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Comparison of physically- and economically-based CO_2-equivalences for methane

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Abstract

There is a controversy on the role methane (and other short-lived species) should play in climate mitigation policies and no consensus on what an optimal methane CO_2-equivalence should be. We revisit this question by discussing the relative merits of physically-based (i.e. Global Warming Potential or GWP and Global Temperature change Potential or GTP) and socio-economically-based climate metrics. To this effect we use a simplified Global Damage Potential (GDP) that was introduced by earlier authors and investigate the uncertainties in the methane CO_2-equivalence that arise from physical and socio-economic factors. The median value of the methane GDP comes out very close to the widely used methane 100-year GWP because of various compensating effects. However there is a large spread in possible methane CO_2-equivalences (1–99 % interval: 10.0–42.5; 5–95 % interval: 12.5–38.0) that is essentially due to the choice in some socio-economic parameters (i.e. the damage cost function and the discount rate). The methane 100-year GTP falls outside these ranges. It is legitimate to increase the methane CO_2-equivalence in the future as global warming unfolds. While changes in biogeochemical cycles and radiative efficiencies cause some small changes to physically-based metrics, a systematic increase in the methane CO_2-equivalence can only be achieved by some ad-hoc shortening of the time horizon. In contrast using a convex damage cost function provides a natural increase in the methane CO_2-equivalence for the socio-economically-based metrics. We also show that a methane CO_2-equivalence based on a pulse emission is sufficient to inform multi-year climate policies and emissions reductions as long as there is some degree of visibility on CO_2 prices and CO_2-equivalences.

1 Introduction

Methane (CH_4) is one of the greenhouse gases that are present in trace concentrations in the Earth's atmosphere. Its concentration has increased steadily since the beginning of the industrial era, from 715 ppbv in 1750 to 1774 ppbv in 2005 (Forster et al., 2007). The radiative efficiency of methane is larger than that of carbon dioxide (CO_2), so that methane is the second most important anthropogenic greenhouse gas although its concentration only increased by about 1 ppmv. Methane is responsible for a radiative forcing (RF) of 0.48 Wm^{-2} in 2005 to be compared to a RF of 1.66 Wm^{-2} for carbon dioxide (Forster et al., 2007).

It has been shown that a multi-gas mitigation strategy is cheaper than a CO_2-only mitigation policy (e.g. van Vuuren et al., 2006) because it offers more flexibility in emission reductions across sectors, space and time. A multi-gas approach, such as the Kyoto protocol, requires to define CO_2-equivalences for the non-CO_2 gases. Such CO_2-equivalences usually rely on a metric of climate change. It is the Global Warming Potential (GWP) with a 100-year time horizon that has been chosen to provide this equivalence in the Kyoto protocol. The 100-year GWP for methane used in the Kyoto Protocol is 21, but this value has been re-evaluated in the IPCC Third Assessment Report (with a value of 23) and again in the IPCC Fourth Assessment Report (up to a value of 25). Boucher et al. (2009) have argued that the methane GWP should be increased by ≈2 units for fossil-fuel methane to account for the oxidation of methane into CO_2. Alternatively methane emissions from fossil reservoirs should be reported both as CH_4 and CO_2 emissions in national inventories (Gillenwater, 2008), which is not the case at the moment (IPCC, 2006).

There are different views held among climate change stakeholders regarding the importance of methane emission reductions in mitigation policies (Boucher, 2010). Some argue that methane anthropogenic emissions should be curbed now and to a large extent because, given the short atmospheric lifetime of methane, this will lead to a rapid decrease in RF and consequently to a rapid slowdown of climate change. The same argument can be applied to other short-lived species such as tropospheric ozone – another greenhouse gas – or black carbon – an aerosol species that contribute to global warming. This view was initially promoted by Hansen et al. (2000) and is held by some scientists and environmental groups. A more ambitious emission reduction target for methane does not mean that emissions of carbon dioxide should not be reduced, but overall this line of thinking argues for a larger CO_2-equivalence for methane.

Others argue that the emphasis should currently be on CO_2 emission reductions because a significant fraction of the CO_2 emitted today will stay in the atmosphere for as long as centuries. Given that mitigation of climate change bears a cost for society, and that only a fraction of public wealth can be spent on climate change, it is further argued that it is more important to start reducing CO_2 emissions now or to invest in research and development in order to decrease CO_2 emissions cheaper and quicker later on. Methane emission reductions can come in a few decades time because the atmospheric concentration of methane will respond quickly when these occur. This line of thinking argues for a smaller CO_2-equivalence for methane.

It is unfortunate however that the public debate on the methane CO_2-equivalence is often largely disconnected from physical and socio-economic considerations. Ideally the methane CO_2-equivalence should rely on a suitable climate metric that seek to compare the climate effects of different greenhouse gases. IPCC (2009) reviewed existing climate metrics and made the point that a climate metric is a function of the climate policy. There are essentially two classes of climate metrics: physically-based and socio-economically-based metrics.

Physically-based metrics compare the relative effects of forcing agents in terms of a physical quantity of the climate system such as the cumulative radiative forcing in the case of the GWP or the global-mean surface temperature change in the case of the Global Temperature change Potential (GTP, Shine et al., 2005, 2007). Socio-economically-based metrics compare the relative costs of forcing agents on the climate system. This can be done in a cost-benefit framing that seeks to optimise the emission and concentration pathways of CO_2 and non-CO_2 forcing agents. In that case the CO_2-equivalence is defined as the ratio of the marginal costs of abatement of the non-CO_2 gas with that of CO_2 and is equal to the ratio of cumulative damages caused by unit emissions of the two gases (Kandlikar, 1996). Such a CO_2-equivalence varies in time as we progress along some economic optimum which may also evolve over time as

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more knowledge becomes available. This approach was used by Manne and Richels (2001) who showed that for a climate target of 2 °C, the methane CO_2-equivalence should increase from 5–10 at the beginning of the 21st century to 40–50 at the end of the 21st century. However, when they introduce a further climate target to limit the rate of global warming to 0.2 °C per decade, Manne and Richels (2001) found that the methane weight takes a value in the range 20–30 during all of the 21st century. A socio-economically-based climate metric can also be framed in a cost-effectiveness analysis. In that case the CO_2-equivalence is calculated as the ratio of the climate damages caused by unit emissions of the two gases along some a priori concentration or temperature pathway (Kandlikar, 1996). This is the concept of the economic-damage index introduced by Hammitt et al. (1996), which we refer to here as a Global Damage Potential (GDP). Tol et al. (2008) showed how different existing climate metrics could be reconciled under a common framework.

