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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 there is no consensus on what an optimal methane CO_2-equivalence should be. We revisit this question by discussing some aspects 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-yr GWP because of various compensating effects. However, there is a large spread in possible methane CO_2-equivalences from this metric (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 main factor differentiating the methane 100-yr GTP from the methane 100-yr GWP and the GDP is the fact that the former metric is an end-point metric, whereas the latter are cumulative metrics. There is some rationale for an increase in the methane CO_2-equivalence in the future as global warming unfolds, as implied by a convex damage function in the case of the GDP metric. 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 enough visibility on CO_2 prices and CO_2-equivalences for the stakeholders.

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 directly responsible for a radiative forcing (RF) of $0.48\,W\,m^{-2}$ in 2005, compared to a RF of $1.66\,W\,m^{-2}$ for carbon dioxide (Forster et al., 2007). Methane emissions also contribute an indirect RF through changes in tropospheric ozone, stratospheric water vapour and CO_2 concentrations.

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 industrial sectors, space and time. A multi-gas approach, such as the Kyoto protocol, requires defining 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-yr time horizon that has been chosen to provide this equivalence in the Kyoto protocol. The 100-yr 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

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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 precursors to 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 more cheaply and more quickly 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 seeks 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 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 introduced 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 CO_2-equivalence takes a value in the range 20–30 during all of the 21st century. The cost-effective temperature change potential introduced by Johansson (2012) can be seen as a simplified version of this metric that reduces to the GTP before the climate target is reached but can be extended beyond that. Shine et al. (2007) introduced a time horizon that is a function of the proximity to a target year, which makes the physical metric dynamic, and reproduces qualitatively the results of Manne and Richels (2001).

A socio-economically-based climate metric can also be framed 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 restrictive set of assumptions.

The simplicity of the GWP, with 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 active literature on GWP (e.g. Boucher et al., 2009; Reisinger et al., 2010; Gillett and Matthews, 2010; Reisinger et al., 2011). 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 yr is used to estimate the total (i.e. CO_2-equivalent) greenhouse gas emissions for each country, and emission 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

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. to revisit the concept of GDP and its sensitivity to input variables,
2. to compare the GWP and GTP with a simplified GDP in terms of their uncertainties and future time evolution,
3. and to discuss whether different usages of CO$_2$-equivalences require one or more climate metrics, e.g. in the context 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 a starting time t in the future:

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

where 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. The time horizon is usually set to 100 yr, but other values can be used, or it can decrease in time.

2.2 Global temperature change potential

The methane GTP is defined as the ratio of the absolute GTP of methane and CO$_2$ for a starting time t in the future:

$$\mathrm{GTP}_{\mathrm{CH_4}}(t) = \frac{\mathrm{AGTP}_{\mathrm{CH_4}}(t)}{\mathrm{AGTP}_{\mathrm{CO_2}}(t)} = \frac{\delta T_{\mathrm{CH_4}}(t+\mathrm{TH})}{\delta T_{\mathrm{CO_2}}(t+\mathrm{TH})} \quad (2)$$

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 of either CO$_2$ or CH$_4$ 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 a starting time t in the future:

$$\mathrm{GDP}_{\mathrm{CH_4}}(t) = \frac{\mathrm{AGDP}_{\mathrm{CH_4}}(t)}{\mathrm{AGDP}_{\mathrm{CO_2}}(t)} = \frac{\int_{t'=0}^{\infty} [D(\Delta T(t+t') + \delta T_{\mathrm{CH_4}}(t+t')) - D(\Delta T(t+t'))]/(1+\rho)^{t'}\mathrm{d}t'}{\int_{t'=0}^{\infty} [D(\Delta T(t+t') + \delta T_{\mathrm{CO_2}}(t+t')) - D(\Delta T(t+t'))]/(1+\rho)^{t'}\mathrm{d}t'} \quad (3)$$

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. Integrating climate damage over time is justified, because climate impacts either depend on the repetitiveness of climate extremes (e.g. droughts, floods, ...) or on the cumulative amount of warming (e.g. sea level rise, glacier melting, sea-ice melting, permafrost thawing). Moreover, time-integrated damage underlies most cost-benefit analysis of climate change.

