Reviewer 1 Response:

This paper usefully links the well-used GWP metric with more economic comparisons of the ratios of damages. It is suitable for publication and I only have minor comments.

We would like to thank the referee for their comments. For responses comment by comment, see below. All author replies are in red. There is also a summary of new sensitivity analyses that is included at the end of this comment reply.

The relationship to the Paris goals are only briefly alluded to. I suggest including a longer discussion of the differences between: a temperature limit, a long-term temperature goal, and least economic cost. Presumably neither a temperature limit nor a long-term temperature goal are optimal economically using the damage function here? Is this a problem with the Paris agreement? The choice of metric depends entirely on the choice of target, and the authors here are implicitly assuming that least economic damage is the most important target. The authors dismiss short-term GTPs as implying unrealistic discount rates, which of course they do for an economic damage target. However, if the Paris agreement is taken to imply that temperatures should not be allowed to exceed 2 degrees, then a GTP with a time horizon ending at the time of peak warming (20-30 years) is an entirely appropriate metric. Similarly, if the Paris agreement is taken to mean a long-term goal to stabilise at 2 degrees then GWP* is the appropriate metric.

The reviewer brings up an interesting question regarding the goals of global climate agreements. To some extent, the optimal design of a global goal is beyond the scope of this manuscript, but given that one important use of climate metrics is within cap and trade programs that are meant to help achieve these global goals, some discussion would be appropriate. To that end, we brought some of the text that was originally in the SI into the main manuscript, with some updating and editing:

> While this paper focuses on a cost-benefit approach, there is also a potential need for cost-efficiency approaches, particularly in regard to stabilization targets such as 2 °C. However, a number of authors have argued that pulse-based metrics such as the GWP are not well-suited to achieve stabilization goals (Sarofim et al. 2005, Smith et al. 2012, Allen et al. 2016). Some actors (Brazil INDC, 2015) have claimed that certain metrics such as the Global Temperature Potential (Shine et al. 2005) or the Climate Tipping Potential (Jorgensen et al. 2014) are more compatible with a stabilization target such as 2 °C because they are temperature based. However, any pulse-based approach faces at least two major challenges related to stabilization scenarios. The first is that as a temperature target is approached, a dynamic approach will shift from favouring long-lived gas mitigation to favouring short-lived gases. While this shift may be optimal for meeting a target in a single year, it will be sub-optimal for any year after that year. The second challenge is that once stabilization has been achieved, any trading between emission pulses of carbon dioxide and a shorter-lived gas will cause a deviation from stabilization. For example, trading a reduction in methane emissions for a pulse of CO2 emissions will lead to a near term decrease in temperature, but also a long-term increase in temperature above the original stabilization level. One solution to the problem is a physically-based one. Allen et al. (2016) suggest trading an emission pulse of carbon dioxide against a sustained change in the emissions of a short-lived climate forcer. This resolves the issue of trading off what is effectively a permanent temperature change against a transient one. However, the challenge becomes one of implementation, as current policy structures are not designed for addressing indefinite sustained mitigation. A second solution is a dynamically updating global cost potential approach that optimizes shadow prices of different gases given a stabilization constraint (Tol et al. 2016), but again, implementation would be challenging. Alternatively, a number of researchers (Daniel et al. 2012, Jackson 2009, Smith et al. 2012) suggest addressing CO2 mitigation separately from short-lived gases. Such a separation recognizes the value of the cumulative carbon concept in setting GHG mitigation policy (Zickfeld et al. 2009). However, this approach requires a central decisionmaker and loses the

> “what” flexibility that makes the use of metrics appealing (Bohringer et al. 2006). In economic terms, a temperature based target is equivalent to the assumption of infinite damage beyond that threshold temperature, and zero damages below that threshold (Tol et al. 2016).

The overall formula for the damage function needs to be shown as a function of temperature, discount rate, GDP etc.

The following text was added:

Damages as a percent of GDP were calculated by multiplying a constant times by the square of the temperature change since the baseline period squared. E.g., $D(2050) = a*\Delta T(2050)^2*GDP$. The net present value is then calculated using the discount rate such that NPV(D(t)) = D(t)/(1+r)t-2010.

Page 1, line 26: Maybe a different word other than “endpoint” could be used so as to avoid confusion with the later discussion of integrated and endpoint metrics.

We replaced endpoint here with “measure of impact”

Page 2, first paragraph: The main difference between GTP and GWP is the difference between endpoint and integrated metrics. This should be brought out more in this paragraph. The iGTP could be mentioned as it is more similar to GWP than GTP.

Integrated metrics are addressed in the following:

> Mallapragada and Mignone (2017) present a similar framework and also note that metrics can consider a single pulse of a stream of pulses over multiple years. Several authors have recognized that under certain simplifying assumptions, the GWP is equivalent to the integrated GTP, and therefore any timescale arguments that apply to analyses of one metric would also apply to the other (Shine et al. 2005, Sarofim 2012).

Page 2, second paragraph: Boucher ESD 2012 should also be discussed for economically-based equivalences.

Boucher 2012 and Fuglesvedt 2003 are now discussed in more depth in the introduction, sensitivity analyses, and conclusion sections.

Page 4, line 1. These GDP pathways should be shown (maybe in the supplement).

We are including a graph of the GDP pathways in the SI.

Page 4, line 6. It is not obvious why 1951-80 should be chosen as a baseline. A problem with damage functions that are non-linear functions of temperature is that a point needs to be chosen when temperatures were optimal.

We agree that there is no clear best baseline: that is why we did a sensitivity analysis using a baseline of 0 (effectively, that damages are a function of temperature change relative to 2010) and a baseline of 0.8 degrees (assuming that damages are a function of temperature change since preindustrial times) were used. Table 1 indicates that this choice can have a difference of up to 26% in terms of damages.

Figure 1: I was surprised by the shape of 1 (c). Why does the damage from CH4 keep increasing? Is the damage an integral quantity, or is this increase purely due to an exponential increase in GDP? In 1(d) the damage decreases. Is this because the

discount rate is larger than the GDP growth? With the GDP growth of 2.06% would a discount rate of less than 2% give an increasing damage for a gas like CO2 with a non-decaying component?

The following was added to address this question:

> In the case of CH_4, damage peaks in 2032 and declines until 2080 as a result of the short lifetime of the gas. The increase in damages after 2080 is due to the component of the temperature response function that includes a 409 year timescale decay rate, such that after 100 years the decrease in the ΔT^2 component of the damage equation is about 0.5%/year, and because that decay rate is slower than the rate of GDP growth, net damages grow.

Page 6, line 13: I don't think "exponential function of temperature" is the right term for temperature raised to a power.

Changed to "polynomial function".

Table 2: The ranges (either 25%-75% or 10%-90%) need to be shown as well as the central value. These are quite large for the timescales and may well include 1.0 for many of the damage ratios.

We have updated the table as follows, including uncertainty ranges for CH_4: Uncertainty ranges for the longer-lived gases are more challenging, as the non-monotonicity adds complications.

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. Results in this table are derived assuming as discount rate of 3%.

Gas	Lifetime	Optimal timescale	GWP_{100}/damage ratio	GWP_{20}/damage ratio
CH_4	12.4	120 (84-172)	1.15 (1.52-0.87)	3.4 (4.49-2.57)
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. Interquartile uncertainty ranges are presented for the timescale and damage ratios for CH_4. Results in this table are derived assuming as discount rate of 3%.

Page 6, line 25: GWP100 seems to agree very well with the 3% discount rate within the uncertainty rather than overvaluing or undervaluing.

We have modified the text “However, the analysis shows that the 100-year timescale is consistent, within the interquartile range, with the 3% discount rate that is commonly used for climate change analysis.”

Page 6, line 25-29: I didn’t understand this sentence. Are you saying that the uncertainty in GWP100 is such that it covers agreement with the 3% discount? If so, that seems to contradict the previous sentence which suggested a under/overvaluing

We chose to delete the sentence in question. Upon reflection, the uncertainty in the GWP100 is due to factors like uncertainty in radiative efficiency, but (as shown in a sensitivity calculation) the timescale is not sensitive to radiative efficiency uncertainty.

Additional Sensitivity Analyses in response to various Referee Comments:

The four referees raised a number of points, several of which were inter-related. In response to these points, we have performed a number of additional sensitivity analyses, which will be detailed here. One lesson from these analyses: the analysis is robust to a surprising number of changes. This relates to the fact that any change in the analysis which changes both the GWP and the damage ratio generally cancels out in terms of calculating the relationship between discount rate and timescale: e.g., most factors in the causal chain from emissions through radiative forcing. That includes the size of the emissions pulse, the radiative efficiency of the gas, and the lifetime of the gas (within certain limits). Note that changes in these parameters may well change the best estimate of the relative importance of reducing methane compared to CO_2, but they do not change the implicit timescale that is the focus of this paper.

In contrast, anything which changes only the damage ratio can have a larger impact on the implicit timescale. This includes the factors which have the largest influence on the uncertainty, as reflected in Table 1: the rate of GDP growth, the damage exponent, the scenario (because the GWP assumes constant concentrations), the baseline temperature from which damages are calculated, and the climate sensitivity.

