Present global warming: a justifiable and stable metric for evaluating short-lived climate pollutants

Andrew E Pomerantz and Robert L Kleinberg

Schlumberger, Cambridge, MA, United States of America
Columbia University, New York, United States of America
Boston University, Boston, MA, United States of America

E-mail: apomerantz@slb.com

Supplementary material for this article is available online

Abstract
The impacts of short-lived climate pollutants (SLCPs) such as methane are typically described using metrics that compare their climate impacts to carbon dioxide’s climate impact. The metrics consider a climate pollutant’s atmospheric heat-trapping effectiveness and atmospheric lifetime. Here we introduce an alternative metric called the Present Global Warming (PGW), which uses economic exponential discount modelling to characterize short-term and long-term effects simultaneously, resulting in a justifiable, familiar, and stable metric for evaluating SLCPs. We recommend quantifying the climate impacts of methane emissions using 2.5% annual discounting—consistent with the discount rates recently proposed in academic work and traditionally used in climate policy—corresponding to methane PGW$_{2.5\%} = 50$. In this context, one ton of emitted methane has the same climate impact as 50 tons of emitted carbon dioxide.

1. Introduction

Anthropogenic emissions have increased the atmospheric concentrations of several greenhouse gases (GHGs), and each of these gases contribute to climate change [1]. The potency of a GHG or other climate pollutant is typically quantified by considering both its lifetime in the atmosphere and its heat-trapping effectiveness while in the atmosphere. Short-lived climate pollutants (SLCPs) are GHGs or other atmospheric compounds that warm the planet and whose atmospheric lifetimes are below approximately 20 years, making them short-lived compared to carbon dioxide [2]. The most significant SLCP is methane, whose lifetime is considerably shorter but whose radiative efficiency per unit mass is 120-fold larger than carbon dioxide’s [3, 4].

Effective strategies to mitigate climate change can, and likely must, reduce emissions of multiple compounds, not just carbon dioxide [2, 3, 5, 6]. Effective planning therefore requires metrics that quantify the potency of different compounds, such that the impacts of different compounds (and therefore, the benefit of mitigation strategies) can be readily evaluated. Numerous metrics have been proposed, each with a use case that makes it relevant to one or more of the diverse communities studying the causes and effects of climate change [4]. The development of metrics is an on-going activity of the climate change communities, with emergent metrics such as GWP$^*$ figuring prominently the in the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [3]. In this work we propose a new metric, Present Global Warming (PGW). This metric builds on the physics of the familiar global warming potential (GWP) while adding concepts from economics that may make it a useful tool for socio-economic policymaking and for emissions reporting.

2. Traditional emission metrics

While many metrics are available [4], the most common metric to evaluate the impact of SLCPs is the GWP. The GWP compares the integrated radiative forcing resulting from a pulse of a given SLCP over a specified time horizon to the integrated radiative forcing resulting from an equal mass pulse of carbon dioxide over the same time horizon [7]. The radiative
A E Pomerantz and R L Kleinberg

Figure 1. Construction of GWP (top path) and PGW (bottom path). In the top path, the radiative forcings for methane and carbon dioxide (left) are multiplied by step function weights (top middle) to produce the weighted radiative forcing curves (top right) which are integrated to obtain the GWP. In the bottom path, the radiative forcings for methane and carbon dioxide (left) are multiplied by exponential discount function weights (bottom middle) to produce the discounted radiative forcing curves (bottom right) which are integrated to obtain the PGW. To facilitate comparison, the radiative forcing (left) and weighted/discounted radiative forcing (right) are normalized such that the curves for carbon dioxide $= 100 \text{ W m}^{-2}$ at time $= 0$. Because methane has a much larger radiative forcing than carbon dioxide—at time $= 0$ the radiative forcing for methane is 120-fold larger than that for carbon dioxide—the corresponding curves for methane are additionally divided by 100 so both gases can be seen on the same plot $[11, 20]$. 