The simplicity of the GWP and the lack of robustness of other metrics has led to its adoption as the metric for CO_2-equivalence in the Kyoto protocol, with the consequence of casting the concept in stone (Shine, 2009). Earlier alternative metrics such as those of Hammitt et al. (1996) and Kandlikar (1996) have somewhat become forgotten, while there is still an active literature on GWP (e.g. Boucher et al., 2009; Reisinger et al., 2010, 2011; Gillett and Matthews, 2010). Only the concept of GTP has recently been gaining some momentum as an alternative (IPCC, 2009; Fuglestvedt et al., 2010).

In the real world, CO_2-equivalences are used in a number of different contexts. In the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto protocol, the GWP with a time horizon of 100 years is used to estimate the total (i.e. CO_2-equivalent) greenhouse gas emissions for each country and emission reduction targets are also formulated in terms of CO_2-equivalent emissions. A CO_2-equivalence is also required by policymakers to guide the breakdown of their emission reduction target between gases within their own countries. Where a multi-gas emission trading scheme (ETS) exists, a CO_2-equivalence is required to trade emissions of different greenhouse gases between them. Finally the private sector also needs to consider

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CO_2-equivalences when deciding between different investments aimed at cutting emissions. A legitimate question is whether the different usages of CO_2-equivalences identified above call for the same or different metrics. A related question is how to value pulse (i.e. one-off) and sustained (i.e. perennial) emission reductions of greenhouse gases such as methane.

The objectives of this study are threefold:

1. revisit the concept of GDP and its sensitivity to input variables,

2. compare the GWP and GTP with a simplified GDP in terms of their uncertainties and future time evolution,

3. and discuss the implication of using a CO_2-equivalence based on a pulse emission in situations of perennial emission reduction.

We define the different metrics in Sect. 2, compare them in Sect. 3, and finally discuss the use of CO_2-equivalences in Sect. 4.

2 Definition of climate metrics used in this study

2.1 Global warming potential

The methane GWP is defined as the ratio of the methane and CO_2 absolute GWP at time t:

$$\mathrm{GWP}_{\mathrm{CH_4}}(t) = \frac{\mathrm{AGWP}_{\mathrm{CH_4}}(t)}{\mathrm{AGWP}_{\mathrm{CO_2}}(t)} = \frac{\int_0^{\mathrm{TH}} \mathrm{RF}_{\mathrm{CH_4}}(t + t')\,\mathrm{d}t'}{\int_0^{\mathrm{TH}} \mathrm{RF}_{\mathrm{CO_2}}(t + t')\,\mathrm{d}t'} \tag{1}$$

where $\mathrm{RF}(t+t')$ is the radiative forcing at time $t+t'$ of a pulse emission of 1 kg occurring at time t and TH is an arbitrary time horizon (usually set to 100 years).

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2.2 Global temperature change potential

The methane GTP is defined as the ratio of the absolute GTP of methane and CO_2 at time t:

$$\mathrm{GTP}_{\mathrm{CH}_4}(t) = \frac{\mathrm{AGTP}_{\mathrm{CH}_4}(t)}{\mathrm{AGTP}_{\mathrm{CO}_2}(t)} = \frac{\Delta T_{\mathrm{CH}_4}(t + \mathrm{TH})}{\Delta T_{\mathrm{CO}_2}(t + \mathrm{TH})} \tag{2}$$

where $\Delta T(t+\mathrm{TH})$ is the global-mean surface temperature (GMST) at a time horizon TH caused by a pulse emission of 1 kg occurring at time t.

2.3 Global damage potential

We define a simplified GDP for methane as the ratio of the absolute GDP of CH_4 and CO_2 for a pulse emission at time t:

$$\mathrm{GDP}_{\mathrm{CH}_4}(t) = \frac{\mathrm{AGDP}_{\mathrm{CH}_4}(t)}{\mathrm{AGDP}_{\mathrm{CO}_2}(t)} = \frac{\int\limits_{t'=0}^{\infty} [D(\Delta T(t+t') + \delta T_{\mathrm{CH}_4}(t+t')) - D(\Delta T(t+t'))]/(1+\rho)^{t'}\,\mathrm{d}t'}{\int\limits_{t'=0}^{\infty} [D(\Delta T(t+t') + \delta T_{\mathrm{CO}_2}(t+t')) - D(\Delta T(t+t'))]/(1+\rho)^{t'}\,\mathrm{d}t'} \tag{3}$$

where D is a damage cost function, $\delta T_{\mathrm{CH}_4}(t+t')$ and $\delta T_{\mathrm{CO}_2}(t+t')$ are the GMST changes at time $t+t'$ due to pulse emissions of 1 kg of CH_4 and CO_2 at time t superimposed on a trajectory of GMST change $\Delta T(t+t')$, and ρ is a discount rate which is discussed in the next section.

It should be noted that, if we omit potential future changes in radiative efficiencies and residence times, $\mathrm{AGDP}_{\mathrm{CH}_4}$, $\mathrm{AGDP}_{\mathrm{CO}_2}$ and $\mathrm{GDP}_{\mathrm{CH}_4}$ are constant if $\Delta T(t) \equiv 0$ or if D is a linear function of ΔT, but are a function of the baseline year t otherwise. In a warming climate (i.e. ΔT increases with time), $\mathrm{GDP}_{\mathrm{CH}_4}$ increases with the baseline year if D is a convex function of ΔT, which is usually the case.