A third category is influences which are specific to a given gas, whether the efficacy of that gas (e.g., Modak et al. noted by Referee #3), or the health effects of methane-related ozone productions. Like changes to radiative efficiency or lifetime, these influences can also change the best estimate of the relative importance of reducing methane compared to CO_2, but because they are specific to a single substance and not generalizable between substances, they would not be appropriate for calculating implicit timescales.

Herein, we summarize the additional sensitivity analyses:

Pulse Size:

In response to a comment by Referee #2, we performed a sensitivity analysis on the size of the emissions pulse. Using 373 MMT (one year's emissions according to Saunois 2016, http://iopscience.iop.org/article/10.1088/1748-9326/11/12/120207, where global emissions are 559 MT of which 2/3rds are anthropogenic), the relative damage ratios of CH_4/CO_2 are the following:

quartile	25%	50%	75%
Damage Ratio	18.80	25.05	32.69

A similar analysis for the 28.3 MMT used in the paper, performed in response to a comment by reviewer 1, yields

quartile	25%	50%	75%
Damage Ratio	18.84	25.12	32.86

The differences between the two analyses are less than 1%. We will note this sensitivity analysis in the paper. Arguments can be made for either the larger quantity or the smaller quantity depending on the purpose of the analysis. When GWPs are used to inform decision making, these decisions are often regarding mitigation actions at the national or sub-national scale, which is closer to the 28 MMT scale than the 370 MMT scale. When GWPs are used to compare CO_2equivalents for global scenarios, then the global annual number might be more appropriate. But in any case, this appears to be an uncertainty much smaller than any of the others considered in this paper.

Radiative Efficiency:

Referee #2 also raised a question regarding the use of the IPCC AR5 radiative efficiencies rather than the more recent Etminan et al. 2016 article. In order to test the general sensitivity of this approach to changes in the radiative efficiency of methane, a sensitivity analysis was performed, wherein forcing from CH_4 was doubled compared to the standard calculation. Relative damages of CH_4 and CO_2, as might be expected, also doubled:

quartile	25%	50%	75%
Damage Ratio	37.98	50.35	65.50

However, calculated GWPs based on the updated radiative forcing also double: the new GWP100 being 56.79, and the new GWP20 being 166.92. The optimal timescale using the central parameters ends up being 119.79 years, under 1/10th of a percent different than the original calculated timescale of 119.85 years.

We can also mention this in the paper.

Consistent Climate Carbon Feedbacks:

Referee #4 points out, with good cause, that it would be a good sensitivity analysis to calculate an implicit timescale using consistent assumptions about climate-carbon feedbacks for both carbon and methane lifetimes (whereas, in the main body of the paper, we used a CO_2 lifetime that included climate-carbon feedbacks, and a methane lifetime that did not, consistent with the approach of the IPCC AR4 and the GWP values reported in the main body of chapter 8 in IPCC AR5). Using the "no-climate-carbon-feedback" CO_2 equation from Gasser et al. 2017, we can calculate CH_4/CO_2 damage ratios:

quartile	25%	50%	75%
Damage Ratio	20.57	27.16	35.23

This can be compared to the original damage ratios from the paper:

quartile	25%	50%	75%
Damage Ratio	18.84	25.12	32.86

The damage ratios are about 8% larger under the consistent no-CC-feedback case than in the CO_2-feedback/CH_4-nofeedback case, due to what is now a shorter CO_2 lifetime. But a GWP calculated with consistent assumptions regarding climate-carbon feedbacks also changes. The no-feedback GWP100 is now 30.74 rather than 28.64, a 7% increase. These two effects largely cancel out, leaving the effect on implicit timescales smaller, again, than most of the other sensitivities examined in the paper.

quartile	25%	50%	75%
consistent no cc feedback timescales	170.56	117.9	83.38
original analysis	170.87	118.30	83.81

So while the damage-ratio differences are on the order of 8%, the implicit timescale differences are less than 1%. Similar to the impact of changing methane's radiative forcing, a large impact on damage ratios has a small impact on implicit timescales because the update happens in both the calculation of the damage-ratio AND in the calculation of the GWP, and therefore cancels out to a large extent.

We show here a calculation that was consistent in not including climate carbon feedbacks in either damage calculation. While it would be possible to do a similar consistent calculation with climate carbon feedbacks in both damage calculations, implementation of the climate-carbon feedback for methane is not without challenges. Such a calculation requires first calculating of the temperature impact resulting from an emissions pulse over the full time period (as done in the original), and then, for the temperature change in each year, requires a calculation of the carbon perturbation resulting from that temperature change over the remainder of the time period, and then calculating the additional forcing and temperature change resulting from that carbon perturbation. Therefore, we decline to do this calculation at this time (absent an already available methane lifetime equation with the CC feedback built in, which the authors do not have on hand). The authors are already on record as preferring a GWP metric that does not include CC feedbacks in either the CO_2 or the CH_4 response rather than inclusion of CC feedbacks in both CO_2 and CH_4 responses – see the response by Sarofim, Giordano, and Crimmins to the Gasser paper for a more detailed explanation (https://www.earth-syst-dynam-discuss.net/esd-2016-55/esd-2016-55-SC1.pdf)

Ramsey Discounting:

Of all the sensitivity analyses (other than discount rate), the calculation of implicit timescales was most sensitive to changes in the assumption about future GDP growth rates. The original draft raised the question as to what extent this sensitivity to GDP growth might diminish were the discount rate to be a function of GDP, as in a Ramsey discounting framework. In this case, a high GDP growth rate (which implies large future damages, and therefore a low methane/CO2 damage ratio) would be counteracted by a high discount rate which would be expected to lead to a high methane/CO2 damage ratio.

For this sensitivity analysis, the Ramsey discounting approach was calibrated to yield an average discount rate for the first 30 years of the analysis of 5% for the reference GDP growth rate, with a pure rate of time preference of 0.01% (a very low pure rate of time preference being consistent with the assumption that, holding consumption constant, all generations should be given equal weight). That required an elasticity of marginal utility of consumption of 1.53.

Interestingly, the ratio of the median damage estimate from the low GDP scenario to the high GDP scenario was still about a factor of 2, except that now the low GDP scenario leads to the lowest damage ratio and the high GDP scenario leads to the highest damage ratio: effectively, in the Ramsey case, the discount rate effect overwhelms the GDP growth rate effect. Note that the equivalent timescale in the median GDPref case under this set of assumptions is 135 years.

GDP scenario		GDPlow	GDPref	GDPhigh
Discount rate, first 30 years->		2.5%	5%	7.5%
Discount rate, full run->		0.8%	1.5%	2.3%
Ramsey discounting approach	25%	11.28	15.71	21.78
	50%	16.08	22.72	31.05
	75%	18.42	26.40	35.16
		3%	3%	3%
Original constant discount rate approach	25%	29.96	21.11	14.46
	50%	38.69	27.58	18.70
	75%	42.52	30.29	19.81

Rate of Change Calculation:

Referee #4 also brought up the idea of adding in damages from rate of change of temperature as well as from absolute temperature change. This was an important addition in, for example, Manne & Richels (2001) where it turned a dynamic optimization metric from one that didn't value methane until a decade or two before threshold temperatures were reached to a metric which had fairly constant value over time.

In order to test this, we added code that included damages from rate of change. The damage is calculated by taking the square of the rate of change and multiplying by the GDP and a constant – similar to the damage calculation for absolute temperature. For the first test, peak rate of change damages under the central scenario were calibrated to be equal to the damages in 50 years (2060), where there is 1 degree of temperature change (above the temperature offset) under central parameter estimates. This led to an increase in damage ratio of 2.4%.

A second test, with peak rate of change damages 10 times as large, led to an increase in the damage ratio of 5.1%. That yields a timescale change from 120 years to 112 years.

The small impact of the rate of change damage is likely due to timing of peak rates of change under RCP6. In this analysis, there is an initial high rate of change for the first few years, followed by a secondary (though smaller) peak about 60 years in. Because of the GDP growth in the interim, damages at the 60 year secondary peak are higher than damages in the initial years. Therefore, reducing the rate of temperature growth 60 years into the run is more important than reducing the rate of growth at the beginning of the run, and for this reason, reducing short-lived forcer emissions does not have large advantages over reductions in CO_2 emissions.

However, this raises a question about the importance of the scenario assumption. Therefore, we also tried the same exercise with the RCP3PD scenario as the baseline. In RCP3PD, in this analysis, the rate of temperature change is at its highest in the first years of the scenario, which means that the increase in rate of change due to additional radiative forcing in those early years can have a disproportionately large impact, favoring short-lived climate forcers. Note that because RCP3PD cools in later years, we chose to set the damages resulting from a negative rate of change to zero.

In this case, the first rate of change analysis yields an increase in the damage ratio of 53%, and the second analysis yields a damage ratio increase of 85%. This yields a timescale change from 94 years (the timescale for RCP3PD without rate of change damages) to 54 years to 42 years.