It should be noted that, if we omit potential future changes in radiative efficiencies and residence times, AGDP$_{\mathrm{CH_4}}$, AGDP$_{\mathrm{CO_2}}$ and GDP$_{\mathrm{CH_4}}$ are independent of t, 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), GDP$_{\mathrm{CH_4}}$ increases with the baseline year, if D is a convex function of ΔT, which is usually the case.

2.4 Parametrising and sampling parametric 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 that sample possible future (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

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

where $\Delta T_0 = 0.7\,°\mathrm{C}$ is the observed present-day warming, the parameter α varies between 1 and 4 °C century^{-1} and all values are considered equiprobable (i.e. we assume a flat distribution). This lower bound (i.e. 1 °C) is consistent with the range of climate projections for 2100 given in IPCC (2007), while the upper bound is consistent with an upper climate projection with little mitigation.

We then need to convert pulses of CO$_2$ and CH$_4$ emissions into their corresponding GMST changes, $\delta T_{\mathrm{CO_2}}(t')$ and $\delta T_{\mathrm{CH_4}}(t')$. 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 yr 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 yr, which is consistent with a rough 10 % uncertainty in the methane sources and sinks. We follow Ramaswamy et al. (2001) to estimate the direct radiative forcings (in $\mathrm{W\,m^{-2}}$) 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

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

where $F_{\mathrm{O_3}}$ and $F_{\mathrm{H_2O}}$ are the enhancement factors for the O_3 and H_2O indirect effects and the last term corresponds to the methane oxidation effect, whose calculation follows Boucher et al. (2009). We take $F_{\mathrm{O_3}}$ and $F_{\mathrm{H_2O}}$ equal to 0.25 and 0.15, respectively, with a 0.05 standard deviation and a Gaussian distribution of the uncertainties. The uncertainty on $F_{\mathrm{O_3}}$ is consistent with the uncertainty on the ozone forcing, as given by Forster et al. (2007) in terms of a 5 to 95 % confidence interval. The uncertainty on $F_{\mathrm{H_2O}}$ is larger and reflects our limited understanding of the stratospheric water vapour budget. 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 time scales τ_1 and τ_2 of 8.4 and 410 yr, and climate sensitivities λ_1 and λ_2 of 0.631 and 0.429 K $(\mathrm{W\,m^{-2}})^{-1}$, 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 time scales and their associated climate sensitivities within a ±30 % range using flat distributions. This representation of uncertainties is somewhat arbitrary but results in an equilibrium climate sensitivity ranging from 2.7 to 5.1 °C for a doubling of CO_2, while also sampling uncertainties on the transient climate response.

There is relatively little in the scientific literature to justify a particular damage function (e.g. Weitzman, 2010). An exponent function of the GMST change is often chosen to approximate the fact that the damage function is presumably convex (e.g. Tol et al., 1998):

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

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 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. 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. 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. Catastrophic climate change would imply a more convex damage function than implied by a quadratic or cubic function. We will test the linear and cubic damage functions in Sect. 3.1 for completeness and consistency with previous studies. We will also investigate and discuss the structural uncertainties caused by the damage function in Sect. 3.5.

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 unacceptable social implications, such as the impoverishment of the current generation in order to protect all future generations (Pearce et al., 2003). 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; Hallegatte, 2008), 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. It should also be noted that the use of time horizons in the GWP is equivalent, albeit in a complex way, with the application of discounting, as discussed in Fuglestvedt et al. (2003). 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). We also investigate the use of a time-varying discount rate, as recommended in the UK Green Book (2011) in Sect. 3.5 and test extreme values of the discount rate of 0.5 and 5 %.

Table 1. List of parameters going into the calculations of the methane GWP, GTP and 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 CO_2-equivalence.