Forcing is weighted by a step function that equally weights all times during the selected timeframe and excludes times after the timeframe (see figure 1). The formula for computing methane GWP for different timeframes is shown in equation (1), in which $\text{RF}(t)$ represents the radiative forcing at time $t$ following an instantaneous, unit mass pulse of gas at $t = 0$; $M$ represents methane; $K$ represents carbon dioxide; $T$ represents the upper bound of the timeframe; and $H(t; T)$ is the step function where $H(t; T) = 1$ for $t \leq T$ and $H(t; T) = 0$ for $t > T$. Note that equation (1) is generalizable to all climate pollutants by replacing the radiative forcing for methane with the radiative forcing for any climate pollutant

$$\text{GWP}_T = \int_0^\infty \text{RF}_M(t) H(t; T) \, dt \int_0^T \text{RF}_K(t) H(t; T) \, dt.$$  

(1)

GWP provides a single number that enables ‘apples to apples’ evaluation of any SLCP by directly comparing its potency to the potency of carbon dioxide. Additionally, numerous alternative metrics have been proposed, each designed to evaluate different aspects of the climate system $[4, 8-19]$. As reviewed by Balcombe $[4]$, these metrics evaluate different timeframes, physical bases, emission durations, and more. These metrics are typically ‘step function metrics’ where the temporal weighting involves the step function $H(t; T) = 1$ for $t \leq T$ and $H(t; T) = 0$ for $t > T$.

3. PGW

Here we propose a new metric, which we call the PGW. The only difference between GWP and PGW is the choice of the temporal weighting function. Whereas GWP weights radiative forcing with a step function, PGW weights radiative forcing with a smoothly varying exponential decay (see figure 1). The PGW weighting function discounts the importance of future radiative forcing analogously to the weighting function used to discount the importance of future revenue streams in an economic net present value (NPV) calculation. Similar to how NPV determines the present value of future revenues, PGW determines the present value of future climate effects. In calculating PGW, a discount rate is selected, analogous to the selection of a timeframe in calculating GWP. As with numerous other metrics, PGW is normalized to carbon dioxide such that the PGW for carbon dioxide is equal to unity at all discount rates. In the formula for computing methane PGW at different discount rates (equation (2)), $r$ represents the discount rate, and the other variables are defined above. PGWs for methane calculated at different discount rates, climate effects, and emission durations are presented in table 1. Note that equation (2) is also generalizable to all climate pollutants by replacing the radiative forcing for methane with the radiative forcing for any climate pollutant
PGW has the following desirable characteristics: PGW provides a smoothly varying weight where each successive year is weighted incrementally less. This exponential weighting contrasts the step function weighting used in most other metrics that creates an abrupt distinction where climate effects during the timeframe are all considered equally while climate effects after the timeframe are ignored [19].

PGW accounts for both short-term and long-term climate effects simultaneously. This attribute of PGW parallels the ability to account for both short-term and long-term financial effects simultaneously in NPV. NPV determines the present value of revenues at any point in the future by discounting future revenues by an amount that depends on how far into the future they occur. Typically, an exponential weighting function is used for that discounting, such that revenues further into the future are given less weight. NPV considers short-term and long-term financial effects simultaneously by integrating the present value of all future revenues, including integrating to infinite time. The ability to consider all time horizons simultaneously is one of the main reasons why NPV is widely used, because it allows different investments with different short-term and long-term ramifications to be evaluated logically and consistently. Similarly, the exponential discounting in PGW captures the present impact of future global warming. By integrating climate effects to infinity and appropriately weighting future climate effects, PGW similarly considers both short-term and long-term effects simultaneously and allows different climate pollutants with different lifetimes to be evaluated logically and consistently. The simultaneous consideration of short-term and long-term effects contrasts typical step function metrics that consider either short term (commonly considered as 20 years) or long term (commonly considered as 100 years) effects separately [8].

Short-term or long-term effects can be emphasized in PGW by choice of discount rate. This selection provides needed flexibility because different users have different priorities for short-term and long-term effects. While PGW considers short-term and long-term effects simultaneously, higher discount rates emphasize short-term effects while lower discount rates emphasize long-term effects. This ability to shift emphasis is familiar to those who use exponential discounting and NPV calculations in other decision-making processes.