This is consistent with some other literature such as Bowerman et al. (2013), which suggests that under stringent CO_2 mitigation scenarios, the rate of change peaks in the near future, and therefore reduction of short-lived climate forcers can be particularly valuable – but that in scenarios where CO_2 emissions continue to rise in the near term, the rate of change peaks further in the future, and therefore delay in short lived climate forcer mitigation will lead to the greatest reductions in peak rate of change.

However, this particular sensitivity analysis was rather crude. In order to improve it, we would have to develop a better reasoning for choosing the parameters involved (e.g., the damage exponent for rate of change, and the damage constant), but also investigate how well our approach models near-term rate of change compared to more complex models, as that is of importance for this calculation.

Reviewer 2 Response:

The paper provides an interesting analysis on the connection between GWP timescale and discounting rates. However, I think that before publication, some major issues need to be addressed.

We would like to thank the referee for their comments. For responses comment by comment, see below. All author replies are in red. There is also a summary of new sensitivity analyses that is included at the end of the reply to William Collins.

First, while the paper acknowledges a lot of recent articles that discuss GWP, it does not adequately discuss recent articles that look at climate metrics in an economic frame- work (such as Tol et al. 2012 and Mallapragada and Mignone 2017). There needs to be more incorporation of these types of studies to show how this study builds on the existing literature.

We have moved SI material into the main text, and added several references and additional discussion.

Second, the authors seem to misunderstand the messages of several recent studies, such as Shindell et al. 2017 and Ocko et al. 2017. These studies are not advocating for a shorter time horizon for GWP, as this paper implies in both the main text and the supplemental information. Rather, they are advocating for using BOTH short AND long-term time horizons to capture the full scope of climate impacts over all timescales – a key distinction that is not depicted in the text. The paper in its current forms criticizes these studies for something that they are not doing. Further, the authors frame their motivation around the fact that studies are advocating GWP20 to then show that GWP100 fits better with discount rates, but because these studies are not simply advocating GWP20, it makes the authors appear naïve to the existing literature. Further, there is a strong reason behind why other timescales are not promoted which needs to be acknowledged (it is not simply a lack of quantification in research efforts) – that just as it is difficult to move the policy community away from the comfortable GWP, it is reasonable to believe that it will be equally as difficult to move the community away from 20 and 100 year timescales of which they are also most familiar with.

We will add clarification that in some cases authors are often suggesting presentation of short (about 20 years) timescales alongside, not in place of, 100 year timescales. However, we do feel that “promoting more emphasis on shorter time horizons” is an accurate description, as providing both GWP20 and GWP100 (for example) is “more emphasis” on shorter time horizons than just providing GWP100. Presented with values for 2 time horizons, one might also expect a decision-maker to have some probability of choosing to use only the shorter one, or to weigh them equally, which would look like a GWP60 (for comparison, a GWP60 would have an median equivalent discount rate of 5% using our methodology). Meanwhile, some authors (e.g., Howarth) do explicitly state that use of the 20 year GWP would better account for relevant climate impacts than 100 year GWPs, and a number of NGOs have followed suit. We have added a sentence about Ocko et al. to reflect some more nuance:

> These studies each have different nuances regarding their recommendations – for example, Ocko et al. (2017) suggest pairing the GWP100 with the GWP20 to reflect both long-term and near-term climate impacts – and therefore there is no simple summary of the policy implications of this body of literature, but it is plausible that more consideration of short-term metrics would result in policy that weights near-term impacts more heavily.

Third, it would be great if the damages function description went into more details about what is included in “damages.” For example, I believe the authors make it clear later on that health or agriculture impacts from methane were not included. So what is included? Those damages are part of what makes near-term impacts so important to reduce, which justifies the use of a shorter time horizon.

Damages in this case are only climate-related damages. Inclusion of damages due to, for example, the health impacts of O_3 are relevant for policymaking purposes as one of the authors has argued elsewhere (see, e.g., Sarofim, Waldhoff, and Anenberg), but we would argue are not appropriate for the timescale discussion. One support for keeping timescale & non-climate effects separate is that if the timescale is adjusted to increase the value of methane to account for the methane-ozone effects, then it will equally increase the value of HFC-134a which has a similar lifetime: but HFC-134a does not have an equivalent ozone-effect. Therefore, instead, the relative climate effects of gases should be calculated using this timescale approach, and then the value of reducing methane can be increased to account for its ozone effects (and the value of reducing CO_2 can be adjusted to account for fertilization and acidification effects).

We have added some more discussion about how to address non-climatic impacts like the methane-ozone effect.

Finally, I wonder about the argument that we should select a time horizon based off of appropriate discount rates. What if the GWP timescale tells us which discount rates are more appropriate? Why is it necessarily the other way around? The literature on appropriate discount rates is vast and its value is debated as much as GWP timescale selection. The paper makes it seem like there is solid agreement on appropriate discount rates but not GWP timescales, but both are subject to similar challenges and debates.

Our analysis can be used in either direction, as is discussed in the paper:

> 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.

While we agree that there is no single consensus on an appropriate discount rate, we do think that that the framing of discount rates is good way to formally demonstrate the implications of GWP timescales for valuation over time. Part of the impetus of this paper was due to the possibility that some proponents of shorter timescales might not recognize the implicit discount rate embodied in the timescale choice, and might not consider a high discount rate to be desirable. We recognize that the discount rate implications calculated in this paper are a result of many decisions regarding parameters and analytical approaches, and that other approaches might yield different results, but we think that this is an important discussion to have.

We have also added a sensitivity analysis on the use of a Ramsey discounting approach as recommended by the National Academies for use in Social Cost of Carbon calculations (see response to William Collins) as that is an important alternate approach to discounting.

Minor comments:

1.26: Key criticisms also include the reliance of GWP value on a specified time horizon (that is a value judgement) (e.g. Ocko et al. 2017) and that emissions are not continuous (Alvarez et al. 2012). Would also include citations for each point of criticism that you mention. http://www.pnas.org/content/109/17/6435

The paragraph has been modified as follows:

> Criticisms include the following:: from arguments that radiative forcing as an endpoint measure of impact is not as relevant as temperature or damages (Shine et al. 2005); , to critiques of that the assumption of constant future GHG concentrations (Wuebbles et al. 1995, Reisinger et al. 2011) is unrealistic;, to the position that discounting is preferred to a constant time period of integration (Schmalensee, 1993); disagreements about the choice of time horizon in the absence of discounting (Ocko et al. 2017);, to the view that dynamic approaches would lead to a more optimal resource allocation over time (e.g., Manne and & Richels, 2001, Manne & Richels 2006), and to the fact that the GWP does not account for non-climatic effects such as carbon fertilization or ozone produced by methane (Shindell 2015); and that pulses of emissions are less relevant than streams of emissions (Alvarez et al. 2012).

2.1: Definitely one of the reasons, stronger than “likely.”

“likely” was deleted.

2.3: Please explain upfront *why* you assess the choice of time horizon – as it wasn't even listed in your list of criticisms other than in reference to discounting (and it is problematic aside from discounting as well).

We now start the 3rd paragraph with the following sentence:

> In this paper, we focus on the choice of time horizon in the GWP as a key choice that can reflect decision-maker values, but where additional clarity regarding the implications of the time horizon could be useful. We also investigate the extent to which the choice of time horizon can incorporate assess the choice of time-horizonmany of the complexities of assessing impacts described in the previous paragraph.

2.3: 100 year was also selected as middle ground from IPCC FAR as values for 20, 100, and 500 years were given.

We modified the text as follows:

> The 100-year time horizon of the GWP (GWP100) is the horizon endorsed by the WMO and UNFCCCtime horizon most commonly used in many venues, for example in trading regimes such as under the Kyoto Protocol, perhaps in part because it was the middle value of the three time horizons (20, 100, and 500 years) analysed in the IPCC First Assessment Report.

2.8: Not sure why the word "therefore" is here. A description of why 100 year was selected does not in itself provide justification for why scientists are promoting 20 years. It is because 100 years does not adequately capture near-term impacts as it masks the importance of short-lived climate pollutants in the near-term. There needs to be a better transition from the 100 year discussion to the 20 year discussion.

We replaced "therefore" with "recently".

2.10: Papers such as Ocko et al. 2017 are not pushing for shortened time horizon, they are pushing for a two-valued GWP metric that includes BOTH 20 and 100 year time horizons. Very important distinction that needs to be clarified, as there are efforts (some livestock groups) that push for short time horizon only.

As noted above, we have attempted to present a more nuanced summary.

2.13: Part of the reason that other timescales are not suggested is because of the climate policy community's familiarity with 20 and 100 years. Just as they don't want to adopt a whole new metric, it is very plausible that they will reject a new time horizon. Since 20 and 100 years are adequate for near- and long-term, pushing for say 30 and 200 year time horizons may be counter-productive.

We have tried to clarify that we want more quantitative justifications of timescales in general (whether 20, 100, or 500, or anywhere in between).

2:20: There are more recent papers that need to be cited that look at the intersection of climate metrics and economics (Tol et al. 2012; Mallapragada and Mignone 2017). http://iopscience.iop.org/article/10.1088/1748-9326/7/4/044006/meta http://iopscience.iop.org/article/10.1088/1748-9326/aa7397

See above for our language including some of these references and adding better context, and also our responses to other referees.