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2.4 Parametrising and sampling uncertainties

Our list of variable parameters, their central value and their uncertainties are summarised in Table 1.

We consider a set of simplified underlying scenarios which sample possible future (unmitigated and mitigated) worlds under the form of a linear trend in GMST for one century followed by a trend twice as small for another century and then a stabilisation. The equation for the GMST change is therefore

$$\begin{cases} \Delta T(t) = \Delta T_0 + \alpha t/100 & \text{if } t \leq 100 \text{ years} \\ \Delta T(t) = \Delta T_0 + \alpha + \alpha(t-100)/200 & \text{if } 100 \leq t \leq 200 \text{ years} \\ \Delta T(t) = \Delta T_0 + 3\,\alpha/2 & \text{if } 200 \text{ years} \leq t \end{cases} \quad (4)$$

where $\Delta T_0 = 0.7\,^{\circ}\mathrm{C}$ is the observed present-day warming, the parameter α varies between 1 and $4\,^{\circ}\mathrm{C}\,\mathrm{century}^{-1}$ and all values are considered equiprobable (i.e. we assume a flat distribution).

We then need to convert a pulse in CO_2 and CH_4 emissions into their corresponding GMST changes, $\delta T_{CO_2}(t')$ and $\delta T_{CH_4}(t')$. The first step involves estimating the RFs in response to the pulse emissions. For CO_2 we use the simple equation provided in Forster et al. (2007) which is also used in Boucher and Reddy (2008). For CH_4 we assume an e-folding time for the methane pulse of 12 years as in Boucher et al. (2009) as the methane perturbation time is longer than its lifetime. We assume a Gaussian distribution for this parameter with a standard deviation of 1 year. We follow Ramaswamy et al. (2001) to estimate the direct radiative forcings (in Wm^{-2}) by CO_2 and CH_4. Although the RF induced by a pulse emission of CO_2 (CH_4) depends on the background concentration of CO_2 (CH_4 and N_2O), we neglect these dependencies and assume constant present-day values as it is the case for instance in GWP calculations. The total methane radiative forcing can then be written as:

$$\mathrm{RF}^{\mathrm{total}}_{\mathrm{CH_4}} = \mathrm{RF}^{\mathrm{alone}}_{\mathrm{CH_4}}\left(1 + F_{\mathrm{O_3}} + F_{\mathrm{H_2O}}\right) + \mathrm{RF}_{\mathrm{CH_4} \Rightarrow \mathrm{CO_2}} \quad (5)$$

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where F_{O_3} and F_{H_2O} are the enhancement factors for the O_3 and H_2O indirect effects and the last term corresponds to the methane oxidation effect which calculation follows Boucher et al. (2009). We take F_{O_3} and F_{H_2O} equal to 0.25 and 0.15, respectively, with a 0.05 standard deviation and a Gaussian distribution of the uncertainties. The rate of CH_4 conversion to CO_2 varies from 0.60 to 1.0 and follows a flat distribution (Boucher et al., 2009). Finally we assume that the RF by CO_2 follows a Gaussian distribution with a standard deviation set to 5 % of the RF value (Forster et al., 2007).

In a second step we convert the time profile of RF into a time profile of GMST change through the integration of a GMST impulse response function as done in Boucher and Reddy (2008) and Fuglestvedt et al. (2010):

$$\delta T(t') = \int_0^{t'} \mathrm{RF}(t'')\, \delta T^{\mathrm{p}}(t' - t'')\, \mathrm{d}t''. \tag{6}$$

The impulse response function, δT^{p}, is parameterised as the sum of two exponential decay functions with timescales τ_1 and τ_2 of 8.4 and 410 years, and climate sensitivities λ_1 and λ_2 of 0.631 and 0.429 K $(\mathrm{Wm}^{-2})^{-1}$, which is a fit to a climate model (Boucher and Reddy, 2008):

$$\delta T^{\mathrm{p}}(t) = \frac{\lambda_1}{\tau_1} \exp\left(\frac{-t}{\tau_1}\right) + \frac{\lambda_2}{\tau_2} \exp\left(\frac{-t}{\tau_2}\right). \tag{7}$$

We vary the timescales and their associated climate sensitivities within a ±30 % range using flat distributions.

Finally we define the damage cost function as a power of the GMST change:

$$D(\Delta T) = \beta \Delta T^{\gamma} \tag{8}$$

where γ is an exponent and β is a constant. The constant β plays no role as we assume here the same value for CH_4 and CO_2. It should be noted that this assumption may not hold because CO_2 has a direct impact on terrestrial ecosystems and ocean

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acidification beyond its radiative impact (Huntingford et al., 2011). The exponent γ determines the sensitivity of climate impacts with temperature change. While a quadratic damage function ($\gamma = 2$) is often chosen, the shape of the damage function is uncertain (Warren et al., 2006). The damage cost function can also be parametrised as a polynomial function of the GMST change but we use Eq. (8) instead for simplicity. We consider a range of 1.5 to 2.5 for γ with a central value of 2 and a flat distribution. This is a smaller range than in earlier work from Kandlikar (1996) and Hammitt et al. (1996) who both considered linear ($\gamma = 1$), quadratic ($\gamma = 2$) and cubic ($\gamma = 3$) damage functions. We will test the linear and cubic damage functions in Sect. 3.2 however for completeness and consistency with previous studies. A larger exponent for the damage cost function implies a less impacted or more "adaptable" world in the short term relative to the long term and puts more weight on long-lived species.

