Earth Syst. Dynam. Discuss., https://doi.org/10.5194/esd-2018-6
Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 6 February 2018

A quantitative approach to evaluating the GWP timescale through implicit discount rates

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Abstract. The 100-year Global Warming Potential (GWP) is the primary metric used to compare the climate impacts of different greenhouse gases (GHGs). The GWP relies on radiative forcing rather than damages, assumes constant future concentrations, and integrates over a timescale of 100 years without discounting: these choices lead to a metric which is transparent and simple to calculate, but have also been criticized. In this paper, we take a quantitative approach to evaluating the choice of time-horizon, accounting for many of these complicating factors. By calculating an equivalent GWP timescale based on discounted damages resulting from CH_4 and CO_2 pulses, we show that a 100-year timescale is consistent with a discount rate of 3.3% (interquartile range of 2.7% to 4.1% in a sensitivity analysis). This range of discount rates is consistent with, or larger than, those usually considered for climate impact analyses. With increasing discount rates equivalent timescales decrease. We recognize the limitations of evaluating metrics by relying only on climate impact equivalencies without consideration of the economic and political implications of metric implementation.

1. Introduction

The Global Warming Potential (GWP) has become the primary metric used to assess the equivalency of different greenhouse gases (GHGs) for use in multi-gas policies and aggregate inventories. This primacy was established soon after its development in 1990 (Lashof and Ahuja, 1990, Rodhe 1990) due to its early endorsements by the WMO (1992) and UNFCCC (1995). However, despite the GWP's long history of political acceptance, the GWP has also been a source of controversy and criticism (e.g., Wigley et al. 1998, Shine et al. 2005, Allen et al. 2016, and Edwards et al. 2016).

Key criticisms of the metric are wide ranging: from arguments that radiative forcing as an endpoint is not as relevant as temperature or damages, to critiques of the assumption of constant future GHG concentrations, to the position that discounting is preferred to a constant time period of integration, to the view that dynamic approaches would lead to a more optimal resource allocation over time (e.g., Manne and Richels, 2001), and to the fact that the GWP does not account for non-climatic effects such as carbon fertilization. Unfortunately, including these complicating factors would make the metric less simple and transparent and would require reaching consensus regarding appropriate parameter values, model choices, and other methodology issues. The simplicity of the calculation of the GWP is likely one of the reasons that the use of the metric is so widespread.

In this paper, we assess the choice of time-horizon. The 100-year horizon of the GWP (GWP_{100}) is the horizon endorsed by the WMO and UNFCCC. However, the 100-year time horizon has been described by some as arbitrary (Rodhe, 1990). The IPCC AR5 (Myhre et al. 2013) stated that "[t]here is no scientific argument for selecting 100 years compared with other choices". The WMO (1992) assessment has provided one of the few justifications for the 100-year time horizon, stating that "The GWPs evaluated over the 100-year period appear generally to provide a balanced representation of the various time horizons for climate response". Therefore, some researchers and NGOs have recently been promoting more emphasis on shorter time horizons, such as 20 years, which would highlight the role of short-lived climate forcers such as CH_4 (Howarth et al. 2011, Edwards and Trancik, 2014, Ocko et al. 2017, Shindell et al. 2017). In contrast to this push for a shortened time horizon of the GWP, some governments have been suggesting the use of the 100-year Global Temperature Potential (GTP) based on the greater physical relevance of temperature in comparison to forcing, in effect downplaying the role of the same short-lived climate forcers (Chang-Ke et al. 2013). However, there have been few quantitative justifications of other timescales within the GWP structure, as opposed to qualitative justifications such as a need for urgency to avoid tipping points as in Howarth et al. (2012). A more in-depth discussion of the interaction between metrics and stabilization targets, other research that has used similar global damage potential approaches, and short timescale metrics is included in the SI. It is in this context that this paper provides the most rigorous evaluation to date of different timescales for the GWP.

This paper provides a needed quantification and analysis of the implications of different GWP time horizons. We follow the lead of economists who have proposed that the appropriate comparison between different options for GHG emissions policies is to compare the net present discounted marginal damages (Schmalensee 1993). However, instead of proposing a switch to a global damage potential metric, we take the structure of the GWP as a given due to the simplicity of calculation and the widespread historic acceptance of its use. Under the assumption that the ratio of discounted marginal damages from GHG emissions is the correct metric for evaluating relative impacts (along with choices regarding the most likely future radiative forcing pathway, climate sensitivity, and relationship of temperature to damages), we find that the 100 year timescale for the GWP is consistent with a damage ratio calculated using a discount rate of 3.3% (interquartile range for a sensitivity calculation of 2.7 to 4.1%), whereas a 20 year timescale is more consistent with a discount rate of 12.6% (interquartile range of 11.1% to 14.6%).