2.31: Why CO2 and CH4 only? Justification needed, such as represent the largest long-lived and short-lived climate pollutant contributor's to today's radiative forcing.

We have added the following sentence:

The paper focuses on CO2 and CH4 as the two most important historical anthropogenic contributors to current warming, but the methodology is applicable to emissions of other gases and sensitivity analyses consider N2O and some fluorinated gases.

3.5: Why is a pulse of 28.3 Mt of CH4 used, just bc of 10ppb? Why not today's annual emissions of methane from human activities (around 300-400 Mt)?

See our reply to William Collins for a description of the sensitivity analysis we performed in response to this comment, showing that sensitivity to the size of the pulse is small compared to other uncertainties.

3.12: What radiative efficiencies are used? Should specify this since you go into so much detail of other parameter values. I'm assuming radiative efficiencies are from IPCC AR5 but as you cite in your references, there are more recent calculations in Etminan et al. 2016.

The source of the radiative calculations is described here:

> 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.

As noted, Etminan has been cited as an example of updated information on radiative efficiency. Referee 3 also cited Modak et al. as showing the efficacy of methane forcing being lower than for CO_2 forcing.

See our reply to William Collins for a description of the sensitivity analysis we performed in response to this comment, showing that sensitivity to even a doubling of methane's radiative forcing would be very small compared to other uncertainties.

3:28: What damages are included by using this function?

This is meant as a simple approximation of all climate damages (sea level, health, ecoystems, etc.).

3:30: Please include citations for the first alternative.

We can cite the National Academies Social Cost of Carbon assessment here.

4.2: Suggest mentioning how these results fit in with scientific literature that has looked at these tradeoffs for decades.

We’re not sure what tradeoffs the referee is referring to here: we discuss the Nordhaus GDP growth rates in the context of Gillingham et al. (now Christensen et al.).

Reviewer 3 Response:

I am not an expert in "Economics of climate change" and "discount rates" applied in estimating damages from climate change. Hence, I ask the editor to rely on the opinion of reviewers who are experts in assessing the economic damage from climate change. Here I am providing just a couple of minor comments.

We would like to thank the referee for their comments. For responses comment by comment, see below. All author replies are in red. There is also a summary of new sensitivity analyses that is included at the end of the reply to William Collins.

A recent paper (Modak, A., G. Bala, K. Caldeira, and L. Cao, 2018: Does shortwave absorption by Methane influence its effectiveness? Climate Dynamics, https://doi.org/10.1007/s00382-018-4102-x) shows that the efficacy of methane forcing is only 80% relative to CO2 forcing. The lower efficacy affects the estimation of GTP and hence the damages. What is the implication of this result to the conclusion reached in your study? Discuss.

Modak et al. 2018 appears to be a similar paper, though opposite in direction, from Etminan et al. 2016 which was referred to by Referee #2 and in the original paper. We have performed a sensitivity analysis wherein we double the radiative efficiency of methane. In this case, while damage ratios double, the GWP calculated with the updated radiative efficiency also doubles, such that the net effect on calculated timescales is less than 1/10th of a percent (see sensitivity analysis in the reply to William Collins).

Modak et al. is slightly different than Etminan, as it occurs after radiative efficiency in the causal chain. However, it seems likely that an updated GWP calculation for methane might take into account forcing efficacy, much the way it takes into account ozone and stratospheric water vapor perturbations.

In the abstract and in the 2nd paragraph of the Introduction section, it is stated that GWP assumes constant future concentrations. I believe this is true only for the baseline state. GWP is estimated for a case where the concentration of the gases decay with time. The integrated radiative forcing is calculated for the time evolving concentrations relative the baseline.

The GWP assumes constant background concentrations, which is what the abstract and 2nd paragraph refers to. An additional increment to the concentration at time zero from an emissions pulse is added, and this additional increment decays over time.

Fig. 1c and d: Is the unit for the damages and discounted damages correct? Should it be Billion $ per year? Same issue for Fig. S1

Correct. We will update the axis titles accordingly.

Reviewer 4 Response:

The manuscript makes a useful contribution to the literature by exploring explicitly how different time scales for GWP relate to GHG equivalence ratios based on damage costs and different discount rates. It is clearly written and highly readable. I have no fundamental concern with the technical approach and quantitative results, but I feel the manuscript needs to work a bit harder to develop its value proposition, discussion of results including sensitivity analysis, and finally the conclusions, before it is fit for publication.

We would like to thank the referee for their comments. For responses comment by comment, see below. All author replies are in red. There is also a summary of new sensitivity analyses that is included at the end of the reply to William Collins.

I'm comfortable with and largely endorse the comments already posted by Bill Collins and anonymous referee #2, and will try not to repeat the specific points they made.

My main concerns where I feel the manuscript needs to work harder are as follows:

1) value proposition: it is mainly in the SI that the authors acknowledge prior work that linked GHG equivalencies based on damage costs and discount rates to GWP. I believe this needs to be brought into the main paper up-front, and the authors need to do a better job explaining where their study adds value to those existing studies. For example, one could argue that their approach is simply a reverse reading of Boucher (2012). I don't think that accusation would be justified, but neither is it justifiable for the manuscript not to recognise the fact that a range of studies have already found that discount rates around 2-3% give the same GHG equivalence between CH4 and CO2 as GWP100. In this context, in the discussion, I would have liked to see a better explanation why their GWP100-equivalent discount rate of 3.3% is higher than that derived by both Boucher and Fuglestvedt et al.

We have brought much of the SI discussion into the main text and expanded upon it, particularly with the comparison to Boucher & Fuglestvedt. See our response to Collins. We have also determined that at least part of the difference between Boucher & Fuglestvedt and the current work is the assumption that damages are a percent of GDP rather than an absolute function of temperature, which increases the relative value of long-lived gases when assuming economic growth into the future.

2) discussion of results including sensitivity analysis: in my view, the authors should include an explicit simulation of results if climate-carbon cycle feedbacks following a pulse emission of CH4 are included. The IPCC AR5 and subsequent studies demonstrated that including this results in a significant increase in the GWP100. This is flagged (p7 of the manuscript) but appears not to have been included in the actual sensitivity analysis. It should be fairly easy to modify the radiative forcing calculations to simulate climate-carbon cycle feedbacks and it doesn't have to change the study design at all. There really is no good justification in my view not to include this, other than this is not how the GWP has been defined historically – but from a scientific consistency perspective, it makes no sense to include an effect for one gas (CO2) but not for the other. Including this in the sensitivity analysis (perhaps as a special case, since this is a binary choice rather than something that can be expressed via a pdf) would at least tell us how important this is when we are concerned about choosing GHG equivalencies based on damage functions and discount rates. I could even live with the authors running this only for a central estimate for all other parameters so we can get an order-of-magnitude sense.

See our description of sensitivity analyses at the end of the response to William Collins for a description of the sensitivity analysis we performed in response to this comment, showing that sensitivity to exclusion of the climate-carbon feedback from CO_2 had only a small effect. (as well as discussing why we chose that approach rather than inclusion of the climate-carbon feedback in the CH_4 effect). We agree that this was an important analysis to do. The effect of the exclusion was small, due to cancellation when the GWP and the damage ratio are both calculated using consistent assumptions about gas lifetimes and radiative efficiencies. This sensitivity analysis has been included in the manuscript.

Related to this, but more difficult to do (hence I would not insist that this is done quantitatively) is consideration of the rate of change as a source of damages. Again this could be parameterised and quantified, but there is a large degree of arbitrariness how much weight to place on rate of change vs amount of change. The manuscript would be much stronger though if it could demonstrate under what circumstances including the rate of change might affect the conclusions, or whether the conclusions might be robust even if rate of change damages have been incorporated within reasonable bounds.

We have implemented a crude rate of change analysis within our framework (see discussion in the sensitivity analysis at the end of the reply to William Collins for details), and determined that under RCP6 inclusion of even extreme damage estimates due to rate of change have little effect on implicit timescales. However, under the RCP3PD scenario, the incorporation of rate of change has a larger effect, reducing the implicit timescale by almost half under the rate of change damage parameters that may be more realistic in magnitude. Our approach is not sophisticated enough to become a major component of the paper, but we do have a brief discussion of this as a sensitivity analysis, along with reference to Bowerman (2013) and the finding that near-term reduction of SLCFs only reduces peak rate of change for stringent mitigation scenarios.

3) interpretation and conclusions: I would endorse some of the comments made by anonymous reviewer #2, that the authors are effectively beating up a strawman. Yes some people have argued that we should simply ‘switch’ to GWP20, but the more intelligent arguments are all for considering the effect of multiple alternative time horizons to inform abatement decisions and policy choices. See e.g. the conclusions in Levasseur et al 2016 (doi: 10.1016/j.ecolind.2016.06.049) regarding the use of multiple time horizons and metrics in lifecycle assessment. The discussion and conclusions need to add quite a bit of nuance to reflect what those studies actually say, and hence the degree to which this manuscript challenges their conclusions or simply adds another dimension that can help choosing the right metric for the right purpose.