While time discounting is almost universal in economic analysis, it is also very controversial (e.g. Heal, 1997; Stern, 2007; Weitzman, 2007; Sherwood, 2007). Not discounting the future has inacceptable social implications. Discounting (or discounting too much) also has unethical implications, especially for long-term environmental problems. Various solutions have been proposed to this dilemma such as the addition of a term to lower the effect of the discount rate (Pearce et al., 2003), the possibility that the discount rate decreases with the timescale considered (Heal, 1997; Pearce et al., 2003), or differential discounting (Nordhaus, 1997). While there are guidelines for selecting discount rates in short-term public policies, there is no consensus on how discounting should be performed for longer-term environmental issues. We choose here a range of discount rates from 1 to 3 % per year in order to encompass discount rates usually used in climate change socio-economic studies. As for some of the other parameters, we assume the values of ρ to be equiprobable. Our minimum and maximum values for the discount rate are the same as in Hammitt et al. (1996).

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2.5 How do GWP, GTP and GDP relate to each other?

Neither the GWP, nor the GTP introduced by Shine et al. (2005, 2007) are straightforward special cases of Eq. (3). The GWP is a function of the RF rather than a function of the GMST change (i.e. $\delta T(t') \equiv \text{RF}(t')$ and $\gamma = 1$), there is no underlying climate change (i.e. $\Delta T(t) = 0$), it has no discounting (i.e. $\rho = 0$) and the integration is made only up to a fixed time horizon. The GTP depends on the GMST change (i.e. $\gamma = 1$), there is no underlying climate change (i.e. $\Delta T(t) = 0$), it is for a fixed time horizon rather than a cumulative function (i.e. $D = \delta_{\text{TH}} \Delta T$ with δ being here the Dirac function) and it has no discounting (i.e. $\rho = 0$). The GTP is therefore an end-point metric, whereas the GWP and the GDP are both cumulative metrics. A cumulative version of the GTP has been proposed by Gillett and Matthews (2010) (under the name of mean GTP or MGTP) and Peters et al. (2011) (under the name of integrated GTP or iGTP). It is in fact equivalent to a GDP with a linear damage function, no discount rate and a fixed time horizon in Eq. (3). All three metrics are for pulse emissions of CH_4 and CO_2 and metrics for sustained emissions have also been proposed. We will compare results from the different metrics in the next section.

3 Calculations of the methane CO_2-equivalences

3.1 Comparison between the different CO_2-equivalences

The 100-year GTP for methane (3.9 and 6.2 with and without CH_4 conversion to CO_2) is much lower than the 100-year GWP (25.2 and 27.2) as already noted by Shine et al. (2007) and Gillett and Matthews (2010). The methane GDP estimated from the central values of the parameters are 24.3 and 26.3 without and with the CH_4 conversion to CO_2, respectively. This is fairly close to the 100-year methane GWP value of 25. This similarity in values can be explained through a range of compensating effects as illustrated in Fig. 1. Considering a cumulative function of the GMST change rather

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than a cumulative function of RF increases the methane CO_2-equivalence only slightly. The effect is much larger when going from an end-point GTP to a cumulative function of GMST change as already noted by Gillett and Matthews (2010). Discounting contributes to increase the methane CO_2-equivalence substantially (i.e. by 14–15 units for a linear GDP and a time horizon of 100 years) by giving more weight to the earlier climate impacts of methane. Integrating the methane and CO_2 AGDP to infinity rather than to a 100-year time horizon only decreases the methane CO_2-equivalence by about 5 units because of the effect of discounting. Going from a linear to a quadratic damage cost function decreases the methane CO_2-equivalence by about 13 units from 37.6 and 39.4 to 24.3 and 26.3. Overall the compensation of effects between the 100-year GWP and our simplified GDP is mostly between the opposing effects of discounting at a rate of 2 % and going from a linear to a quadratic damage cost function. Finally, the large differences in GDP evaluated for linear, quadratic and cubic damage functions should be noted, with values of 37.6/39.4, 24.3/26.3 and 14.4/16.5, respectively. These values are larger than those of Hammitt et al. (1996) and Kandlikar (1996) but the sensitivities to parameters are similar.

3.2 Future evolution in methane CO_2-equivalence

The methane GWP can vary in time because the atmospheric residence times and radiative efficiencies of marginal changes in CO_2 and CH_4 change over time. Caldeira and Kasting (1993) found that the decreasing radiative efficiency of CO_2 when the concentration increases compensates for an increase in atmospheric residence time as the ability of the ocean to absorb CO_2 decreases. This question was revisited by Reisinger et al. (2011) who found that the 100-year absolute GWP of CO_2 can be expected to decrease as the CO_2 background concentration increases. Changes in methane residence time and radiative efficiencies can also affect its GWP (Brühl, 1993). Reisinger et al. (2011) estimated that the 100-year methane GWP can change by up to 20 % due to the combined effects of future changes in radiative efficiencies and residence times of CO_2 and CH_4. The 100-year methane GWP would increase by

≈10 % by 2100 in the RCP3PD and RCP4.5 scenarios, but would decrease by ≈10 % by the middle of the century in the RCP8.5 scenario. We have not evaluated these effects here but retain a ±20 % range in the methane GWP due to changes in the CH_4 and CO_2 radiative efficiencies and atmospheric lifetimes in future climates.

As anticipated earlier, the GDP increases with the start time for the GDP calculation (variable t in Eq. 3, which is different from a time horizon). For our choice of central value parameters (i.e. a quadratic damage cost function and a 2 % discount rate), the GDP increases from a present-day value of 24.3 to 34.6 in 100 years and 37.6 in 200 years. This is entirely due to the non-linearity of the damage cost function in a warming climate. This is a clear advantage of a GDP-like metric over the GWP and GTP metrics whose values can only be increased systematically by an ad-hoc shortening of the time horizon.