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 yr	Gaussian: s.d. 1 yr	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. Time scale τ_1	8.4 yr	Flat: ±30 %	−30 %	+30 %
7. Climate sensitivity λ_1	$0.631\,\mathrm{K}\,(\mathrm{W\,m^{-2}})^{-1}$	Flat: $\pm 0.2\,\mathrm{K}\,(\mathrm{W\,m^{-2}})^{-1}$	$0.831\,\mathrm{K}\,(\mathrm{W\,m^{-2}})^{-1}$	$0.431\,\mathrm{K}\,(\mathrm{W\,m^{-2}})^{-1}$
8. Time scale τ_2	410 yr	Flat: ±30 %	+30 %	−30 %
9. Climate sensitivity λ_2	$0.429\,\mathrm{K}\,(\mathrm{W\,m^{-2}})^{-1}$	Flat: $\pm 0.18\,\mathrm{K}\,(\mathrm{W\,m^{-2}})^{-1}$	$0.249\,\mathrm{K}\,(\mathrm{W\,m^{-2}})^{-1}$	$0.609\,\mathrm{K}\,(\mathrm{W\,m^{-2}})^{-1}$
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 %

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) is a straightforward special case of Eq. (3). The GWP is a function of the RF rather than a function of the GMST change (i.e. $\delta T(t') \equiv \mathrm{RF}(t')$). It is consistent with a linear damage function ($\gamma = 1$). 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 linearly 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. $D = \delta_{\mathrm{TH}} \Delta T$ 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

We now compare the methane CO_2-equivalence from the GWP, GTP and GDP metrics. Both the GWP and GTP require the choice of a time horizon. The 100-yr time horizon that is frequently used corresponds more or less to the typical time scale, on which the climate change problem will be faced and should be addressed. It should be noted that the choice of a time horizon is implicitly related to the choice of a discount rate (the two quantities have inverse dimensions), although it is difficult to establish a one-to-one relationship between the two quantities. We stick here to the 100-yr time horizon, but revisit this issue in Sect. 3.2 where we discuss time-evolving metrics and Sect. 3.5 where we discuss structural uncertainties.

The 100-yr GTP for methane (3.9 and 6.2 with and without CH_4 conversion to CO_2) is much lower than the 100-yr GWP (25.2 and 27.2), as already noted by Shine et al. (2007) and Gillett and Matthews (2010). The methane GDPs 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-yr methane GWP

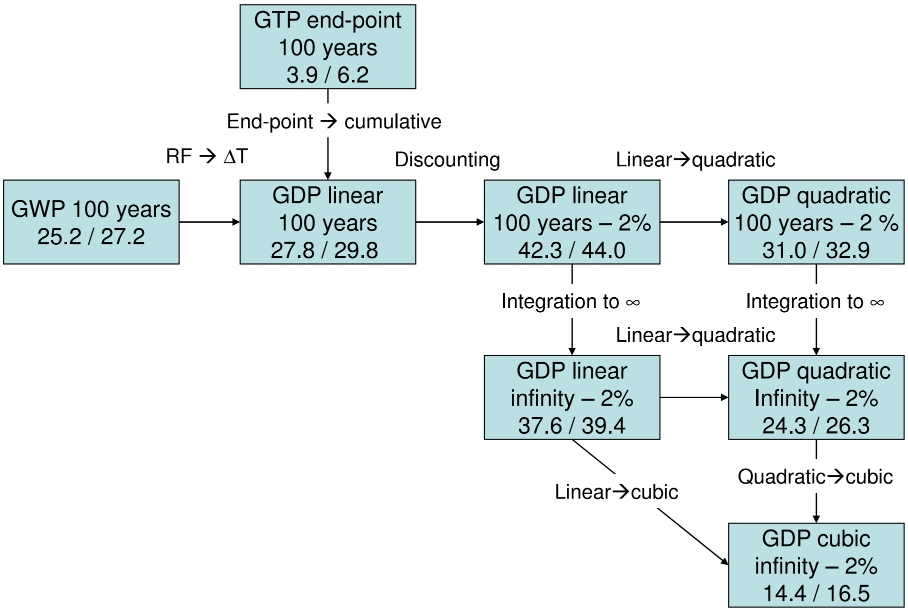

Fig. 1. Sensitivity of the methane CO_2-equivalence (without/with the conversion of methane into CO_2) to the construction of the climate metric (see text for more details).

