± 1.8Trn to $15 ± 8Trn under different economic assumptions (Methods). It is important to note, though, that the greatest reductions to global warming are of course when both CO_2 and CH_4 are reduced simultaneously (MC−c, figure 1(a)).

5. Discussion

The emissions trajectories explored here are of course highly idealized scenarios; for instance after the GMP, emissions will surely not return in 2031 to what they otherwise would have been. As stated above, the purpose of the '–2' scenarios is to explore and compare the temperature effects of emissions reductions in the 2020s alone, and the purpose of scenarios with emissions reductions in different greenhouse gases is to allow us to compare temporal patterns of global warming mitigation resulting from emissions reductions in each. Our study contributes to the literature on methane mitigation [2–5, 7, 14] by comparing CH_4 versus CO_2 emission reductions over time. It is particularly important to note that some fractions of different greenhouse gases' emissions are more challenging to reduce than others, such that the same relative decreases in 2031 and beyond with or without the GMP or its carbon dioxide equivalent are not equally achievable or plausible. Methane's sources are more diverse than those of carbon dioxide, and progress on reducing emissions from methane sources may not easily translate to momentum on reducing emissions from others. Nonetheless these scenarios do allow us to compare the global temperature effects over time of different emissions reduction strategies, and the above results do show that striking long-term benefits can arise from capitalizing on short-term methane emission reduction.

Successfully mitigating climate change to meet the Paris agreement will require a mixture of strategies including the reduction of both methane and carbon dioxide emissions, with emissions reductions providing greater benefits the larger they are and the sooner they occur. Carbon dioxide emissions will always play a central role in any suite of climate mitigation policies, and it is essential that any focus on methane emission reduction does not take effort away from fossil fuel reductions, which themselves will bring substantial methane emission reductions. These results underscore the complementary role that methane emission reduction can play, and how much of a reduction in global warming can be achieved by altering the methane emissions trajectory along the lines of the GMP, or in other words capitalizing on methane emission reduction momentum resulting from the GMP. We hope that in future work, the effects of reducing different greenhouse gases' emissions can be compared via intercomparison of simulations using more complex Earth System Models, including the investigation of spatial differences and interannual variability.

6. Methods

We rely on the widely-used two-layer model [15–17] to simulate the climate system response to anthropogenic forcing:

$$c\,\mathrm{d}T/\mathrm{d}t = F + \lambda T - \gamma\left(T - T_D\right),$$
$$c_D\,\mathrm{d}T_D/\mathrm{d}t = \gamma\left(T - T_D\right) \quad (1)$$

where T [K] is the Earth's global mean surface temperature, F [W m^{-2}] is anthropogenic radiative forcing, c [J m^{-2} K] is the heat capacity of the active surface layer of the climate system whose temperature is represented by T, λ [W m^{-2} K] is the climate feedback, and T_D [K] is the temperature of a deep ocean layer with heat capacity c_D [J m^{-2} K] and with which the surface layer mixes heat at a rate determined by the mixing coefficient γ [W m^{-2} K]. This physical model is widely used in integrated assessment modelling [22]. To quantify uncertainty in the response of the climate system to different forcing scenarios, we generate an ensemble of 10 000 parameter quadruplets $(c, c_D, \lambda, \gamma)$ by taking the parameter estimates of this model tuned to match the response of 30 CMIP6 Earth System Models [23], estimating the mean and covariance properties of the parameters from the mean and covariance of these 30 parameter combinations, and sampling 10 000 parameter combinations from a multivariate Gaussian distribution with the same mean and covariance. Using the CMIP5 model parameter estimates in [24] did not change our conclusions. Note that including an 'efficacy' term [25] in the above model makes no difference to our results because this term does only affects the interpretation of the model's deep layer heat capacity, not its dynamics.