3.3 Sensitivity to individual parameters

Figure 2 shows the ranges in methane GDP when each of the input parameters are varied within some reasonable range and all other parameters are held to their central values (see Table 1). For parameters which follow a Gaussian distribution we vary the parameters within $\pm 2\,\sigma$ for this sensitivity study. The GDP, as we defined it, shows very little sensitivity to the details of the climate impulse response function and the methane to CO_2 conversion factor. It has a medium sensitivity to uncertainties in the O_3 and H_2O enhancement factors and the CO_2 radiative forcing, a somewhat larger sensitivity to the the uncertainties on the methane perturbation lifetime and the underlying warming scenario. Finally it exhibits a large sensitivity to the shape of the temperature damage function (our exponent γ) and the largest sensitivity to the choice of discount rate ρ within the 1 to 3 % range. It is remarkable that the largest sensitivity is from the choice of socio-economic parameters which are potentially less constrained and more value-laden than the physical parameters.

3.4 Total uncertainty

Although the choices of the central value and range are guided by the existing literature, we recognize that there is some degree of expert and value judgement in some of these parameters. We run a 10 000 point Monte-Carlo calculation that sample the uncertainties in all of these variables (assuming errors are independent). Because we consider a large number of parameters, the overall uncertainty is not overly sensitive to small variations in the uncertainty ranges that could arise from a particular expert judgement.

Figure 3 shows how the 50 first members of the Monte Carlo simulation evolves over time, along with our minimum, maximum and central values for the GDP. The kink that occurs around year 100 in some of the members is because of the change in the rate of global warming in that year as evident from Eq. (4). One can note that the increase in GDP over the next 200 years is largest for the smallest present-day GDP at least in relative terms. A smaller present-day methane CO_2-equivalence implies a steeper relative increase over time in the next 100 years. The rest of the section is now focused on the present-day GDP value.

The probability distribution function (PDF) for the methane GDP is shown in Fig. 4 and Table 2. Our 90 % confidence interval for the methane 100-year GWP [20.5–30.5] is fairly close to the [19.3–31.5] range reported by Reisinger et al. (2010) even though we have neglected some of the uncertainties. However our 90 % confidence interval in the methane 100-year GTP [2.0–6.5] is significantly different to the [3.9–13.5] range reported by Reisinger et al. (2010) suggesting that the uncertainties in GTP are not well understood.

The median values for the GDP are the same as the central values quoted above. The uncertainty on the methane GDP is significant with a standard deviation of 6.7. It is significantly larger than the uncertainty on the 100-year GWP and GTP for which the standard deviations are 2.8 and 1.8, respectively. In that sense, it is a less robust

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climate metric than GWP, but it offers more flexibility for adjustment as our knowledge on climate change and its impacts progress, as already noted by Hammitt et al. (1996).

The maximum values for the methane GDP that can be obtained from the parameter ranges in Table 1 are 61.8 and 63.9 without and with the CH_4 conversion to CO_2, respectively. This maximum value is about 2.5 times larger than the 100-year GWP for methane. The minimum values for the methane CO_2-equivalence that can be built are 4.3 and 5.9 without and with CH_4 conversion to CO_2, respectively. This is 5 to 6 times less than the 100-year GWP, but fairly close to the central value for the 100-year GTP. These minimum and maximum values for the methane GDP are actually well outside the 1–99 % uncertainty ranges which are 10.0–42.5 and 12.5–44.5 without and with the CO_2 conversion effect, respectively, and can be considered as outliers.

4 Interpreting the methane CO_2-equivalence

Most climate metrics which have been defined are for pulse emissions. Climate metrics for sustained emissions have been proposed (e.g. Shine et al., 2005) and used in some studies (e.g. Jacobson, 2002; Dessus et al., 2008). Metrics for sustained emissions give larger CO_2-equivalences than their pulse emission counterpart for short-lived species such as methane or black carbon (Shine et al., 2005). It has been argued that a metric for sustained emissions should be used to trade perennial emission reductions. We show here this not to be the case. To this effect we introduce a generalised sustained GDP (denoted GDP_s) which compares the relative discounted climate effects of CH_4 and CO_2 emissions over n years:

$$\mathrm{GDP_s} = \frac{\sum_{t=0}^{n-1} \mathrm{AGDP}_{\mathrm{CH_4}}(t)/(1+\rho)^t}{\sum_{t=0}^{n-1} \mathrm{AGDP}_{\mathrm{CO_2}}(t)/(1+\rho)^t}$$

$$= \frac{\sum_{t=0}^{n-1} \int_{t'=0}^{\infty} \left[D\left(\Delta T(t + t') + \delta T_{CH_4}(t')\right) - D(\Delta T(t+t'))\right] / (1 + \rho)^{t+t'} \, dt'}{\sum_{t=0}^{n-1} \int_{t'=0}^{\infty} \left[D\left(\Delta T(t + t') + \delta T_{CO_2}(t')\right) - D(\Delta T(t + t'))\right] / (1 + \rho)^{t+t'} \, dt'}. \tag{9}$$

Let us try to reconcile the viewpoint of a policymaker who wants to define an equivalence between CH_4 and CO_2 which is based on a climate target and the viewpoint of an investor who wants to maximize the value of his investment in the context of the financial tools set up by the policymaker. We assume there is an upfront cost X_{CH_4} and a running cost $Y_{CH_4}(t)$ to reduce CH_4 emissions by 1 kg yr^{-1}. Likewise for 1 kg yr^{-1} of CO_2 with the costs being noted X_{CO_2} and $Y_{CO_2}(t)$.

The investor wants to pay back his investment by avoiding paying a greenhouse gas tax or buying emission credits, or by selling emission credits if he has reduced his emissions beyond expectation, which implies:

$$X_{CO_2} + \sum_{t=0}^{n-1} Y_{CO_2}(t)/(1 + \rho)^t = \sum_{t=0}^{n-1} P_{CO_2}(t)/(1 + \rho)^t \tag{10}$$

where $P_{CO_2}(t)$ is the price of 1 kg of CO_2 which evolves over time. We have discounted both the CO_2 price and the CO_2 emission reduction cost to reflect uncertainties on the future. The discount rate needs not to be the same as in Eq. (1) though. To invest in CH_4 emission reductions also requires the ratio of the discounted CH_4 and CO_2 costs to be equal to the ratio of the financial benefits our investor can get out of it:

$$\frac{X_{CH_4} + \sum_{t=0}^{n-1} Y_{CH_4}(t)/(1 + \rho)^t}{X_{CO_2} + \sum_{t=0}^{n-1} Y_{CO_2}(t)/(1 + \rho)^t} = \frac{\sum_{t=0}^{n-1} P_{CH_4}(t)/(1 + \rho)^t}{\sum_{t=0}^{n-1} P_{CO_2}(t)/(1 + \rho)^t} \tag{11}$$

where $P_{CH_4}(t)$ is the price of 1 kg of CH_4 which can also evolve over time.