2. Methods

The general approach taken in this manuscript is to calculate the impact of a pulse of emissions of either CO_2 or CH_4 in the first year of simulation on a series of climatic variables. The first step is to calculate the perturbation of atmospheric concentrations over a baseline scenario. The concentration perturbation is transformed into a change in the global radiative forcing balance. The radiative forcing perturbation over time is used to calculate the impact on temperature and then damages due to that temperature change. Discount rates are then applied to these impacts to determine the net present value of the impacts. The details of these calculations are described here.

Concentrations: The perturbation due to a pulse of CO_2 is determined by use of IPCC AR5 equations (see Table 8.SM.10 from the IPCC AR5 assessment). The perturbation due to a pulse of CH_4 is calculated by the use of a 12.4 year lifetime, consistent with Table 8.A.1 from IPCC AR5. In this manuscript, a pulse of 28.3 Mt of CH_4 is used (sufficient for a 10 ppb change in global CH_4 concentrations in the pulse year). The mass of the gas is converted to concentrations by assuming a molecular weight of air of 29 g/mole, and a mass of the atmosphere of 5.13 *10^18 kg. These perturbations are added to baseline concentration pathways: for this study, we use the 4 RCP scenarios, based on data from http://www.pik-potsdam.de/~mmalte/rcps/. This approach parallels the standard IPCC approach: however, various papers have noted that the lifetime of CO_2 presented in the IPCC includes climate carbon feedbacks, whereas the lifetime of CH_4 does not, which is a potential inconsistency (Gasser et al. 2017, Sterner and Johansson 2017). The discussion in Sect. 3.4 elaborates on the consequences of these choices.

Radiative Forcing: The perturbation of radiative forcing from additional GHG concentrations are based on the equations in Table 8.SM.1 from IPCC AR5. CH_4 forcing is adjusted by a factor of 1.65 to account for effects on tropospheric ozone and stratospheric water vapor, as is standard in GWP calculations. N_2O forcing is adjusted by a factor of 0.928 to account for N_2O's impacts on CH_4 concentrations, as is also standard in GWP calculations. Baseline radiative forcing is derived from the RCP scenario database.

Temperature: Temperature calculations are all based on IPCC AR5 Table 8.SM.11.2. It should be noted that the IPCC equations were designed for marginal emissions changes; therefore, using this approach to calculate temperatures resulting from the background RCP concentration pathways as well as the additional emissions pulses introduces a potential uncertainty. In order to calculate future temperatures, we also account for the present-day radiative forcing imbalance. Medhaug et al. (2017) suggest that this imbalance likely lies between 0.75 and 0.93 W/m^2. We use the mean (0.84 W/m^2) as the central estimate, and the range of this estimate in the sensitivity analysis presented above. The sum of the coefficients of the equations in the IPCC temperature impulse response functions (1.06) is the sensitivity of the climate to an additional W/m^2: assuming that a doubling of CO_2 yields 3.7 W/m2, then the climate sensitivity implied by the IPCC suggested coefficients is 3.92. As a sensitivity analysis, the coefficients were scaled to yield climate sensitivities of 1.5 and 4.5 to mirror the likely range estimated by the IPCC.

Damages: Damages as a percent of GDP were calculated by multiplying a constant times the temperature squared. Hsiang et al. (2017) present a recent justification for using a quadratic function. For sensitivity analysis, damage exponents of 1.5 or 3 were considered. Other formulations of the damage function have been considered in the literature. The first alternative is explicit calculation of damages within integrated assessment models. Another alternative is to include a higher power term in addition to the square exponent, so that at low temperatures damages rise quadratically, but at high temperatures damages accelerate (Weitzman 2010). Finally, some analyses account for the impact of climate change on the economic growth rate, finding substantially higher damages (Dell et al. 2012, Moore and Diaz, 2015). The damage constant (which cancels out in this particular application) as well as the GDP pathway are taken from the Nordhaus DICE model (Nordhaus 2017). Sensitivity analyses used a growth of 0.5 and 1.5 times that of the growth for each five-year time period in the Nordhaus scenario. The GDP growth rates from DICE, and the growth rate uncertainty used, are reasonably consistent with the estimate of long-run productivity growth from Gillingham et al. (2015) of 2.06% (with a standard deviation of 1.12%), when added to the population growth rate of 0.4% from DICE. A temperature offset was also used because it is not clear what baseline temperature should be used for the damage function. A central value of 0.6 °C (the temperature change from 1951-1980 compared to 2011 based on the NASA GISStemp surface temperature record, GISTEMP 2016) is used, with sensitivities of 0 °C as a lower bound and 0.8 °C (the temperature change from 1880 to 2012 from the 2014 National Climate Assessment) as an upper bound. For the RCP3PD scenario, some future years are cooler than present: in years that are sufficiently cool that the temperature change plus the temperature offset is less than zero, this value is set to zero to avoid numerical problems.