We take our baseline F and CO_2 and CH_4 emissions and concentration time-series from the Reduced Complexity Model Intercomparison Project [26]. We use SSP2-4.5 as our baseline scenario, but perform the same calculations for SSP1-2.6 and SSP3-7.0 to explore the sensitivity of our results to SSP scenario. Results are very similar for different SSPs and results from SSPs other than SSP2-4.5 are therefore not discussed further. We find non-CO_2-non-CH_4 radiative forcing in each case by subtracting the CO_2 and CH_4 forcing from the total F, and add these forcings to all CO_2 and CH_4 forcing in all cases without further alteration. We relate CO_2 and CH_4 concentrations to forcing by fitting the forcing ϕ vs. concentration κ values from all scenarios and years with functions of the form $\phi = p_1\kappa^{p_2} - p_3$, which results for both CO_2 and CH_4 in an $r^2 > 0.9999$ and a root-mean-square-error of <0.0025 W m^{-2}. We then generate CO_2 and CH_4 concentration time-series based on different emissions pathways, and translate these into total F. For all CO_2-reduction scenarios, from these emission and concentration time-series we compute the fraction of cumulative emitted CO_2 that remains in the atmosphere as a function of time under each SSP, and assume that this does not change with the adjustments to total CO_2 emissions considered. In other words, if 50% of cumulative emitted CO_2 is in the atmosphere at a certain year for a certain SSP, reducing the CO_2 emissions in that year by 1PgCO_2 will result in 0.5PgCO_2 less CO_2 in the atmosphere. This assumption is justified by the fact that we are interested in enough perturbations to total overall emissions small enough not to appreciably change the air-sea-land-balance of anthropogenic carbon.

For each SSP we consider two forms each of CO_2 and two forms of CH_4 emission reduction. CH_4 emissions are reduced linearly from 2020 to 2030 by a final total of 30%, and CO_2 emissions are reduced by the same amount multiplied by the 20 year GWP value of CH_4 of 82.5 [1]. Using other GWP timescales, e.g. 100 years, changed the results quantitatively as expected; GWPs over different timescales are calculated using the standard definition [1]. CH_4 emissions are either then returned to the same emissions after 2030 in order to isolate the effect of the avoided emissions in the 2020s, or continue on the same relative trajectory thereafter to quantify the effect of changing the emissions trajectory. In other words, in the latter case, an X% emission reduction in 2040 in the baseline SSP would correspond to the same X% emission reduction in 2040 in the GMP-continued-trajectory scenario, where 2040 CH_4 emissions are reduced by 30% relative to the baseline due to emissions reductions in the 2020s. In the corresponding CO_2 emissions reduction scenario, CO_2 emissions are reduced in the same relative amount each year to the baseline SSP CO_2 emissions in the same way. If emissions reach zero at any year under any scenario, the emissions trajectories with and without emissions reductions in the 2020s are the same thereafter.

For each CO_2 emission reduction scenario and SSP, we (i) release the emissions of CO_2 each year to the climate system, (ii) partition $f(t)$ of this previously stored CO_2 into the atmosphere, (iii) determine the difference in CO_2 in the atmosphere each year in this case versus the baseline SSP scenario, and (iv) subtract this difference from the baseline SSP scenario's atmospheric CO_2 concentration. For each CH_4 emission reduction scenario and SSP, we (i) release the emissions of CH_4 each year to the atmosphere, (ii) remove CH_4 from the atmosphere according to simple exponential decay with an atmospheric lifetime of 11.8 years [1], (iii) determine the difference in CH_4 in the atmosphere each year in this case versus the baseline SSP scenario, and (iv) subtract this difference from the baseline SSP scenario's atmospheric CH_4 concentration. These concentrations are then converted into F time-series, and equation (1) is then forced with these F time-series to determine $T(t)$. F time-series start at 1750 and we initialize equation (1) with $T(1750) = T_D(1750) = 0$.

For the economic calculations, we use a 2020 global purchasing-power-parity-adjusted global domestic product of 85 trillion USD as reported by the World Bank [27]. We use a baseline discount rate $r = 2\%$ as in [21], which reflects a combination of the pure rate of time preference ρ, the elasticity of the marginal utility of consumption η, and an underlying rate of consumption growth g according to $r = \rho + \eta g$; we also assess sensitivity to discount rate by performing the same calculations with $r = 1\%$ and $r = 3\%$, a reasonable range of uncertainty as determined by both philosophers and economists [28]. We use the damage function that the percentage of global gross domestic product lost as damages to climate change D [%] is equal to $D = 0.7438T^2$ [20]. This was identified as the preferred model for non-catastrophic damages in a meta-analysis [20] and substantiated by subsequent econometric observations [29]; it is also the median damage function, over 0–6 °C, of the damage functions considered in [20]. We also assess sensitivity to the damage function by performing the same calculations with higher and lower damage functions of $D = 1.145T^2$ and $D = 0.267T^2$ from the same meta-analysis [20], which correspond respectively to including catastrophic damages and productivity loss or to more optimistic assumptions about the nature of climate change impacts on the global economy.

Data availability statement

No new data were created or analyzed in this study.

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Author Contributions

Cael lead and Goodwin assisted with all aspects of this study.

Conflict of interest

The authors have no competing interests to declare.

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