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For his policy to be most effective, the policymaker wants the ratio of the discounted CH_4 and CO_2 prices to be equal to the ratio of their climate benefits:

$$\frac{\sum_{t=0}^{n-1}\int_{t'=0}^{\infty}\left[D\left(\Delta T(t+t') + \delta T_{CH_4}(t')\right) - D(\Delta T(t+t'))\right]/(1+\rho)^{t+t'}\,dt'}{\sum_{t=0}^{n-1}\int_{t'=0}^{\infty}\left[D\left(\Delta T(t+t') + \delta T_{CO_2}(t')\right) - D(\Delta T(t+t'))\right]/(1+\rho)^{t+t'}\,dt'} = \frac{\sum_{t=0}^{n-1} P_{CH_4}(t)/(1+\rho)^t}{\sum_{t=0}^{n-1} P_{CO_2}(t)/(1+\rho)^t}. \quad (12)$$

Noting $R_{CH_4}(t)$ the ratio between the CH_4 and CO_2 prices, the previous equation becomes:

$$\frac{\sum_{t=0}^{n-1} \mathrm{AGDP}_{CO_2}(t)\ \mathrm{GDP}_{CH_4}(t)/(1+\rho)^t}{\sum_{t=0}^{n-1} \mathrm{AGDP}_{CO_2}(t)/(1+\rho)^t} = \frac{\sum_{t=0}^{n-1} P_{CO_2}(t)\ R_{CH_4}(t)/(1+\rho)^t}{\sum_{t=0}^{n-1} P_{CO_2}(t)/(1+\rho)^t}. \quad (13)$$

The equation above is verified if the variations of $P_{CO_2}(t)$ follow those of $\mathrm{AGDP}_{CO_2}(t)$ and if the variations of $R_{CH_4}(t)$ follow those of $\mathrm{GDP}_{CH_4}(t)$. Said differently, the price of CO_2 needs to increase as the absolute GDP of CO_2 increases over time, and the CO_2-equivalence of methane for pulse emission needs to increase as its GDP increases over time. The investor can then use Eqs. (10) and (11) to optimise his strategy for emission reductions.

There are several implications of the above: (i) there is no scientific reason for the methane CO_2-equivalence to be constant over time, (ii) there is no need to introduce a metric for sustained emissions as long as the methane CO_2-equivalence for pulse emission evolves over time, and (iii) there needs to be some visibility from policymakers that both the price of CO_2 and the methane CO_2-equivalence are going to increase in the future if financial tools are to drive the split between CO_2 and CH_4 investment in a way that is effective for minimising the impacts of climate change. It should be noted that the conclusions reached here hold even if a different climate metric had been used to calculate the methane CO_2-equivalence.

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5 Conclusions

We defined a simplified GDP for methane as the ratio of the discounted cumulative climate change impacts due to the pulse emission of 1 kg of methane relative to 1 kg of CO_2. The simplified GDP is a function of 12 parameters which we have varied in order to (i) explore the sensitivity to various parameter choices and (ii) bound the methane CO_2-equivalence. We produced a probability distribution function for the methane GDP by varying input parameters within some reasonable ranges.

Our findings can be summarised as follows:

1. If the damage cost function is a convex function of the GMST change, as it is usually considered, the methane GDP naturally increases as global warming unfolds. This is an advantage as compared to the GWP and GTP which can only be increased by shortening the time horizon. The GDP as defined here can be used consistently as we approach and go past a climate target in a stabilisation scenario.

2. The median value of the methane GDP is 24.3, which is very close to the 100-year methane GWP. This is because the decrease in methane CO_2-equivalence caused by the introduction of a temperature-linked damage cost function (instead of a cumulative RF) is compensated by the introduction of a discount rate that gives more importance to the short lifetime of methane. For a damage cost function which is a quadratic function of the GMST and a discount rate of 2 % this compensation is almost perfect.

3. There is a large spread in our GDP calculations (larger than the spread in GWP and GTP) when we vary input parameters within some reasonable ranges. The largest uncertainties come from uncertainties or judgement value on two economic parameters: the degree of convexity of the damage cost function and the discount rate. It should be noted that the choice of the discount rate is related to the choice of a time horizon when the GWP or GTP metric is used.

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4. The 1–99% uncertainty ranges for the methane GDP are 10.0–42.5 and 12.5–44.5 without and with the CH_4 to CO_2 conversion effect, respectively. This provides some lower and upper bounds for the methane CO_2-equivalence. It should be noted that the methane 100-year GTP falls outside this range. Moreover comparing our results with previous work suggests that the uncertainties of the methane GTP are not well understood.

5. Reconciling the legitimate objectives of a policymaker and an investor willing to invest money in order to decrease CH_4 emissions in the long-term requires that both the price of CO_2 and the methane CO_2-equivalence for a pulse emission increase over time in some known and visible way. There is no need for policymakers to introduce an additional metric for sustained emission to make perennial investment decisions as long as there is some degree of visibility on future prices and equivalences.

Our GDP remains a simplified metric. One assumption in particular merits more investigation. Climate impacts vary geographically and across sectors and parametrising the damage cost function as a power of the GMST is probably an oversimplification. Moreover there is an increasing recognition that different species have different impacts on the Earth System. For instance CO_2 has a radiative effect, a fertilisation effect on plants and an acidification effect on the ocean while CH_4 has a radiative effect only. These different effects may result in different impacts on ecosystem services and this needs to be factored in climate metrics (Huntingford et al., 2011). Finally the very large sensitivity to the discount rate suggests that more work should be done to better frame this concept into socio-economic scenarios for climate change adaptation and mitigation.