Discounting: Discount rates at 0.1% intervals between 0.5% and 15% were used in the analysis.

Equivalent GWP timescale: The above calculations produce a net present damages resulting from a pulse of CH_4 and for a pulse of the same mass CO_2. The ratio of these two values is a measure of the relative impact of CH_4 and CO_2. This measure of relative impact can be used to calculate the equivalent GWP timescale that would produce the same ratio.

3. Results

3.1. Evaluating the Climate Effects of an Emission Pulse of CH_4

The analysis starts by calculating the climate effects of an emission pulse of CH4. We introduce an emission pulse of 28.3 MT in 2011 (yielding a 10 ppb increase in CH4 concentration in the initial year) applied on top of the GHG concentrations of Representative Concentration Pathway (RCP) 6.0 (Myhre et al. 2013). Figure 1 shows the changes in radiative forcing (RF; a), temperature (T; b), damages (c), and damages discounted at a 3% rate (d) out to the year 2300 resulting from such a pulse (using central estimates of the uncertain parameters, as discussed in the Methods section). The impacts of an emission pulse of CO_2 are also shown, using 24.8 times the mass of the CH_4 pulse (this factor is chosen to create equivalent integrated damages over the full time period when discounted at 3% as shown in Fig. 1d). Fig. 1a and 1b demonstrate the tradeoffs between near-term and long-term impacts when assigning equivalency to emission pulses of different lifetimes. After 100 years, the radiative forcing effects of the CH_4 pulse decay to 0.04% of the initial forcing in the year of the emission pulse, and the temperature effects decay to 4% of the peak temperature (reached 10 years after the pulse). In contrast, after 100 years the radiative forcing effects of the CO_2 pulse decay to 22% of the initial forcing, and the temperature effects decay to 51% of the CO_2 peak temperature (reached 18 years after the pulse). The immediacy of the temperature effects for the CH_4 pulse creates larger damages in both overall and discounted dollar terms for the first 42 years. After 43 years, the sustained CO_2 effects overtake the CH_4 effects. With a different discount rate, a different factor would have been used to calculate the CO_2 mass used for the CO_2 pulse, which would change the crossing point for damages – a higher discount rate would require a larger CO_2 equivalent pulse relative to the CH_4 pulse, and therefore an earlier crossing point (and vice versa). Fig. 1c demonstrates the dramatic increase in damage over time due to the relationship of damage to economic growth, and 1d demonstrates the dramatic decrease in future damages when applying a constant discount rate. Taken as a whole, these 4 figures demonstrate the tradeoffs required when attempting to create equivalences for gases with very different lifetimes.

3.2. Implying a Discount Rate

This analysis of evaluating the radiative forcing, temperature, damages and discounted damages of a pulse emission can be used to calculate the consistent GWP timescale for a given discount rate or, conversely, the discount rates that are consistent with a given GWP timescale by comparing the net present discounted marginal damages of CH_4 to CO_2. Figure 2 shows the relationship between the discount rate and the GWP timescale. Here we focus on what discount rates are consistent with a GWP time horizon in order to show the discount rates implied by common choices of GWP timescales. The converse calculation is relevant for an audience that has a preferred discount rate and is interested in the implied GWP timescale.

From Fig. 2, the discount rate implied by the GWP 100 is 3.3% (interquartile range of 2.7% to 4.1%). The discount rate implied by a 20-year GWP timescale is 12.6% (interquartile range of 11.1% to 14.6%). Results in the figure are truncated to the year 2300 and the calculation is truncated to the year 2500, which may matter at very low discount rates due to the long lifetime of CO_2. At a 3% discount rate, 90% of the discounted CO_2 damages from an emissions pulse comes in the first 157 years, and 95% in 189 years. For CH_4, the equivalent 90/95% is 87/123 years, with the long tail on temperature effects causing elongated damages beyond the lifetime of the gas itself. Even at a 2% discount rate, 95% of the CO_2 damages come in the first 287 years. At discount rates lower than 2%, however, truncation effects can account for errors in damage ratio estimates of greater than a percent, indicating that longer calculation timeframes may be necessary to capture the full effect of the emissions pulse.

There is much discussion regarding which discount rate are most appropriate for use in evaluating climate damages. Since 2003, the US Government has used discount rates of 3% and 7% to evaluate regulatory actions, where 3% was deemed appropriate for regulation that “primarily and directly affects private consumption” and 7% for regulations that “alter the use of capital in the private sector” (OMB, 2003). From the current analysis, a 3% discount rate is consistent with a GWP of 118 years (interquartile range of 84-171 years) and 7% with a GWP of 38 years (interquartile range of 32-47 years). The OMB Circular also recognizes that there are special ethical considerations when impacts may accrue to future generations, and climate change is a prime example of an impacts where discount rates lower than 3% could be justified. A number of researchers have advocated for time-dependent declining discount rates (Weitzman 2001, Newell and Pizer 2003, Gollier et al. 2008). The UK and France both already use declining discount rates in policymaking, and in both cases, the certainty equivalent discount rate drops below 3% within a hundred years, and approaches 2% within 300 years (Cropper et al. 2014).