We have added more nuance to our description (see responses to other referees), as well as additional context to our results.

There are two additional points that the discussion and conclusion needs to address:

(a) one is that a key context in which GHG metrics are used are in emission trading schemes, and to help governments evaluate policy choices that directly affect near- term commercial decisions, i.e. policy that would “alter the use of capital in the private sector”. So there are very different contexts in which GHG metrics are actually used in climate policy and where different discount rates are commonly applied, and the paper would be stronger and more relevant if it recognised and addressed these explicitly.

We recognize that there is common justification (e.g., OMB Circular A-4) for the use of one discount rate for social problems and another for policies that “alter the use of capital in the private sector”. We would argue, however, that comparing the relative impacts of CO_2 v. CH_4 should always been considered a social problem in this context, regardless of whether it is being used in decisions regarding capital or by governments within emission trading programs. This is a somewhat tricky topic, as it can pose consistency challenges that go well beyond the implications of this paper. For example, a decisionmaker deciding between investing in a CNG vehicle and a gasoline vehicle might want to look at vehicle costs, maintenance, and fuel prices under a high discount rate to reflect the opportunity cost of that investment, but, because the benefits of the GHG abatement are not received by the decisionmaker but by society as a whole, it could be argued that the latter issue should be considered with a societal discount rate. It is unclear how to bring those two monetization streams into a single analysis given the difference in discount rates.

(b) The second is a recognition that IAMs used to design cost-minimising emission pathways often use a discount rate of 5%. Given that a(nother) key use of GHG metrics is to help IAMs make trade-offs between different gases with different mitigation costs, this should enter into the discussion in this paper. I don’t think this materially changes the conclusions since we know that different GHG metrics don’t have a massive effect on total mitigation costs (although there is a systematic effect especially when moving towards GWP20), but the issue is not trivial especially for countries or sectors with non-negligible non-CO2/SLCF sources. Some discussion on this is needed.

We plan to add more discussion regarding some of the IAM-based tradeoff work such as van den Berg et al. (2015), Reisinger et al. (2013), and Smith et al. (2013). The common use of a 5% discount rate is now briefly mentioned in that context.

I believe that all the above points (with the exception of quantifying the effect of including climate-carbon cycle feedbacks for CH4) can be addressed by a careful revision of the text itself. The manuscript needs to avoid what currently appears as the too- simplistic conclusion that "actually, GWP100 is largely ok, let's move on" (which is how I read P8L22). The fundamental finding from virtually all metrics papers is that the right metric depends on the application, and hence it is rather jarring to read a conclusion that continued use of GWP100 is 'reasonable' without any caveat.

We have made a number of changes to the conclusion to better explain our position. While we do believe that this analysis is strong support for a 100 year GWP in many contexts, it is important to define the key assumptions involved in that finding, including the fact that there are some uses of metrics for which the structure of this analysis may not be appropriate.

I am not repeating the above points in my specific comments below and would be happy for the authors to decide how they can best address them.

Specific comments:

P1L22: insert 'emission' after gases – we're talking about emission metrics here

Done.

P2L3: 'endorsed' is too strong in my view for the UNFCCC – 'used' is more factual, I cannot recall an explicit endorsement in the sense that the UNFCCC would have explained and justified its choice.

Discussion updated to:

> The 100-year time horizon of the GWP (GWP100) is the time horizon most commonly used in many venues, for example in trading regimes such as under the Kyoto Protocol, perhaps in part because it was the middle value of the three time horizons (20, 100, and 500 years) analysed in the IPCC First Assessment Report.

P2L11: I believe the correct term for GTP is Global Temperature CHANGE Potential

In our defense, AR4 and other sources also refer to the GTP as the Global Temperature Potential: e.g., "2.10.4.2 The Global Temperature Potential"). But "change" seems to be more standard, including in AR5, and so the manuscript has been updated to use the correct terminology.

P2L12: the reason why GTP downplays SLCFs is not primarily that it is temperature based but that it is a point metric. iGTP is very similar to GWP.

We are updating language to better differentiate integrated versus endpoint metrics. We note, however, that Brazil and New Zealand specifically suggest the GTP, not the iGTP, and justify it based on the temperature argument.

P2L22-27: editorial only: I prefer if introductions don't include the conclusions but rather focus on making the point of why the conclusions are worth having.

We have edited accordingly.

P3L15: shouldn't the N2O effect on CH4 forcing depend on the RCP pathway? Perhaps this was done but this isn't clear to me from the text.

The particular adjustment for N_2O cited here is based on 8.SM.11.3.3, which estimates that emissions of 100 molecules of N_2O will lead to a destruction of 36 molecules of CH4. For this effect, the RCP pathway does not matter.

This is in contrast to the overlap between N_2O and CH_4 radiative absorption bands, which does depend on the RCP pathway, and is captured in the radiative forcing equations used for this paper (and for the GWP).

P4L9: 'future years are cooler than present': helpful if you could indicate what years we are talking about (presumably you mean after 2200 or thereabouts, depending on the reference period/warming – meaning that much of those will be heavily discounted anyway).

Under RCP3PD, with climate sensitivity of 3.92, and a forcing imbalance of 0.84, temperatures drop below the starting temperature only 458 years into the analysis. Therefore, in this case, when the damage function is relying on temperature change since present (rather than since 1950-1980 or earlier), these years would need to be set to zero. It is possible that under different climate sensitivities or forcing imbalances, this could occur somewhat earlier, but we believe that the referee's intuition that this effect will be negligible due to discounting is correct. We have included a sentence noting that this scenario occurs in "fewer than 1 out of 1000 of the total years considered across all sensitivities, and generally only for years near the end of the analysis."

P4L21: here and later, please clarify where you truncate your damage calculations (when I read this sentence, I thought you truncate at 2300, but later (P5L14) it seems you truncate at 2500). You note below that this may matter for very low discount rates. Can you quantify/illustrate this?

We have clarified that the graphs are to 2300, but the calculations do go to 2500. We also include text regarding the size of the effect as follows:

> 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.

P6L4: I think the entire sensitivity discussion should note that projecting damages multiple centuries into the future is increasingly fraught with difficulties. The AR5 chose not to evaluate GWP500 because the authors felt that (deep) uncertainties were simply too large – but here you evaluate damages from temperature responses from forcing 500 years into the future? At least a comment on this is needed here – the discussion of what percentage of total damages occurs up to a given year for CH4 and CO2 is useful in this context and could be linked to this point about uncertainty.

See the response above regarding the low percentage of damages that occur after the first 290 years even under a 2% discount rate. We have also included a discussion of this issue:

> Myhre et al. (2013) justified exclusion of the 500 year GWP based on the large uncertainties and ambiguities involved with far future projections. This analysis extends through 2500, and therefore might be subject to some of those same uncertainties. Therefore, the effect of two shorter time periods were investigated. When truncating the analysis after 150 years, the GWP100 was still found to be consistent with a discount rate of 3.3%, with the upper interquartile bound also remaining constant at 4.1%, though the lower end of the interquartile range decreased

modestly to 2.4%. When the analysis was truncated at 100 years into the future, the implicit discount rates dropped more substantially, to 2.6% (interquartile range of 1.5% to 3.5%). Truncating the analysis will naturally make CH4 mitigation appear more favourable relative to CO2, but even discount rates as small as 3% are sufficient to make effects more than 150 years into the future inconsequential to the results.

P8L2: I feel the statement "We note no metric designed to tradeoff emission pulses is consistent with stabilization" is too strong. Of course, no metric in itself delivers stabilisation, but almost any metric can be used wisely enough to help countries achieve stabilisation.

We have modified our discussion of this issue. We particularly wanted to highlight the challenge of using, for example, a GTPX metric to achieve a cost-optimal approach to achieving a temperature target in a given year, but which when used in that way would lead to increasing challenges of maintaining temperatures at that target in future years (in part because the short-term GTP would lead to more SLCF abatement relative to CO_2 abatement than would be indicated by, for example, a GWP100). This is in addition to the fact that any SCLF/CO_2 trading using any pulse-based metric post-stabilization will lead to moving away from stabilization. The development of the GWP* in Allen et al. 2016 is one possible response to this challenge.

List of relevant changes:

Three substantial changes were made to the original manuscript:

1) A more complete & nuanced description of the existing literature in the introduction.
2) A number of additional sensitivity analyses exploring issues of discouting, climate-carbon feedbacks, pulse sizes, radiative efficiency questions, Ramsey discounting, and rate-of-change damage functions.
3) The conclusion has been rewritten in order to reflect the additional nuances, better characterization of existing literature, and new sensitivity analyses.

In addition, a number of minor edits have been made throughout. A graph of GDPs has been added to the SI (and the portions of the SI that were brought into the main text have been deleted).