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Table 1. List of parameters going into the calculations of our simplified methane GDP. For each parameter the table provides the central value, the uncertainty range, and the values chosen to estimate the smallest and the largest possible methane GDP.

Parameter	Central Value	PDF Shape and Uncertainty Range	Parameter Value for Smallest GDP	Parameter Value for Largest GDP
		Methane atmospheric cycle and radiative forcing		
1. O_3 enhancement factor	0.25	Gaussian: s.d. 0.05	0.15	0.35
2. H_2O enhancement factor	0.15	Gaussian: s.d. 0.05	0.05	0.25
3. CH_4 perturbation lifetime	12 years	Gaussian: s.d. 1 year	10	14
4. CH_4 oxidation rate	80 %	Flat: 60–100 %	60 %	100 %
		Carbon dioxide atmospheric cycle and radiative forcing		
5. CO_2 radiative forcing		Gaussian: s.d. 5 %	+10 %	−10 %
		Climate sensitivity		
6. Timescale τ_1	8.4 years	Flat: ±30 %	−30 %	+30 %
7. Climate sensitivity λ_1	0.631 K $(Wm^{-2})^{-1}$	Flat: ±0.2 K $(Wm^{-2})^{-1}$	0.831 K $(Wm^{-2})^{-1}$	0.431 K $(Wm^{-2})^{-1}$
8. Timescale τ_2	410 years	Flat: ±30 %	+30 %	−30 %
9. Climate sensitivity λ_2	0.429 K $(Wm^{-2})^{-1}$	Flat: ±0.18 K $(Wm^{-2})^{-1}$	0.249 K $(Wm^{-2})^{-1}$	0.609 K $(Wm^{-2})^{-1}$
		Climate scenario		
10. 21st century warming	2.5 °C	Flat: 1–4 °C	4 °C	1 °C
		Economic factors		
11. Exponent in damage function	2	Flat: 1.5–2.5	2.5	1.5
12. Discount rate	2 %	Flat: 1–3 %	1 %	3 %

Table 2. Minimum, maximum, central values, mean, standard deviation, 1–99 % and 5–95 % uncertainty ranges for the 100-year GWP, 100-year GTP and GDP.

Metric	Minimum	Maximum	Central Value (Median)	Mean	Standard Deviation	1–99 % Range	5–95 % Range
100-year GWP w/o CO_2	N/A*	N/A*	25.2	25.3	2.8	19.0–32.5	20.5–30.5
100-year GWP w CO_2	N/A*	N/A*	27.2	27.3	2.8	21.0–34.5	22.5–32.5
100-year GTP w/o CO_2	N/A*	N/A*	3.9	4.1	1.8	1.5–7.5	2.0–6.5
100-year GTP w CO_2	N/A*	N/A*	6.2	6.3	1.8	4.0–10.0	4.5–9.0
GDP w/o CO_2	4.3	61.8	24.3	24.7	6.7	10.0–42.5	12.5–38.0
GDP w CO_2	5.9	63.9	26.3	26.7	6.7	12.5–44.5	15.0–40.0

* N/A means non applicable.

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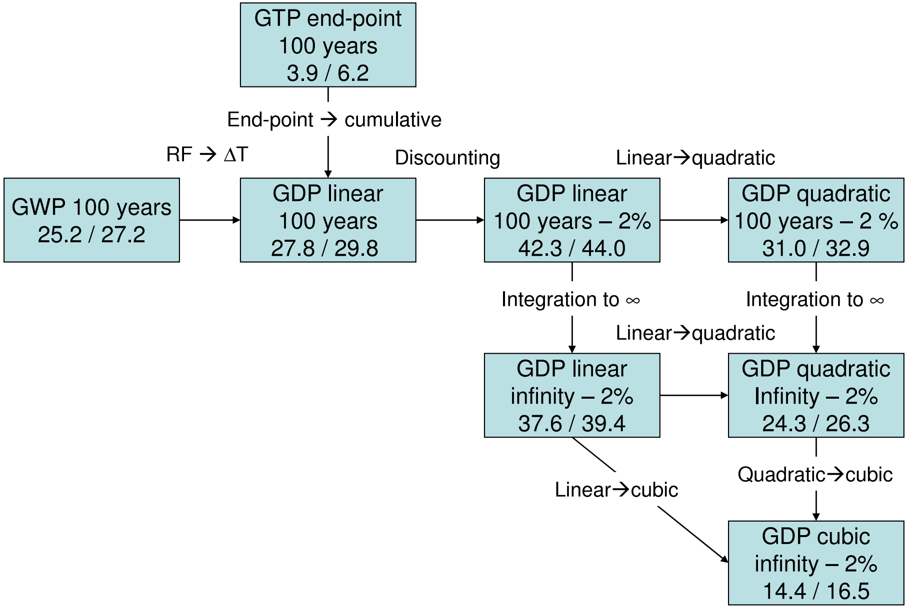

Fig. 1. Sensitivity of the methane CO_2-equivalence (without/with the conversion of methane into CO_2) to the construction of the climate metric. See text for more details.