value of 25. This is consistent with the finding of Fuglestvedt et al. (2003), who showed how discount rate and damage function exponent can be combined to produce a methane GDP that is equivalent to the methane GWP for a given time horizon. This similarity in values for a quadratic damage function and a discount rate of 2 % and a time horizon of 100 yr can be explained through a number of compensating effects (as illustrated in Fig. 1). Considering a cumulative function of the GMST change rather than a cumulative function of RF increases the methane CO_2-equivalence only slightly. 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 yr) 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-yr 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-yr GWP and our simple 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.

The effect is much larger when going from an end-point GTP to a cumulative function of GMST change over 100 yr, as already noted by Gillett and Matthews (2010). Whether a pulse emission metric measures an end-point or a cumulative quantity is therefore a key factor differentiating existing metrics, at least for the longer time horizons

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. As discussed above, there is little literature to justify one or the other value for the exponent, but a quadratic function is often used.

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 pulses in CO_2 and CH_4 change over time. Previous authors have investigated how the GWP and GTP evolve for different but constant-in-time background levels, and similar changes can be expected for time-varying changes in the background levels. 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-yr 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-yr 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-yr methane GWP would increase by $\approx$10 % by 2100 in the RCP3PD and RCP4.5 scenarios, but would decrease by $\approx$10 % by the middle of the century in the RCP8.5 scenario. While these studies examined the impact of changing background (fixed) concentrations and climate in the GWP calculations, they did not attempt to include time-evolving concentrations and climate in the GWP calculation itself. However, we can expect these effects to be of similar magnitude, and we estimate 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 starting 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 yr and 37.6 in 200 yr. This increase is due to the convexity of the damage cost function in a warming climate.

Other climate metrics can also be time-evolving. For instance, the methane CO_2-equivalence implied by the GTP increases when the time horizon is shortened as the climate target is approached. Global cost potential (e.g. Manne and Richels, 2001) or variants of the GTP (e.g. Johansson, 2012) are also designed to evolve with time. Generally speaking, there is some rationale for the methane CO_2-equivalence to increase with time, as climate change becomes more of a problem or is going to require more and more effort to combat. It is nevertheless possible to construct a climate metric where the methane CO_2-equivalence decreases with time or goes up and down, as discussed further in Sect. 3.5. This is the case, for instance, if a constraint on the rate of climate change is added to the climate metric (Manne and Richels, 2001). It is also possible that increased knowledge calls for some revision on the climate policy, which as a result brings down the methane CO_2-equivalence. This would be the case, for instance, if the climate sensitivity turns out to be less than expected (which would buy society some time) or if a threshold has been passed unintentionally and there is limited additional damage to be expected until one approaches the next threshold.

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 that 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 notable 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.

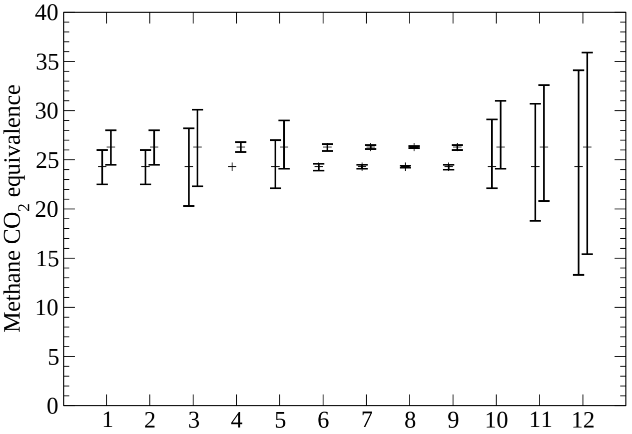

Fig. 2. Uncertainty range in the methane GDP without and with methane conversion when individual parameters from Table 1 (listed from 1 to 12) are varied within the ranges specified in the table and all other parameters are held to their central values. The central values are 24.3 and 26.3 without and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

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), which affect the methane GWP, GTP and GDP. 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 evolve 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 yr 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 yr. The rest of the section is now focused on the present-day GDP value.