Marked-up manuscript (see below):

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 emissions 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~~ often 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~~is the primary metric used to assess the equivalency of emissions 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~~ use 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. Criticisms include the following:~~:~~ ~~from arguments~~ that radiative forcing as a~~n endpoint~~ measure of impact is not as relevant as temperature or damages (Shine et al. 2005); ~~, to critiques of~~ that the assumption of constant future GHG concentrations (Wuebbles et al. 1995, Reisinger et al. 2011) is unrealistic;~~,~~ ~~to the position~~ that discounting is preferred to a constant time period of integration (Schmalensee, 1993); disagreements about the choice of time horizon in the absence of discounting (Ocko et al. 2017);~~,~~ ~~to the view~~ that dynamic approaches would lead to a more optimal resource allocation over time (e.g., Manne ~~and~~ & Richels~~,~~ 2001, Manne & Richels 2006), ~~and to the fact~~ that the GWP does not account for non-climatic effects such as carbon fertilization or ozone produced by methane (Shindell 2015); and that pulses of emissions are less relevant than streams of emissions (Alvarez et al. 2012). 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 focus on the choice of time horizon in the GWP as a key choice that can reflect decision-maker values, but where additional clarity regarding the implications of the time horizon could be useful. We also investigate the extent to which the choice of time horizon can incorporate ~~assess the choice of time horizon~~many of the complexities of assessing impacts described in the previous paragraph. The 100-year time horizon of the GWP (GWP_{100}) is the ~~horizon endorsed by the WMO and UNFCCC~~time horizon most commonly used in many venues, for example in trading regimes such as under the Kyoto Protocol, perhaps in part because it was the middle value of the three time horizons (20, 100, and 500 years) analysed in the IPCC First Assessment Report. 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~~Recently, 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). These studies each have different nuances regarding their recommendations – for example, Ocko et al. (2017) suggest pairing the GWP100 with the GWP20 to reflect both long-term and near-term climate impacts – and therefore there is no simple summary of the policy implications of this body of literature, but it is plausible that more consideration of short-term metrics would result in policy that weights near-term impacts more heavily. In contrast~~ to this push for a shortened time horizon of the GWP~~, some governments have ~~been suggesting~~suggested the use of the 100-year Global Temperature change 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, Brazil INDC, 2015). Therefore, the question of timescale remains unsettled and an area of active debate. ~~However, there have been few~~We argue that more focus on quantitative justifications for ~~of other~~ timescales within the GWP structure would be of value, as ~~opposed to~~differentiated from 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.~~

While we argue that quantitative justifications for choosing appropriate GWP timescales are rare, as reflected by the judgment of the IPCC authors that no scientific arguments exist for selecting given timescales, there is a rich literature addressing many aspects of climate metrics. Deuber et al. (2013) presents a conceptual framework for evaluating climate metrics, laying out the different choices involved in choosing the measure of impact of radiative forcing, temperature, or damages, and temporal weighting functions that can be integrative (whether discounted or time-horizon based) or based on single future time points. Deuber et al. conclude that the Global Damage Potential (GDP) could be considered a “first-best benchmark metric”, but recognize that the time-horizon based GWP has advantages based on limiting value-based judgments to a choice of time horizon, reducing scientific uncertainty by limiting the calculations of atmospheric effects to radiative forcing, and eliminating scenario uncertainty by assuming constant background concentrations. Mallapragada and Mignone (2017) present a similar framework and also note that metrics can consider a single pulse of a stream of pulses over multiple years. Several authors have recognized that under certain simplifying assumptions, the GWP is equivalent to the integrated GTP, and therefore any timescale arguments that apply to analyses of one metric would also apply to the other (Shine et al. 2005, Sarofim 2012).

A few papers have applied GDP type approaches to evaluate the GWP in a manner similar to that of this paper. Boucher (2012) uses as uncertainty analysis similar to that used in this paper to estimate the GDP of methane. Boucher found that the GDP was highly sensitive to discount rate, over a range of 1 to 3%, and damage function over a range of polynomial exponents of 1.5 to 2.5, and that the median value of the GDP was very similar to the GWP100. Fuglestvedt et al. (2003) also used a GDP approach to map time horizons and damage function exponents to a discount rate, using IS92a as an emission scenario. Fuglestvedt et al. found that a discount rate of 1.75% and a damage exponent of 2 led to results equivalent to a GWP100. De Cara (2005), in an unpublished manuscript, also calculated the relationship between discount rates and time horizon, though they assumed linear damages.

An alternate approach is to evaluate metrics within the context of an integrated assessment model (IAM). There are several examples of such an approach. Van den Berg et al. (2015) analyse the implications of the use of 20 year, 100 year, and 500 year GWPs for CH_4 and N_2O reductions over time within an IAM. The analysis estimated optimal costs to meet a 3.5 Wm^{-2} target in 2100 and found that use of the GWP_{20} and GWP_{100} resulted in similar costs (within 4%) but that use of the GWP_{500} resulted in higher costs by 18%. A key caveat here, as with many such analyses (including the present Sarofim and Giordano paper) is that the structure of the test can drive the evaluation result: in the case of van den Berg et al., the analysis ends in 2100, which will reduce the evaluated benefits of long-term metrics particularly for reductions that occur at the end of the century. These IAMs often use a discount rate of 5% for their net present value analysis. Other IAM analyses 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 (e.g., Smith et al. 2013, Reisinger et al. 2013). This is in large part because marginal abatement curves for CH_4 within these models have low-cost options (likely representing mitigation options such as landfill gas to energy projects and oil and gas leakage reduction) and high-cost options (reductions of enteric fermentation emissions from livestock) but few moderate-cost options. Therefore, for even a moderate carbon price, all the low-cost options will be enacted regardless of GWP, and no matter what the GWP, few high-cost options will be enacted. Such analyses may not fully consider non-market barriers or distributional effects for which changes in the GWP could be important.

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While this paper focuses on a cost-benefit approach, there is also a potential need for cost-efficiency approaches, particularly in regard to stabilization targets such as 2 °C. However, a number of authors have argued that pulse-based metrics such as the GWP are not well-suited to achieve stabilization goals (Sarofim et al. 2005, Smith et al. 2012, Allen et al. 2016).

Some actors (Brazil INDC, 2015) have claimed that certain metrics such as the Global Temperature Potential (Shine et al. 2005) or the Climate Tipping Potential (Jorgensen et al. 2014) are more compatible with a stabilization target such as 2 °C because they are temperature based. However, any pulse-based approach faces at least two major challenges related to stabilization scenarios. The first is that as a temperature target is approached, a dynamic approach will shift from favouring long-lived gas mitigation to favouring short-lived gases. While this shift may be optimal for meeting a target in a single year, it will be sub-optimal for any year after that year. The second challenge is that once stabilization has been achieved, any trading between emission pulses of carbon dioxide and a shorter-lived gas will cause a deviation from stabilization. For example, trading a reduction in methane emissions for a pulse of CO_2 emissions will lead to a near term decrease in temperature, but also a long-term increase in temperature above the original stabilization level. One solution to the problem is a physically-based one. Allen et al. (2016) suggest trading an emission pulse of carbon dioxide against a sustained change in the emissions of a short-lived climate forcer. This resolves the issue of trading off what is effectively a permanent temperature change against a transient one. However, the challenge becomes one of implementation, as current policy structures are not designed for addressing indefinite sustained mitigation. A second solution is a dynamically updating global cost potential approach that optimizes shadow prices of different gases given a stabilization constraint (Tol et al. 2016), but again, implementation would be challenging. Alternatively, a number of researchers (Daniel et al. 2012, Jackson 2009, Smith et al. 2012) suggest addressing CO_2 mitigation separately from short-lived gases. Such a separation recognizes the value of the cumulative carbon concept in setting GHG mitigation policy (Zickfeld et al. 2009). However, this approach requires a central decisionmaker and loses the "what" flexibility that makes the use of metrics appealing (Bohringer et al. 2006). In economic terms, a temperature based target is equivalent to the assumption of infinite damage beyond that threshold temperature, and zero damages below that threshold (Tol et al. 2016).

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, Deuber et al. 2013). However, instead of proposing a switch to a ~~global damage potential~~GDP 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. While other analysts have used similar approaches (Fuglestvedt et al. 2003, Boucher 2012), this paper reframes and clarifies key issues, and presents a framework for better understanding how different timescales can be reconciled with how the future is valued. The paper focuses on CO_2 and CH_4 as the two most important historical anthropogenic contributors to current warming, but the methodology is applicable to emissions of other gases and sensitivity analyses consider N_2O and some fluorinated gases.

~~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%).~~

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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: results of a larger pulse are described in Sect. 3.3). 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. 3.3 and 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~~ by the square of the temperature change since the baseline period ~~squared~~. E.g., D(2050) = a*ΔT(2050)^2*GDP. The net present value is then calculated using the discount rate such that NPV(D(t)) = D(t)/(1+r)$^{t-2010}$. Hsiang et al. (2017) present a recent justification for using a quadratic function for damages. For the 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 (a) (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 baseline growth for each five-year time period in the Nordhaus scenario. The GDP growth rates over the 21st century from DICE (2.5%), and the high and low growth rate scenarios (1.3% and 3.8%) ~~uncertainty used~~, are ~~reasonably~~ consistent with the estimate of ~~long-run~~21st century ~~productivity~~ per-capita GDP growth from ~~Gillingham~~ Christensen et al. (2018~~5~~) of 2.1~~06~~% (with a standard deviation of 1.1~~2~~%), when added to the population growth rate of 0.4% from DICE (see the SI for a graph of the GDP scenarios). 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 (fewer than 1 out of 1000 of the total years considered across all sensitivities, and generally only for years near the end of the analysis) are cooler than ~~present~~the baseline temperature: in ~~years that are sufficiently cool that the temperature change plus the temperature offset is less than zero, this value~~those years the net temperature change is set to zero to avoid numerical problems.