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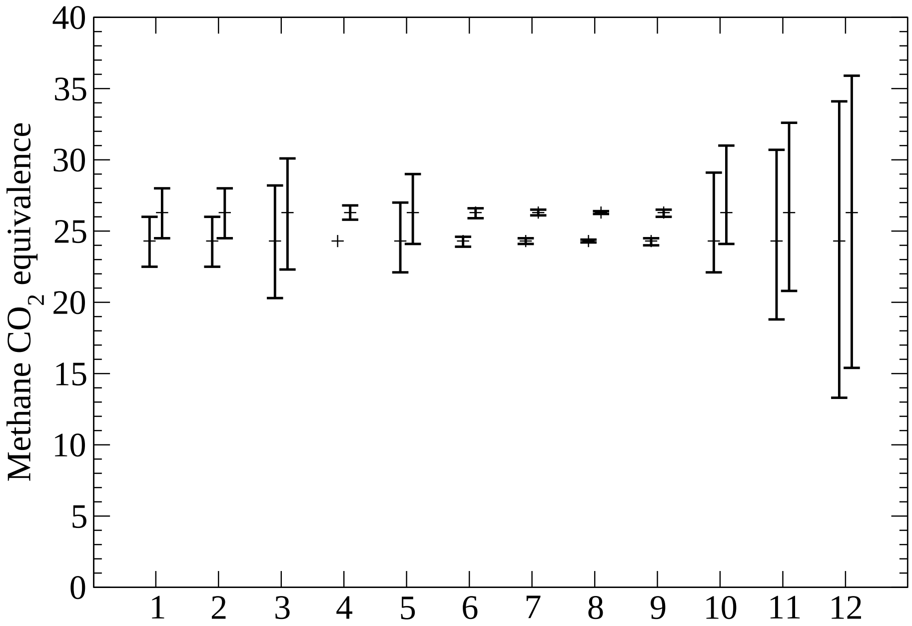

Fig. 2. Uncertainty range in the methane GDP without and with methane conversion when individual parameters from Table 1 (listed from 1 to 12) are varied within the ranges specified in the table and all other parameters are held to their central values. The central values are 24.3 and 26.3 without and with CH_4 conversion to CO_2, respectively.

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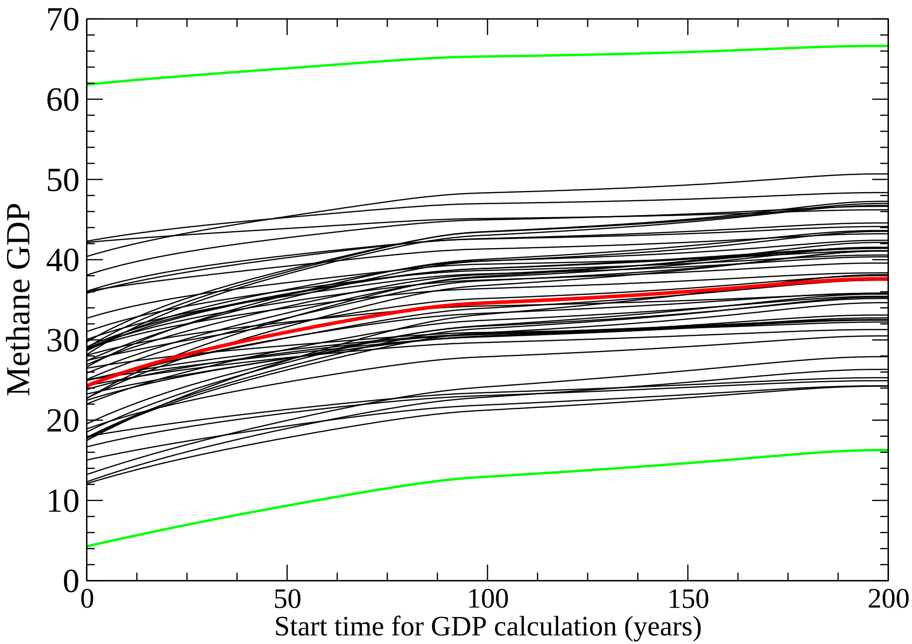

Fig. 3. Methane GDP as a function of the start time for the first 50 members of our Monte-Carlo simulations when randomly perturbing the input parameters with the PDFs specified in Table 1. The red line is for our best guess estimate and the green lines are for the minimum and maximum values for input parameters as specified in Table 1.

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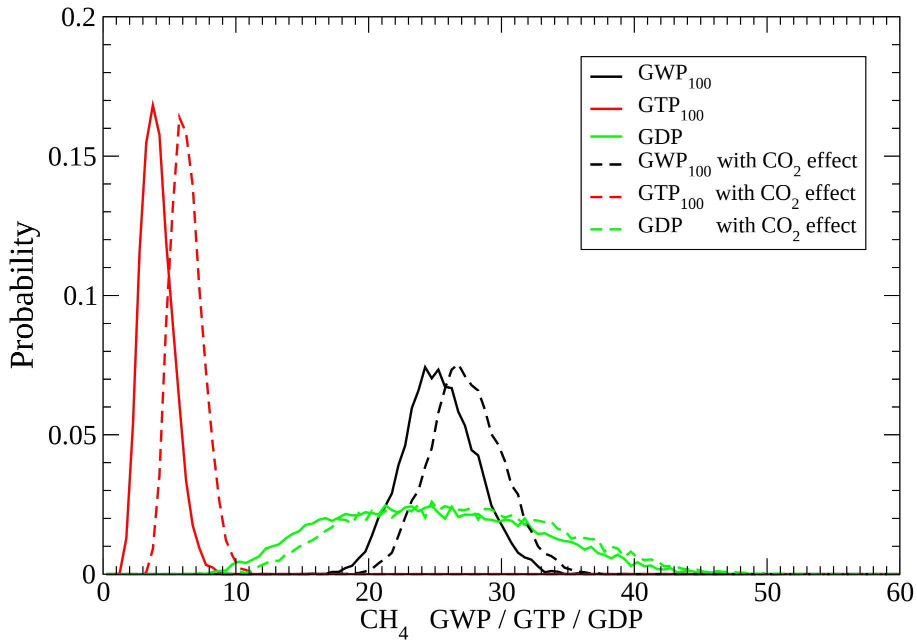

Fig. 4. Probability distribution function of the methane CO_2-equivalence (GWP with 100 years time horizon, GTP with 100 years time horizon, and GDP) obtained from randomly perturbing the input parameters with the PDFs specified in Table 1. The dashed lines account for the CH_4 conversion to CO_2.

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