One option would be a Ramsey framework approach in which discount rates are a function of elasticity of the marginal utility of consumption, pure rate of time preference, and uncertain future growth rate of per capita consumption (NAS, 2017): however, this approach is beyond the scope of this manuscript.

This manuscript does not select a single “correct” discount rate. However, the analysis shows that the 100-year timescale is consistent with discount rates that are commonly used for climate change analysis. In fact, given the long tail on damages a

100-year time horizon for the GWP is more likely too short a timescale than too long. In contrast, a 20-year time horizon for the GWP implies discount rates larger than those used in any climate change analysis publications to date.

3.3. Sensitivity Analysis

Figure 2 shows the interquartile and interdecile ranges from a sensitivity analysis, along with the median, maximum, and minimum of the calculated equivalent GWP timescales at each discount rate. The uncertainty bands were calculated as the 972 combinations of all of the parameter choices used in this manuscript: 4 RCPs, 3 climate sensitivities, 3 damage exponents, 3 forcing imbalance options, 3 temperature offsets, and 3 GDP growth rates. The ranges chosen for each parameter are described in the methods. The parameters with the largest effect on the uncertainty of the calculated GWP (at a discount rate of 3%) are the rate of GDP growth and the damage exponent (see Table 1). These results demonstrate the importance of better understanding the reasonable range of future economic growth rates. Alternatively, using a Ramsey framework might reduce this source of uncertainty as high growth rates and the accompanying high discount rates would have offsetting effects on the calculated timescale. The assumption that damages are an exponential function of temperature is also a limiting factor, as damages might also be a function of rate of change, have a multi-exponential behavior, or have persistent influences on economic growth (Weitzman, 2001, Burke et al. 2015).

Additionally, while CO_2 and CH_4 are the largest contributors to climate change (as evaluated by contributions of historical emissions to present-day radiative forcing as in Table 8.SM.6 in the IPCC, or by the magnitude of present-day emissions as evaluated by the standard GWP_{100}), it is also important to evaluate other gases with these techniques. Table 2 shows 5 gases and their atmospheric lifetimes. For each gas, an "optimal" GWP timescale was calculated that would replicate the ratio of net present damage of that gas to CO_2 at a discount rate of 3%. The ratio of the GWP_{100} and the GWP_{20} to that optimal damage ratio is also shown. For longer-lived gases (e.g. N_2O and HFC-23), there is no integration time period that can produce a ratio as large as the calculated damage ratio at a discount rate of 3%. For these gases, we list the timescale that yields the maximum possible ratio and note that the GWP for longer lived gases is fairly insensitive to timescale (further comparisons of non-CO_2 gases are presented in the SI). This table shows that at a discount rate of 3%, and as evaluated using net present damage ratios, the use of a 100-year timescale overvalues the short-lived gases and undervalues the longer-lived gases. The IPCC found that uncertainties in the GWP_{100} due to uncertainties in forcing and lifetime are on the order of 30 to 40% depending on the gas (Myhre et al. 2013): therefore, the over or undervaluation of damages based on using a 100-year timescale for the GWP are no larger than inherent uncertainties which likely apply to the calculation of any metric.

3.4. Uncertainties in Analysis

There are a number of uncertainties involved in this analysis. They can be divided into three categories: those that may change the relative climate-related discounted damages of CH_4 compared to CO_2 but have minimal effect on the implied timescale of the GWP, those that have a large impact on the implied timescale, and those effects of CH_4 and CO_2 that are unrelated to their climate forcing.

Uncertainties in this analysis that do not have a large impact on the calculated GWP timescale are generally those that cancel out by the time their effects are propagated from predicted radiative forcing impacts to the CH_4:CO_2 discounted damages ratio. One such example would be the potential underestimation of CH_4 forcing due to the IPCC equations not including shortwave forcing for CH_4 (Etminan et al. 2016). Including these forcing effects would lead to an increase in the CH_4 to CO_2 ratio; however, a correction for this effect would also be included in the calculation of the equivalent GWP timescale and these two corrections would cancel each other out.

In contrast, better understanding of climate-carbon feedbacks (Gasser et al. 2017, Sterner et al. 2017), the timescale of ocean heat uptake, the shape of the climate damage function and potential effects of rate of climate change, the difference between the timing of atmospheric temperature response to forcing and the response of sea level, and other issues that are inherent to the timing of climate impacts—but are not necessarily included in the GWP calculation—might all affect the implied timescale. One potential way to explore some of these effects would be to use a more complex climate model to evaluate the RF and temperature effects of the emission pulses.