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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). Fig.~~ure~~ 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.

~~(~~Fig. 1 relies on calculations that ~~using~~ use central estimates of the uncertain parameters, as discussed in the Methods section. ~~)~~While the graph is truncated at 2300, the calculations used in this paper extend to 2500. 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. In the case of CH_4, damage peaks in 2032 and declines until 2080 as a result of the short lifetime of the gas. The increase in damages after 2080 is due to the component of the temperature response function that includes a 409 year timescale decay rate, such that after 100 years the decrease in the ΔT^2 component of the damage equation is about 0.5%/year, and because that decay rate is slower than the rate of GDP growth, net damages grow. ~~, and~~Fig. 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 emissions of gases with very different lifetimes.

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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, within the interquartile range, with the 3% discount rate~~s~~ that ~~are~~ is 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 Analyse~~i~~s

Figure 2 shows the ~~interquartile and interdecile ranges~~median, interquartile, interdecile, and extremes of the equivalent GWP time horizon corresponding to a given discount rate 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~~was calculated ~~as~~ assuming equal likelihood of each of 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). For these 6 parameters, the choices that lead to larger damages from CH_4 relative to CO_2 are a low GDP growth, a low damage exponent, a low emissions scenario, a higher temperature offset (e.g., assuming that damages are a function of warming from preindustrial, not warming from present day), a lower climate sensitivity, and a higher current forcing imbalance. The general trend is that the more that damages are expected to grow in the future (e.g., high GDP growth, damage exponent, or emissions

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scenario), the longer the equivalent timescale is for a given discount rate. ~~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, w~~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~~ informative to evaluate emissions of 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~~ is consistent (interquartile range) with the optimal timescale/damage ratios for ~~short-lived gases~~methane ~~and undervalues the longer-lived gases~~. For gases with lifetimes in centuries, the GWP at any timescale undervalues these gases, but the magnitude of that undervaluation is somewhat insensitive to the choice of timescale. For the longest lived gases, the GWP also undervalues reductions in these gases, but the longer the timescale the better the match.

In addition to investigating the sensitivity of these results to different choices of the six listed parameters, and five different gases, several other sensitivity experiments were performed. These experiments were chosen to investigate whether certain assumptions are important, as well as alternate approaches to constructing the model.

The first set of experiments involve analysis choices that end up having little difference in terms of timescale estimation. In general, this is because changes in these choices effect both the GWP and the damage estimation equally, and therefore cancel out. One experiment involved changing the size of the emissions pulse to 373 MMT (about one year's anthropogenic emissions according to Saunois et al. 2016). The effect on damage ratios of this change was less than 1%. Another experiment involved doubling the radiative efficiency of methane: while this led to a doubling of the estimated damage ratio, it also led to a doubling of the estimated GWP, such that the change in estimated timescale was about 1/10th of 1%. This experiment confirms that timescale estimates are insensitive to updates to estimates of the radiative efficiency of individual gases (such as the finding of Etminan et al. 2016 that methane has greater forcing effects than previously estimated). A third experiment arose because of the question of consistency between the treatment of CO_2 and CH_4 in terms of climate-carbon feedbacks (Gasser et al, 2017, Sterner and Johansson 2017). Using the CO_2 lifetime from Gasser et al. (2017) without climate-carbon feedbacks, an increase in damage ratios of about 8% was estimated, but a similar increase in GWP of about 7% was estimated, with a net effect on

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timescales of less than 1%. The converse experiment (including climate-carbon feedbacks in both the CO_2 and CH_4 lifetimes) was not analysed due to the increased complexity of the calculation. However, given that the virtue of the GWP is its simplicity, the authors suggest that the use of lifetimes without climate-carbon feedbacks for either gas should be preferred over the inclusion of those feedbacks in the lifetimes of both gases (Sarofim 2016).

Another experiment considered the use of a Ramsey type framework for discounting future damages. The use of such a framework has been recommended by the National Academies (NAS, 2017). In this framework, discount rates are a function of the marginal utility of consumption, the pure rate of time preference, and the future growth rate of per capita consumption. It is the latter dependence that makes this sensitivity analysis particularly interesting, as this pairs higher consumption growth (leading to higher damage ratios) with higher discount rates (leading to lower damage ratios). For this experiment, the Ramsey parameters were calibrated to yield an average discount rate for the reference GDP of 5% over the first 30 years of the analysis, given a pure rate of time preference of 0.01%. Under this assumption, the median timescale under the reference GDP scenario increases to 135 years, because even though the initial discount rates are higher than 3%, over the entire period of the analysis the average discount rate is only 1.5%. However, unlike in the original analysis, under the high GDP growth scenario the damage ratio increases and the equivalent timescale decreases to 90 years, because the increase in discount rate resulting from high growth has a larger effect on damages than the long-term increase in GDP (and vice versa for low GDP growth). The difference between the damage ratios for the high and low GDP growth scenarios is still about a factor of 2. A future analysis could pair GDP scenarios with emissions scenarios to take into account the potential correlation of the two.

Boucher (2012) and Fuglestvedt et al. (2003) both applied similar approaches to the one used in this paper, but both papers identified a discount rate consistent with the GWP100 that was somewhat lower than the median 3.3% value found in this paper. The most evident different between the approach in these previous papers and this article is that this article assumes that damages are expressed as a percent of GDP, and the previous analyses did not. In order to more closely emulate the Boucher and Fuglestvedt approach, the model was tested by using constant GDP over the entire time period, and the GWP100 was found to be most consistent with a discount rate of 1.2% (interquartile range of 1.0 to 1.9%) in contrast to 3.3% (interquartile range of 2.7% to 4.1%).

Myhre et al. (2013) justified exclusion of the 500 year GWP based on the large uncertainties and ambiguities involved with far future projections. This analysis extends through 2500, and therefore might be subject to some of those same uncertainties. Therefore, the effect of two shorter time periods were investigated. When truncating the analysis after 150 years, the GWP100 was still found to be consistent with a discount rate of 3.3%, with the upper interquartile bound also remaining constant at 4.1%, though the lower end of the interquartile range decreased modestly to 2.4%. When the analysis was truncated at 100 years into the future, the implicit discount rates dropped more substantially, to 2.6% (interquartile range of 1.5% to 3.5%). Truncating the analysis will naturally make CH_4 mitigation appear more favourable relative to CO_2, but even discount rates as small as 3% are sufficient to make effects more than 150 years into the future inconsequential to the results.

A final experiment considered the inclusion of damages due to rate of change as well as due to absolute temperature. Inclusion of rate of change damages has had important influences on previous analyses. For example, in Manne and Richels (2001), the

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dynamic optimization solution for approaching a temperature threshold placed little value on CH_4 reduction relative to CO_2 until a couple decades before the threshold was reached: but when a rate of change requirement was added, the relative value of CH_4 reduction stayed fairly constant over the time period. The challenge for this analysis is in determining the appropriate damage form, as the literature for estimating damages due to rate of change is not as robust as for absolute changes. As a test case, the peak rate of change damages under the median parameter values were calibrated to be equal to the absolute damages in the year 2060 (50 years into the analysis). The effect of inclusion of this effect was to increase the damage ratio of CH_4 to CO_2 by 2.4%. This fairly modest impact is consistent with results of Bowerman et al. (2013) or Rogelj et al. (2015) which suggest that near-term mitigation of SLCFs have modest effects on reducing the peak rate of change for higher future emissions scenarios, and that delayed SLCF mitigation may yield most of the same benefits as immediate SLCF mitigation in terms of both peak absolute change as well as rate of change. In order examine how this effect could be sensitive to a lower emissions scenario, the analysis was repeated for the RCP3PD scenario by itself. Under this assumption, the damage ratio increases by 53%, resulting in a decrease of the optimal timescale for RCP3PD associated with a discount rate of 3% from 94 years to 54 years. This result is also consistent with Bowerman et al. which found more benefit to reducing near-term SLCF emissions if future emissions are expected to be low.

~~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~~ Additional Uncertainties

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.

As shown above, ~~Uncertainties~~ 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~~include factors that have similar effects on the GWP and the CH_4:CO_2 discounted damage ratio, such as radiative efficiency or consistent treatment of climate-carbon feedbacks. ~~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~~ lag between the timing of atmospheric temperature response to forcing and the response of sea level (e.g., Zickfeld et al. 2017), and other issues that are inherent to the timing of climate impacts—but are not necessarily included in the GWP calculation—might all

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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~~ radiative forcing and temperature effects of the emission pulses. The shape of the damage function can also have a substantial effect: different exponents for the polynomial form were tested, as was the inclusion of rate of change, but the full range of possible damage functions is substantially larger, including multi-polynomial behavior (Weitzman, 2001) or the potential for persistent influences on economic growth (Burke et al. 2015).