The probability distribution functions (PDF) for the methane GWP, GTP and GDP are shown in Fig. 4 and Table 2. Our 90 % confidence interval for the methane 100-yr 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 %

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

Metric	Minimum	Maximum	Central Value (Median)	Mean	Standard Deviation	1–99 % Range	5–95 % Range
100-yr GWP w/o CO_2	16.4	37.3	25.2	25.3	2.8	19.0–32.5	20.5–30.5
100-yr GWP w CO_2	17.9	39.8	27.2	27.3	2.8	21.0–34.5	22.5–32.5
100-yr GTP w/o CO_2	1.0	12.3	3.9	4.1	1.8	1.5–7.5	2.0–6.5
100-yr GTP w CO_2	2.6	15.1	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

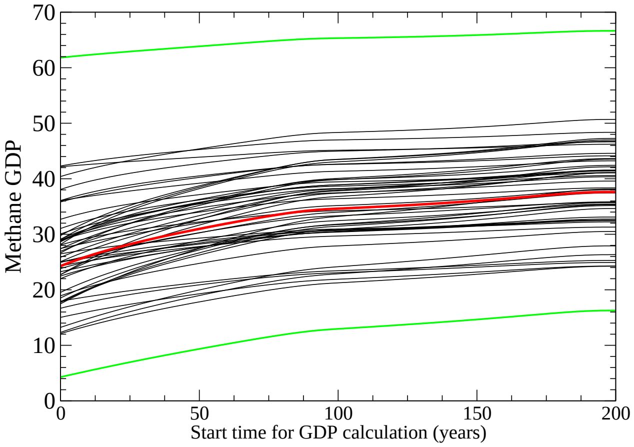

Fig. 3. Methane GDP as a function of the start time for the first 50 members of our Monte Carlo simulations when randomly perturbing the input parameters with the PDFs specified in Table 1. The red line is for our best guess estimate and the green lines are for the minimum and maximum values for input parameters, as specified in Table 1. The figure shows the case without the CH_4 conversion to CO_2.

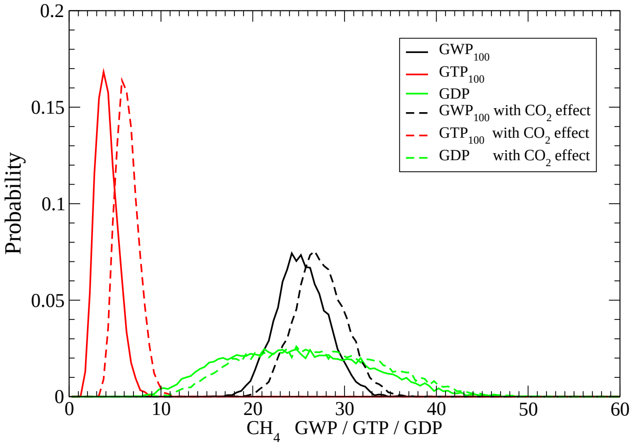

Fig. 4. Probability distribution function of the methane CO_2-equivalence (GWP with 100-yr time horizon, GTP with 100-yr time horizon, and GDP) obtained from randomly perturbing the input parameters with the PDFs specified in Table 1. The dashed lines account for the CH_4 conversion to CO_2.

confidence interval in the methane 100-yr GTP (2.0–6.5) is significantly different to the (3.9–13.5) range reported by Reisinger et al. (2010). This appears to be due to differences in the methane AGTP rather than in the CO_2 AGTP. The discrepancy may partly be explained by the fact that Reisinger et al. (2010) include the effect of the climate-carbon feedback in their calculation of the methane AGTP, when we do not. Further work is required to understand the differences in methane GTP from different authors.