Because discount rates are widely used, users can justifiably select a discount rate for PGW based on the same considerations used to select discount rates in other analyses such as cost-benefit calculations or the social cost of GHGs [21]. Discount rates are widely used by organizations such as governments, researchers, and corporations, and those organizations use discount rates to evaluate many decisions where short-term and long-term effects need to be considered. Because discount rates are so common and so important, discount rates are rarely selected arbitrarily but instead are typically selected after detailed analysis. For example, discount rates can be selected by normative approaches that consider standards of fairness and/or by positive approaches that consider observed market rates [22]. PGW leverages the thoughtful analysis used for discount rate selection to give a value that is both justifiable and consistent with other considerations. Temporal weighting values, such as time horizons in GWP and discount rates in PGW, reflect societal preferences and are mostly political selections [15, 23]. Today there is some consensus on the political choice of discount rate used in climate policy, and that same chosen discount rate could be used for PGW. For many years the U.S. government has used a 3% discount rate, with sensitivities ranging from 2% to 5%, for a variety of climate policies. These rates were proposed by the U.S. Office of Management and Budget during the second Bush administration based on average rates used to discount future consumption as shown by the financial rate of return on long-term government debt [24]. The same rates have been used by the Obama and Biden administrations, and a 3% annual discount rate has become political standard for climate analyses [21, 25, 26]. Recent academic work has proposed that the rates be revised downward [22]. In particular, evaluation of recent literature on real interest rates and a survey of academic economists concluded that that a 2% annual discount rate would be more appropriate [27]. Similar analyses can be used to select discount rates for PGW.

Additionally, PGW is stable because the selection of discount rate is relatively inconsequential in determining the value of PGW. For example, the PGW for methane varies by only a factor of 1.25 between the commonly considered discount rates discussed above: 2% as proposed recently in academic work and 3% as used traditionally by policymakers (see table 1) [21, 25–27]. The stability of PGW contrasts that wide range of values found in other metrics. For example, the social cost of carbon dioxide varies by a factor of 2.31 between the same 2% and 3% discount rates [27]. Among step function metrics, the 20 year GWP and the 100 year GWP for methane differ by a factor of 3 [4]. In some cases when the aggregated effects of multiple GHGs are considered, the selection of which GWP to use determines whether methane is the dominant pollutant or a minor one [28].

PGW is robust, giving the same or similar results for a range of climate effects and emission durations (see table 1). Metrics such as PGW and GWP can
consider different climate effects (such as radiative forcing or temperature increase) or different emission durations (such as a single pulse or a sustained emission). Among step-function metrics, there are different metrics that evaluate these different terms. For example, GWP considers the radiative forcing resulting from a single pulse of emissions, integrated global temperature change potential considers the temperature rise resulting from a single pulse of emissions [4, 29], and sustained-flux global warming potential considers the radiative forcing resulting from a sustained emission [30]. The metrics are designed to evaluate different aspects of the climate system, and the metrics yield widely varying values. Considering only methane, the values of these metrics deviate from GWP by up to a factor of 1.6 for the same timeframe [4]; for cases in which time horizons are selected to align with temperature goals, these metrics deviate from GWP by a factor of 4.6 [15]. Similar considerations result in only minor changes to PGW. Table 1 shows PGW values, across a range of discount rates, for different climate effects and emission durations. The formula for computing PGW considering radiative forcing following a pulsed emission is presented in equation (2). The PGW formula considering radiative forcing following a sustained emission is the same, except \( RF(t) \) represents radiative forcing following a sustained, rather than pulsed, emission [11]. The PGW formula considering temperature rise is the same except the term representing radiative forcing is replaced by a term representing the global mean surface temperature [11]. PGW is nearly identical whether the climate effect considered is radiative forcing or global mean surface temperature and is mathematically identical whether the emission duration considered is pulsed or sustained (see supplementary information for mathematical proof). The similarity of these metrics simplifies climate analysis relative to the traditional case with step function weighting where large differences between these values complicates the metric selection.

4. Discussion

Dealing with climate change at global scale will be an effort of enormous scale, and a diversity of viewpoints and approaches are required to comprehensively characterize climate impacts. The 15 metrics described by Balcombe et al [4], along with those described in Intergovernmental Panel on Climate Change (IPCC) reports, present various points of view. Instruments such as integrated assessment models and social costs calculations capture more complex dynamics [8, 21].