An additional category of uncertainties is one that has no relevance to an analysis of appropriate timescale of climate impacts, but are important for overall valuation. One example is the inclusion of CO_2 fertilization effects, which would reduce the relative importance of decreasing CO_2 compared to other gases, but do not have direct timescale implications. This effect was relevant for results from Marten and Newbold (2012) that showed a CH_4:CO_2 damage ratio that was larger than the GWP at a 3% discount rate, in contrast to the results of this paper. Other examples include CH_4 effects on health (Sarofim et al. 2017) or CO_2 effects on ocean acidification. These effects, like the increase in CH_4 forcing calculated by Etminan (2016), can be important for making mitigation decisions but are outside of the scope of consideration for a manuscript focusing on how to choose a time horizon for comparing climate impacts.

3.5. Caveats

The analysis presented here suggests that the use of a 100-year time horizon for the GWP is in good agreement with what many consider an appropriate discount rate; however, we offer several caveats. Most importantly, this analysis makes the assumption that the net present damage of CH_4 and CO_2 is the best metric for evaluating relative impact of gases. When analysing several different common metrics, Azar and Johansson (2012) asked whether society would prefer integrated metrics such as the GWP, single time period metrics such as the GTP, or economic metrics such as the global damage potential which is parallel to the metric given primary weight in this paper. Considering the applications of a metric within the context of an integrated assessment model could enable analysis of more complex economic interactions. Alternatively, a decision-making framework might consider factors other than damages: for example, in a multi-stage decision-making process under uncertainty, it might be possible that long-lived gas mitigation should be prioritized in order to increase future option-value. Or there might be reasons to prioritize mitigation options that apply to capital stocks with long lifetimes or to decisions which involve path dependence, as those decisions would be more costly to reverse in the future.

This metric approach is also not designed to achieve a long term temperature goal such as stabilization at 2 °C above preindustrial temperatures. We note no metric designed to tradeoff emission pulses is consistent with stabilization: one solution to this dilemma is the GWP* introduced by Allen et al. (2016) which creates an equivalence between an emission pulse of CO_2 and a constant stream of CH_4. This analysis only looks at a pulse of emissions in 2011, and does not examine whether the equivalent timescale might change over time.

4. Conclusions

The 100 year GWP is the inter-gas comparison metric with the widest use. The results presented here show that the 100-year timescale is consistent with an implied discount rate of 3.3% (interquartile range of 2.7% to 4.1%). Therefore, the 100-year timescale is a reasonable choice given that many governments evaluate projects using discount rates in this range. At lower discount rates, which are favored by a number of studies investigating appropriate discount rates for climate change analysis, the appropriate GWP timescale would be longer.

Recently some researchers have suggested the use of shorter GWP timescales in order to highlight the impacts of short-lived greenhouse gases (Shindell et al. 2017, Ocko et al. 2017). Applying the methodology in this paper to calculate the implied intertemporal values of a 20 year GWP shows an equivalency to a discount rate of 12.6% (interquartile range of 11.1% to 14.6%). Given the incompatibility of such a discount rate with the climate change valuation literature, this would seem like an important result for proponents of short timescale metrics to address.

Interestingly, several researchers who assessed the impacts of changing the CH_4 metric within an integrated assessment framework have concluded that changing the CH_4 to CO_2 ratio away from the GWP_{100} has small effects on policy costs and climate outcomes (Smith et al. 2013, Reisinger et al. 2013). The results of these integrated assessment model studies, the timescale analysis presented here, and the potential costs of changing a metrics approach that has been relied upon for the past 15 years, all suggest that continued use of the GWP_{100} is a reasonable decision.

Code Availability

The R code used in developing this manuscript has been submitted as supplemental information.

Author Contributions

Both MCS and MRG contributed to experiment design, coding, figure development, and manuscript writing.

Competing interests

The authors declare that they have no conflict of interest.

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Acknowledgements

M.R.G. was supported as a Science and Technology Policy Fellow by the American Association for the Advancement of Science (AAAS) STPF program. The authors would like to thank numerous colleagues at the EPA for their thoughts and discussions regarding GHG metrics and climate economics.

References

Allen, M. R., Fuglestvedt, J. S., Shine, K. P., Reisinger, A., Pierrehumbert, R. T., & Forster, P. M.: New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nature Climate Change, 6(8), 773-776, 2016.

Azar, C. and Johansson, D.J.A: On the relationship between metrics to compare greenhouse gases – the case of IGTP, GWP and SGTP, Earth Syst. Dynam., 3, 139-147, doi:10.5194/esd-3-139-2012, 2012.

Burke, M., Hsiang, S.M. & Miguel, E.: Global non-linear effect of temperature on economic production. Nature 527, 235-239, 2015.