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-yr GWP and GTP, for which the standard deviations are 2.8 and 1.8, respectively. In that sense, it is a less robust climate metric than GWP, but it offers more flexibility for adjustment (on e.g. the shape of damage function and the discount rate) 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, which 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-yr 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-yr GWP, but fairly close to the central value for the 100-yr 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. They correspond to all parameters taken at their extreme values, which occurs very rarely in the Monte Carlo simulation.

3.5 Sensitivity to some structural uncertainties

We investigate here the sensitivity of our results to some of the structural uncertainties embedded in the GDP metric. As noted earlier, there is no consensus on the shape of the damage function and an exponent function was chosen for simplicity. Other shapes have been proposed, such as a hockey stick (Tol et al., 1998), an S-shaped or sigmoid function (Ambrosi et al., 2003) or a sum of sigmoid functions. Hockey-stick damage functions may be appropriate in cost-benefit analysis (they essentially imply that there is a threshold GMST change, above which we should mitigate at any cost), but would cause some inconsistency in the GDP calculation as the temperature change trajectory is prescribed independently from the damage function. Therefore, we only consider sigmoid damage functions here as an alternative to an exponent function. The sigmoid damage function in arbitrary unit can be written as

$$D(\Delta T) = 1 + \tanh\left(\frac{\Delta T - \Delta T_1}{\mathrm{d}T}\right) \tag{9}$$

where ΔT_1 is a threshold temperature change and dT defines the stiffness of the changes around the threshold (taken to be 0.5 °C). With such a damage function, the impacts are initially small and then increase sharply before reaching a plateau. Although the plateau may not be a realistic feature, a sigmoid function represents the existence of a threshold around a given GMST change. We use a value ΔT_1 of 2 °C and the lower bound of our warming scenario as a sensitivity test. We also consider the sum of two or three sigmoid functions centred on thresholds of 4 and 6 °C and associated with double and triple damages:

$$D(\Delta T) = 1 + \tanh\left(\frac{\Delta T - \Delta T_1}{\mathrm{d}T}\right) + 2\tanh\left(\frac{\Delta T - \Delta T_2}{\mathrm{d}T}\right) \tag{10}$$

and

$$\begin{aligned} D(\Delta T) =\ & 1 + \tanh\left(\frac{\Delta T - \Delta T_1}{\mathrm{d}T}\right) + 2\tanh\left(\frac{\Delta T - \Delta T_2}{\mathrm{d}T}\right) \\ & + 3\tanh\left(\frac{\Delta T - \Delta T_3}{\mathrm{d}T}\right). \end{aligned} \tag{11}$$

These damage functions are considered along with our median and upper bound warming scenarios, respectively. It should be noted that a damage function that corresponds to multiple thresholds of increasing severity becomes similar in shape to an exponent function.

Figure 5 shows the time evolution of the methane CO$_2$-equivalence for a range of climate metrics, including those corresponding to the sigmoid damage functions defined above. For the GWP and GTP metrics, we show how the CO$_2$-equivalence would increase if the time horizon is shortened from 100 yr down to 1 yr. This implies a faster increase in time than for any of the exponent functions chosen here. It also appears that the use of a sigmoid or a sum of sigmoids for the damage function can result in up and down for the methane CO$_2$-equivalence, but these stay in the same range as for the exponent damage functions. A smaller value for dT would result in a larger range of values; however, there is little literature to support the concept of a rapid transition around a threshold under future global warming.