Here, a new metric is presented: the PGW. PGW attempts to characterize the climate impacts of SLCPs by calculating the present value of future climate change caused by an emission of the SLCP. PGW characterizes a physical effect (the climate impact of an emission of a SLCP) using a methodology common in the field of economics (exponential discounting of future effects). In particular, the calculation of the present value of future climate change in PGW is analogous to the calculation of the present value of future revenue streams in a NPV calculation. NPV is a widely used economic metric because it is able to represent both the short-term and long-term effects of an investment in a single number, where the short-term and long-term effects are appropriately balanced by exponential discount weighting. PGW is similarly able to capture the short-term and long-term climate effects of an emissions simultaneously in a single number. Calculating PGW involves selecting one adjustable parameter: the discount rate that weights short-term and long-term effects. It is found that PGW is justifiable because discount rates are commonly used for climate policies in other applications, so the discount rate used for PGW can be taken as the same discount rate determined elsewhere. In particular, a 3% annual discount rate has been used by many US presidential administrations including the current administration, and a 2% annual discount rate has been proposed by recent academic work based on real interest rates and survey results [27]. Either value can be used for computing PGW, and the value of PGW changes only slightly when evaluated at those two discount rates (varying by a factor of 1.25). Thus, PGW is found to be both justifiable—the only adjustable parameter (the discount rate) can be set equal to that determined by detailed analysis performed by various groups for various purposes—and stable—PGW evaluated at any commonly used discount rate is nearly identical. This combination of justifiability and stability may make PGW uniquely useful compared to step function metrics where the motivation to select a particular timeframe is not always clear and the value of the metric changes dramatically at different timeframes.

PGW represents a single number that describes the climate impacts of SLCPs. GWP and other

| Table 1. PGWs for methane calculated at different discount rates, different climate change quantities (RF = radiative forcing; temp = temperature rise), and different emission durations. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Quantity       | Duration        | \( r = 2\% \)  | \( r = 2.5\% \) | \( r = 3\% \)  | \( r = 4\% \)  | \( r = 5\% \)  | \( r = 7\% \)  |
| RF             | Pulsed          | 44              | 44              | 55              | 55              | 64              | 64              |
|                | Sustained       | 44              | 44              | 55              | 55              | 64              | 64              |
| RF             | Pulsed          | 43              | 49              | 54              | 62              | 69              | 79              |
|                | Sustained       | 42              | 48              | 53              | 62              | 69              | 79              |

\( r \) is the discount rate.
step function metrics also provide a single number. Consolidating complex effects in this manner has both strengths and weaknesses. The main strength is that the value is practical for numerous applications. For example, GWP is widely used today for policy-making and for emissions reporting; the social cost of carbon, which consolidates into a single number the complex effects of population growth, economic growth, temperature change, sea level rise, economic damages, and future discounting, is widely used in policy and regulation; and NPV, which consolidates into a single number complex streams of future profits and loss, is perhaps the single most important tool in economic decision making. While more complex tools exist and are important, the metrics listed above are ubiquitous in part due to their simplicity. The main weakness of the single-number approach is the potential for oversimplification. For example, PGW does not consider nonlinear effects such as climate tipping points, which could profoundly and dangerously affect the climate [31]. Neglect of tipping points is limitation of PGW and other metrics like GWP and the social cost of carbon [27, 32].

In conclusion, we suggest future work use PGW when a single number is needed to characterize the climate impacts of SLCPs. Potential cases where PGW could be useful include work where step function metrics are commonly used today, such as regulatory/policy analysis and emissions reporting. For general purposes, we recommend accounting for climate impacts from methane emissions using the base case discount rate of 2.5%, corresponding to methane PGW_{2.5%} = 50. For specific applications, users can select other discount rates, resulting in PGW values that differ slightly from the base case. For example, the methane PGW could be determined using the 2% discount rate recently proposed in academic work (PGW_{2%} = 44) or using the 3% discount rate traditionally considered in climate policy (PGW_{3%} = 55).

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

The authors would like to thank Steve Hamburg, Illisa Ocko, Sam Abernethy, Kate Konschnik, Billy Pizer, and Roger Cooke for useful discussion during the preparation of this manuscript.