Chang-Ke, W., Xin-Zheng, L., & Hua, Z.: Shares Differences of Greenhouse Gas Emissions Calculated with GTP and GWP for Major Countries. Advances in Climate Change Research 4(2), 127-132, 2013.

Cropper, M.L., Freeman, M.C., Groom, B. & Pizer, W.A.: Declining discount rates. American Economic Review: Papers and Proceedings 104(5), 538-543, 2014.

Dell, M, Jones, B.F., & Olken, B.A.: Temperature Shocks and Economic Growth: Evidence from the Last Half Century, American Economic Journal: Macroeconomics, 4(3), 66-95, 2012.

Edwards, M.R. & Trancik, J.E.: Climate impacts of energy technologies depend on emissions timing. Nature Climate Change 4, 347-352, 2014.

Edwards, M.R., McNerney, J., & Trancik, J.E.: Testing emissions equivalency metrics against climate policy goals. Env. Sci & Policy 66, 191-198, 2016.

Etminan, M., Myhre, G., Highwood, E.J., Shine, K.P.: Radiative forcing of carbon dioxide, methane, and nitrous oxide: A significant revision of the methane radiative forcing, Geophys. Res. Lett. 43(24), 12614–12623, DOI: 10.1002/2016GL071930, 2016.

Gasser, T., Peters, G. P., Fuglestvedt, J. S., Collins, W. J., Shindell, D. T., & Ciais, P.: Accounting for the climate–carbon feedback in emission metrics. Earth Syst. Dynam. 8, 235-253, https://doi.org/10.5194/esd-8-235-2017, 2017.

Gillingham, K., Nordhaus, W. D., Anthoff, D., Blanford, G., Bosetti, V., Christensen, P., McJeon, H., Reilly, J., & Sztorc, P.: Modeling uncertainty in climate change: A multi-model comparison (No. w21637). National Bureau of Economic Research, 2015.

GISTEMP Team: GISS Surface temperature analysis (GISTEMP), NASA Goddard Institute for Space Studies, available at https://data.giss.nasa.gov/gistemp/tabledata_v3/GLB.Ts+dSST.txt, 2016

Gollier, C., Koundouri, P., & Pantelidis, T.: Declining discount rates: Economic justifications and implications for long-run policy. Economic Policy, 23(56), 758-795, 2008.

Howarth, R.W., Santoro, R., & Ingraffea, A.: Methane and the greenhouse-gas footprint of natural gas from shale formations. Climatic Change 106, 679, 2011.

Howarth, R., Santoro, R., & Ingraffea, A.: Venting and leaking of methane from shale gas development: response to Cathles et al. Climatic Change 113(2):537–549, 2012.

Hsiang, S., Kopp, R., Jina, A., Rising, J., Delgado, M., Mohan, S., Rasmussen, D.J., Muir-Wood, R., Wilson, P., Oppenheimer, M., Larsen K, & Houser, T.: Estimating economic damage from climate change in the United States. Science 356(6345), 1362-9, 2017.

Lashof, D. A. & Ahuja, D. R.: Relative contributions of greenhouse gas emissions to global warming. Nature 344(6266), 529-531, 1990.

Manne, A. S. & Richels, R. G.: An alternative approach to establishing trade-offs among greenhouse gases. Nature 410, 675–677, 2001.

Marten, A.L. & Newbold, S.C.: Estimating the social cost of non-CO_2 GHG emissions: Methane and nitrous oxide. Energy Policy 51, 957-972, 2012.

Medhaug, I., Stolpe, M. B., Fischer, E. M., & Knutti, R.: Reconciling controversies about the ‘global warming hiatus’. Nature, 545(7652), 41-47, 2017.

Moore, F. and Diaz, D.B.: Temperature impacts on economic growth warrant stringent mitigation policy. Nature Climate Change, 5, 127-131. doi:10.1038/nclimate2481, 2015.

Myhre, G. et al. in Climate Change 2013: The Physical Science Basis (eds Stocker, T. F. et al.) 659–740 (IPCC, Cambridge Univ. Press, 2013).

National Academies of Sciences, Engineering, and Medicine: Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide; available at www.nap.edu/catalog/24651/valuing-climate-damages-updatingestimation-of-the-social-cost-of, 2017.

Newell, R.G. & Pizer, W.A.: Discounting the distant future: how much do uncertain rates increase valuations? J. of Env. Economics and Management 46(1), 52-71, 2003.

Nordhaus, W.D.: Evolution of Assessments of the Economics of Global Warming: Changes in the DICE model, 1992–2017 (No. w23319). National Bureau of Economic Research, 2017.

Ocko I.B., Hamburg S.P., Jacob D.J., Keith D.W., Keohane N.O., Oppenheimer M., Roy-Mayhew J.D., Schrag D.P., Pacala S.W.: Unmask temporal trade-offs in climate policy debates. Science. May 5;356(6337):492-3, 2017.