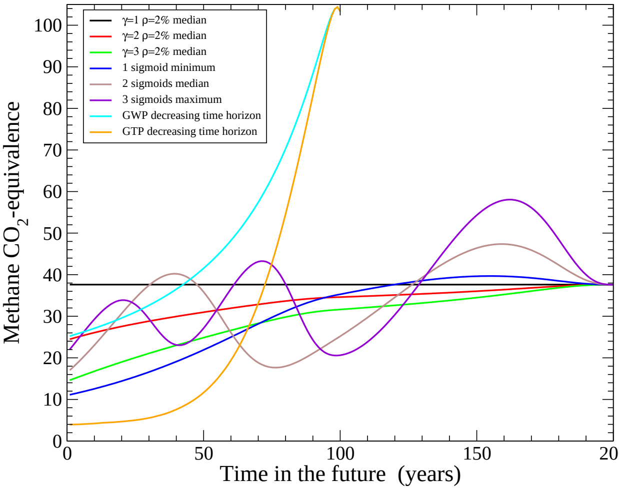

Fig. 5. Time evolution of the methane CO$_2$-equivalence for a set of climate metrics: GDP with linear, quadratic and cubic damage functions, GDP with one sigmoid damage function, GDP with the sum of two or three sigmoid damage functions, GWP with decreasing time horizon (from 100 yr to 1 yr), GTP with decreasing time horizon (from 100 yr to 1 yr). The legend box indicates if the minimum, median or maximum warming scenario was used. The figure shows the case without the CH$_4$ conversion to CO$_2$.

It has been argued that damage from climate change is also a function of the rate of change (Tol, 1996; O'Neill and Oppenheimer, 2004). Manne and Richels (2001) have shown how this translates into the methane CO$_2$-equivalence for their metric. However, there is little quantitative information on how damage responds to the rate of climate change. Moreover, incorporating a constraint on the rate of change can only be done properly if the concentration pathways of both long-lived and short-lived climate forcers are optimized, which is not compatible with the simple approach taken here with the GDP. For these reasons we do not attempt to further examine this issue.

Finally, we investigate the impact of using a time-varying discount rate, as has been proposed for different reasons by Pearce et al. (2003). The decrease in the discount rate over time can be justified by an uncertainty in future levels of consumption (UK Green Book, 2011) or the transition from an individual to an intergenerational discount rate (Hallegatte, 2008). We test here the effect of a discount rate that decreases over time from 3.5 % (for years 1 to 30) down to 1 % (for years beyond 301), as recommended by the UK Green Book (2011). The discount rate recommended by the UK Green Book leads to similar results as our median value of discount rate of 2 % with GDP values of 20.0 and 22.0 without and with the CH_4 to CO_2 conversion effect, respectively. We also test extreme values of the discount rates of 0.5 % and 5 %, with corresponding GDP values 7.8/9.9 and 49.6/51.2, respectively. However, it should be noted that such values find little support in the scientific literature on the economics of climate change.

4 Interpreting the methane CO_2-equivalence

Most climate metrics that 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 is sometimes argued that a metric for sustained emissions should be used to trade perennial emission reductions. To disprove this we introduce a generalised sustained GDP (denoted $\mathrm{GDP_s}$), which compares the relative discounted climate effects of CH_4 and CO_2 emissions over n years:

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

It should be noted that the individual pulses do not add to the ΔT trajectory in this equation.

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

The investor wants to pay back their investment by avoiding paying a greenhouse gas tax or buying emission credits, or by selling emission credits if emissions were reduced beyond expectation. In a fluid market, emission reductions will take place at increasing costs until

$$X_{\mathrm{CO_2}} + \sum_{t=0}^{n-1} Y_{\mathrm{CO_2}}(t)/(1+\rho)^t = \sum_{t=0}^{n-1} P_{\mathrm{CO_2}}(t)/(1+\rho)^t \quad (13)$$

where $P_{\mathrm{CO_2}}(t)$ 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. (3) as long as it is the same discount rate used in the LHS and RHS of Eq. (13). One can then write an analogous equation to Eq. (13) but for CH_4 emission reductions. Ratioing the two equations gives

$$\frac{X_{\mathrm{CH_4}} + \sum_{t=0}^{n-1} Y_{\mathrm{CH_4}}(t)/(1+\rho)^t}{X_{\mathrm{CO_2}} + \sum_{t=0}^{n-1} Y_{\mathrm{CO_2}}(t)/(1+\rho)^t} = \frac{\sum_{t=0}^{n-1} P_{\mathrm{CH_4}}(t)/(1+\rho)^t}{\sum_{t=0}^{n-1} P_{\mathrm{CO_2}}(t)/(1+\rho)^t} \quad (14)$$