An additional category of ~~uncertainties is one that~~effects has ~~no~~ less relevance to an analysis of appropriate timescale of climate impacts, but ~~are~~ would be important for overall valuation. These are generally gas-specific effects which should most appropriately be considered on a case-by-case basis rather than folding into a timescale analysis that will influence the mitigation choices for all gases. 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 the health effects of O_3 produced by reaction of CH_4 in the atmosphere ~~effects on health~~ (Shindell et al. 2015, Sarofim et al. 2017), ~~or~~ CO_2 effects on ocean acidification, or the possible reduced efficacy of CH_4 compared to CO_2 (Modak et al. 2018). 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. As an example, if the solution to undervaluing CH_4 mitigation due to its O_3 effects is to reduce the appropriate timescale for GHG comparisons, an identical gas without O_3 chemistry implications would be similarly prioritized. One potential approach which could be explored might be to apply a multiplier to the GWP after calculation to take into account these non-climatic effects, much like the GWP of methane takes into account indirect effects on climate through the production of tropospheric O_3 and stratospheric H_2O by the use of a multiplicative factor.

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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.~~ This analysis uses a global damage potential approach to calculate the implicit discount rate corresponding with different GWP timescales. While this is not the first analysis to calculate the implicit discount rate of the 100 year GWP (Boucher 2012, Fuglestvedt et al. 2003), the framework presented here allows for a more complete and wide-ranging analysis of sensitivities than has been presented previously, and the connection between the timescale and the implicit discount rate is made more clearly. The 100 year GWP is the inter-gas comparison metric with the widest use, and the ~~. 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%). Alternatively, the 3% discount rate used for calculating social damages in some regulatory impact analysis contexts is consistent with timescales of 84-171 years. The uncertainty range in the results is most sensitive to the assumptions regarding future GDP growth and to the choice of exponent in the damage function. These results are insensitive to assumptions regarding radiative efficiency, pulse size, or consistent treatment of climate-carbon feedbacks. At discount rates of 3% or higher, the analysis can be truncated to 150 years (rather than the default calculation through 2500) with little effect. Inclusion of damages resulting from the rate of change in addition to absolute temperature changes has little effect except in the case of a low emissions future, where it results in a decrease in the timescale consistent with a 3% discount rate to 54 years. Applying the methodology in this paper to calculate the implied intertemporal values of a 20 year GWP, a timescale that has received some recent attention, results in an implicit discount rate of 12.6% (interquartile range of 11.1% to 14.6%).

These results provide support to the contention that 100 years is a reasonable timescale choice for the GWP, given the assumption that the relative climate damage of pulses of different greenhouse gases is an appropriate means of valuation, and that the 3% discount rate is a reasonable measure of the value of the future. This finding is robust to a number of sensitivity analyses. In contrast, the analysis suggests that the 20 year GWP timescale is most consistent with an implicit discount rate much higher than the standard social discount rate, except in scenarios with low future emissions and high rate of change damages, similar to concerns expressed in other analyses (Shoemaker and Schrag, 2013). However, while the implicit timescale was derived from analysing the climate impacts resulting from CH_4 emissions relative to CO_2 climate impacts, the results do not necessarily inform a specific relative importance of CH_4 mitigation compared to CO_2. Such a relative importance

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calculation should take into account the latest research on radiative efficiencies (Etminan et al. 2016). and could potentially also take into account non-climate impacts like the health effects of CH_4-derived O_3 (Shindell, 2015, Sarofim et al. 2017). Inclusion of non-climate impacts could perhaps use an adjustment factor in the same way that the CH_4 GWP already includes adjustment factors for the climate effects of CH_4-derived O_3. Additionally, the appropriate GWP timescales can also be informed by the manner in which the metric is being used for policy or informational purposes.

The methodology presented here is transparent (the code is available in the SI), rigorous (the parameters and functional forms are derived from respected sources), and flexible (as demonstrated by a wide range of sensitivity analyses from inclusion of rate-of-change damages to Ramsey discounting). This framework can be a valuable resource for quantitatively examining appropriate timescales given different assumptions about discounting, the relationship of damages to both absolute and rate of temperature changes, tipping points, future emissions scenarios, and other factors.

~~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.~~

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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.

Disclaimer

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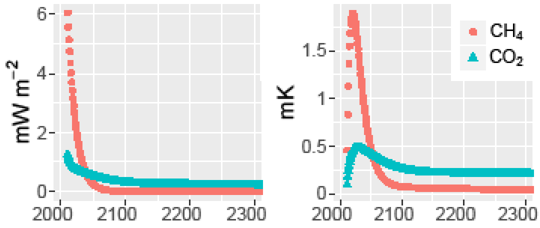
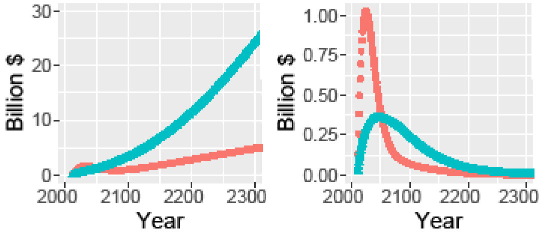
(a) Radiative forcing (b) Temperature



(c) Damages (d) Discounted



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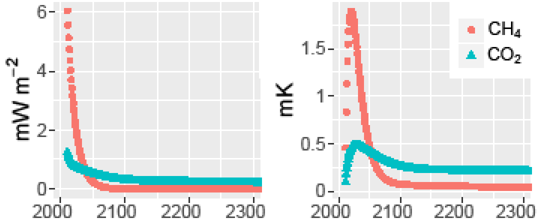

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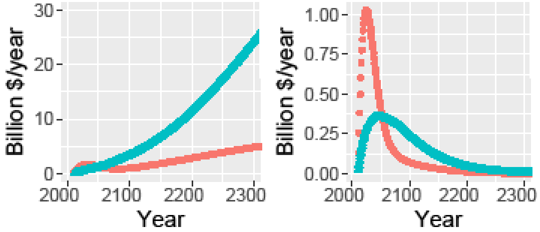

Figure 1: Impacts of emission pulses of CH_4 and CO_2. Radiative forcing (a), temperature(b), damages (c), and discounted damages (3%, d) for an emission pulse of 28.3 MT CH_4 (10 ppb in the first year) and 24.8 times as much CO_2 emissions by mass. The underlying scenario is RCP6.0, with other parameters at their central values. 5

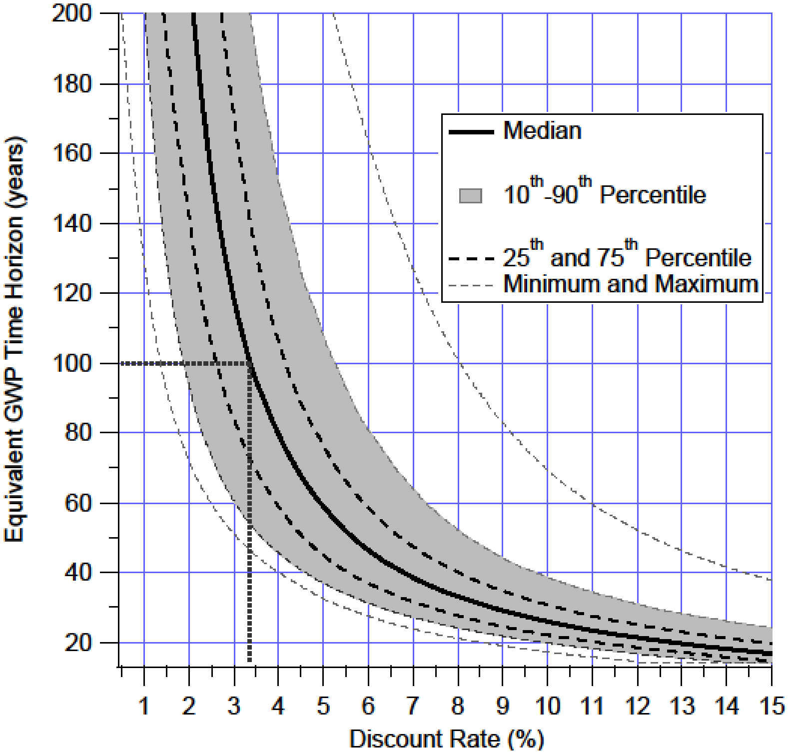

Figure 2: GWP timescales consistent with discount rates based on consistency of the GWP ratio with the ratio of net present damages of CH_4 and CO_2, including the interquartile and interdecile bands and maximum and minimum values based on a sensitivity analysis.

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. Results in this table are derived assuming a discount rate of 3%.

Gas	Lifetime	Optimal timescale	GWP_{100}/damage ratio	GWP_{20}/damage ratio
CH_4	12.4	120 (84-172)	1.15 (1.52-0.87)	3.4 (4.49-2.57)
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. Interquartile uncertainty ranges are presented for the timescale and damage ratios for CH_4. Results in this table are derived assuming a discount rate of 3%.

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