Office of Management and Budget: Circular A-4, available at http://www.whitehouse.gov/omb/circulars_a004_a-4, 2003.

Reisinger, A., Havlik, P., Riahi, K., van Vliet, O., Obersteiner, M., & Herrero, M.: Implications of alternative metrics for global mitigation costs and greenhouse gas emissions from agriculture. Climatic Change, 117(4), 677-690, 2013.

Rodhe, H.:A comparison of the contribution of various gases to the greenhouse effect. Science, 248(4960), 1217, 1990.

Sarofim, M.C., Waldhoff, S.T., & Anenberg, S.C.: Valuing the Ozone-Related Health Benefits of Methane Emission Controls. Env. and Resource Economics 66(1), 45-63, 2017.

Schmalensee, R.: Comparing Greenhouse Gases for Policy Purposes. The Energy Journal 14(1), 245-255, 1993.

Smith, S. J., Karas, J., Edmonds, J., Eom, J., & Mizrahi, A.: Sensitivity of multi-gas climate policy to emission metrics. Climatic change, 117(4), 663-675, 2013.

Shindell D, Borgford-Parnell N, Brauer M, Haines A, Kuylenstierna JC, Leonard SA, Ramanathan V, Ravishankara A, Amann M, Srivastava L.: A climate policy pathway for near-and long-term benefits. Science. May 5;356(6337):493-4, 2017.

Shine, K. P., Fuglestvedt, J., Hailemariam, K., and Stuber, N.: Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases, Climatic Change, 68, 281–302, doi:10.1007/s10584-005-1146-9, 2005.

Sterner, E.O. & Johansson, D.J.A.: The effect of climate–carbon cycle feedbacks on emission metrics. Env. Res. Lett. 12(3), 034019, 2017.

UN Framework Convention on Climate Change: Report of the Conference of the Parties on its First Session CP/1995/7/Add.1, available at https://unfccc.int/resource/docs/cop1/07a01.pdf, 1995.

Weitzman, M.L.: Gamma Discounting. American Economic Review 91(1), 260-271, 2001.

Weitzman, M. L.: What Is The" Damages Function" For Global Warming—And What Difference Might It Make? Climate Change Economics, 1(01), 57-69, 2010.

Wigley, T.M.L.: The Kyoto Protocol: CO_2 CH_4 and climate implications. Geophys. Res. Lett. 25(13), 2285-2288, 1998.

World Meteorological Organization Global Ozone Research and Monitoring Project: Scientific Assessment of Ozone Depletion: 1991 (World Meteorological Organization, Geneva) Report 37, 1992.

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Manuscript under review for journal Earth Syst. Dynam.
Discussion started: 6 February 2018

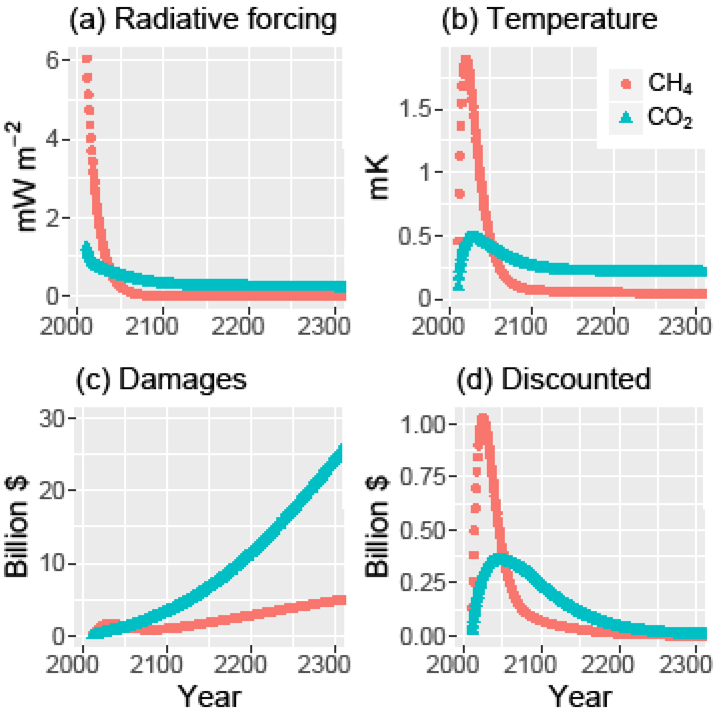

Figure 1: Impacts of emission pulses of CH$_4$ and CO$_2$. Radiative forcing (a), temperature(b), damages (c), and discounted damages (3%, d) for an emission pulse of 28.3 MT CH$_4$ (10 ppb in the first year) and 24.8 times as much CO$_2$ emissions by mass. The underlying scenario is RCP6.0, with other parameters at their central values.