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

For the 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:

$$\frac{\sum_{t=0}^{n-1}\int_{t'=0}^{\infty} \left[D\left(\Delta T(t+t') + \delta T_{\mathrm{CH_4}}(t')\right) - D(\Delta T(t+t'))\right]/(1+\rho)^{t+t'}\,\mathrm{d}t'}{\sum_{t=0}^{n-1}\int_{t'=0}^{\infty} \left[D\left(\Delta T(t+t') + \delta T_{\mathrm{CO_2}}(t')\right) - D(\Delta T(t+t'))\right]/(1+\rho)^{t+t'}\,\mathrm{d}t'} = \frac{\sum_{t=0}^{n-1} P_{\mathrm{CH_4}}(t)/(1+\rho)^t}{\sum_{t=0}^{n-1} P_{\mathrm{CO_2}}(t)/(1+\rho)^t}. \quad (15)$$

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

$$\frac{\sum_{t=0}^{n-1} \mathrm{AGDP_{CO_2}}(t)\,\mathrm{GDP_{CH_4}}(t)/(1+\rho)^t}{\sum_{t=0}^{n-1} \mathrm{AGDP_{CO_2}}(t)/(1+\rho)^t} = \frac{\sum_{t=0}^{n-1} P_{\mathrm{CO_2}}(t)\,R_{\mathrm{CH_4}}(t)/(1+\rho)^t}{\sum_{t=0}^{n-1} P_{\mathrm{CO_2}}(t)/(1+\rho)^t}. \quad (16)$$

The equation above is verified if the variations of $P_{\mathrm{CO_2}}(t)$ follow those of $\mathrm{AGDP_{CO_2}}(t)$ and if the variations of $R_{\mathrm{CH_4}}(t)$ 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. (13) and (14) to optimise their 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 enough visibility from policymakers on how the price of CO_2 and the methane CO_2-equivalence are going to vary 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 pulse climate metric had been used to calculate the methane CO_2-equivalence.

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 explore the sensitivity of the methane CO_2-equivalence to various parameter choices. 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 increases as global warming unfolds. 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-yr methane GWP. This is because replacing the cumulative function of the RF in the GWP with a quadratic function of the GMST in the GDP is compensated by the introduction of a 2 % discount rate, which gives more importance to the short lifetime of methane.

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.

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 uncertainty range only includes parametric uncertainties and not structural uncertainties. It should be noted however that the analysis spans rather large intervals of parametric uncertainties.

5. The main factor differentiating the methane 100-yr GTP from the methane 100-yr GWP and the GDP is the fact that the former metric is an end-point metric, whereas the latter are cumulative metrics. More work is required to understand differences in the methane GTP estimates between different authors.

6. There is some rationale for an increase in the methane CO_2-equivalence in the future as global warming unfolds. This is implied by a convex damage function, in the case of the GDP metric or by shortening the time horizon as the climate target is approached in the case of an end-point metric such as the GTP. The ensemble GDP calculation suggests that the relative increase is more for the smaller values of the GDP.

7. 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 vary over time in some known and visible way. There is no need for policy-makers to introduce an additional metric for sustained emission to make perennial investment decisions as long as there is enough visibility on future prices and CO_2-equivalences for the stakeholders.

Our GDP remains a simplified metric. One assumption in particular merits more investigation. Climate impacts vary geographically and across activities, 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 an indirect effect on ozone, which may further affect the carbon cycle (Collins et al., 2010). 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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