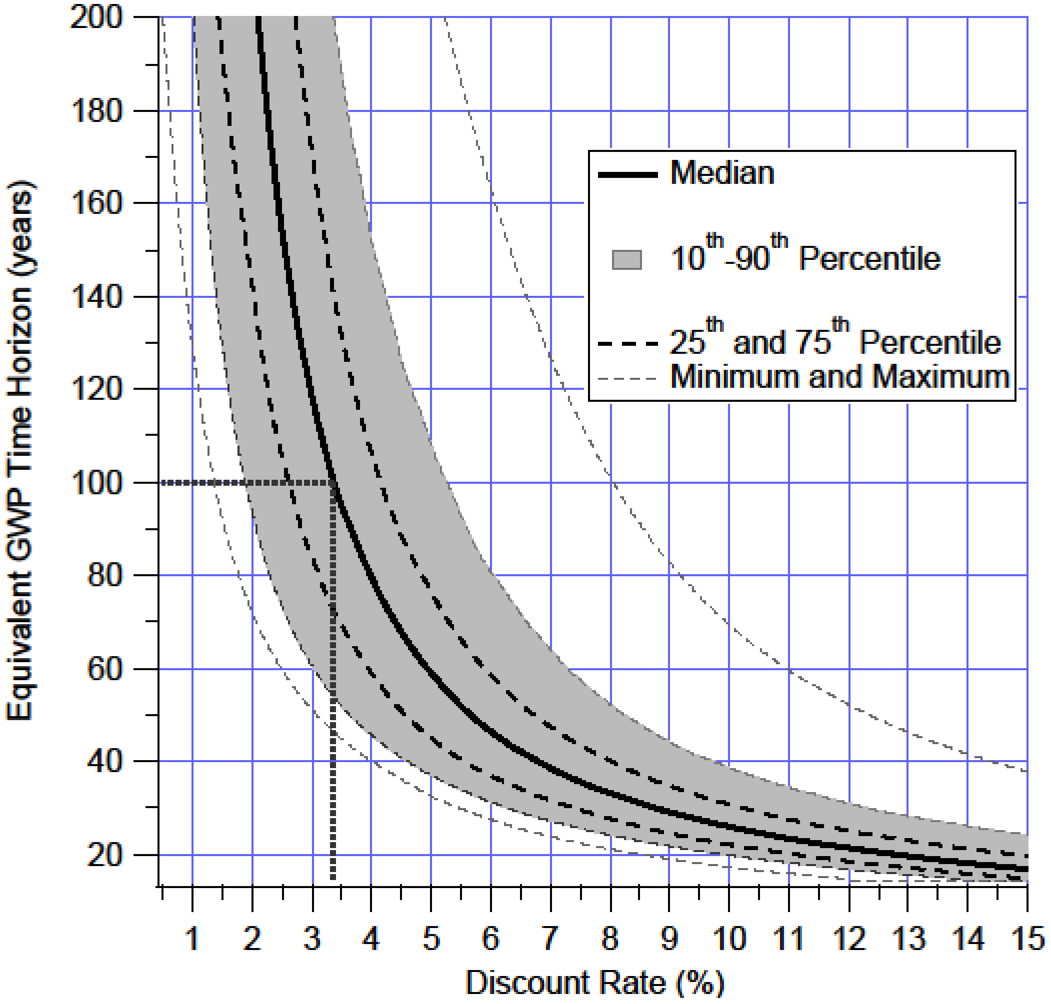

Figure 2: GWP timescales consistent with discount rates based on consistency of the GWP ratio with the ratio of net present damages of CH_4 and CO_2, including the interquartile and interdecile bands and maximum and minimum values based on a sensitivity analysis.

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Parameter	Ratio of highest to lowest damages estimate
GDP	2.07
Damage exponent	1.63
Scenario	1.31
Temperature offset	1.26
Climate sensitivity	1.16
Forcing imbalance	1.02

Table 1: Parameter sensitivity analysis: Examining the sensitivity of the GWP-discount rate equivalency as shown in the uncertainty ranges in Fig. 2 as a function of the individual parameters of the calculation. The ratio is calculated as the ratio of the median of the estimated GWPs given the highest and lowest value of each parameter.

Gas	Lifetime	Optimal timescale	GWP_{100}/damage ratio	GWP_{20}/damage ratio
CH_4	12.4	120	1.15	3.4
N_2O	121	*52	0.85	0.84
HFC-134a	13.4	115	1.11	3.2
HFC-23	222	*105	0.71	0.62
PFC-14	50000	>400	0.62	0.45

Table 2: Optimal timescale of non-CO_2 gases. Implicit timescale evaluated for non-CO_2 gases with the GWP to damage ratio for the two most common GWP timescales. Asterisks indicate no exact match between GWP ratio and damage ratio, closest value is given instead. The third and fourth columns show the ratio of the GWP for a given gas to the calculated damage ratio.