ORCID iDs

Andrew E Pomerantz  https://orcid.org/0000-0003-2639-2682
Robert I. Kleinberg  https://orcid.org/0000-0002-3167-0176

References

[1] Dreyfus G B, Xu Y, Shindell D T, Zaelke D and Ramana M V 2022 Mitigating climate disruption in time: a self-consistent approach for avoiding both near-term and long-term global warming Proc. Natl Acad. Sci. 119 e212536119
[2] Klimont Z and Shindell D 2017 Bridging the gap—the role of short-lived climate pollutants The Emissions Gap Report 2017 United Nations Environment Programme
[3] Masson-Delmotte V et al (ed) 2021 IPCC Climate Change 2021 The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press) (https://doi.org/10.1017/9781009157896)
[4] Balcombe P, Speirs J F, Brandon N P and Hawkes A D 2018 Methane emissions: choosing the right climate metric and time horizon Environ. Sci. Process. Impacts 20 1323–39
[5] Shindell D, Dorfberf-Parnell N, Brauer M, Haines A, Kuylenstierna J C I, Leonard S A, Ramanathan V, Ravishankara A, Amann M and Srivastava L 2017 A climate policy pathway for near- and long-term benefits Science 356 493–4
[6] Ocko I B, Sun T, Shindell D, Oppenheimer M, Hristov A N, Pacala S W, Maier-Reimer E, Xu Y and Hamburg S P 2021 Acting rapidly to deploy readily available methane mitigation measures by sector can immediately slow global warming Environ. Res. Lett. 16 050402
[7] Houghton J, Jenkins G and Ephraums J 1990 Climate Change: The IPCC Scientific Assessment (available at: www.ipcc.ch/site/assets/uploads/2018/05/ipcc_90_92_assessments_far_front_matters.pdf)
[8] Ocko I B, Hamburg S P, Jacob D J, Keith D W, Keohane N O, Oppenheimer M, Roy-Mayhew J D, Schrag D P and Pacala S W 2017 Unmask temporal trade-offs in climate policy debates Science 356 492–3
[9] IPCC IPCC expert meeting on the science of alternative metrics 2009
[10] Cain M, Lynch J, Allen M R, Fuglestvedt J S, Frame D J and Macey A H 2019 Improved calculation of warming-equivalent emissions for short-lived climate pollutants npj Clim. Atmos. Sci. 2 29
[11] Kleinberg R L 2020 The global warming potential misrepresents the physics of global warming thereby misleading policy makers EarthArXiv (https://doi.org/10.31223/XSP88D)
[12] Smith S M, Lowe J A, Bowerman N H A, Gohar L K, Huntingford C and Allen M R 2012 Equivalence of greenhouse-gas emissions for peak temperature limits Nat. Clim. Change 2 535–8
[13] Sarofim M C and Giordano M R 2018 A quantitative approach to evaluating the GWP timescale through implicit discount rates Earth Syst. Dyn. 9 1013–24
[14] Allen M R, Fuglestvedt J S, Shine K P, Reisinger A, Pfefferhubert R T and Forster P M 2016 New use of global warming potentials to compare cumulative and short-lived climate pollutants Nat. Clim. Change 6 773–8
[15] Abernethy S and Jackson R B 2022 Global temperature goals should determine the time horizons for greenhouse gas emission metrics Environ. Res. Lett. 17 024019
[16] Shine K P, Fuglestvedt J S, Hailmeram K and Stuber N 2005 Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases Clim. Change 68 281–302
[17] O’Neill B C 2000 The jury is still out on global warming potentials Clim. Change 44 427–43
[18] Shine K P, Berntsen T, Fuglestvedt J S, Skeie R and Stuber N 2007 Comparing the climate effect of emissions of short- and long-lived climate agents Phil. Trans. A 365 1903–14
[19] Tol R J, Berntsen T K, O’Neill B C, Fuglestvedt J S and Shine K P 2012 A unifying framework for metrics for
aggregating the climate effect of different emissions Environ. Res. Lett. 7 044006

[20] Roy M, Edwards M R and Trancik J E 2013 Methane mitigation timelines to inform energy technology evaluation Environ. Res. Lett. 10 114024

[21] Shindell D T, Fuglestvedt J S and Collins W J 2017 The social cost of methane: theory and applications Faraday Discuss. 200 429–51

[22] Bauer M D and Rudebusch R D 2021 The rising cost of climate change: evidence from the bond market; federal reserve bank of San Francisco working paper 2020–25

[23] Shine K P 2009 The global warming potential—the need for an interdisciplinary retrial Clim. Change 96 467–72

[24] Circular A-4 2003 Office of Management and Budget (available at: www.whitehouse.gov/wp-content/uploads/legacy_drupal_files/omb/circulars/A4/a-4.pdf)

[25] Rennert K and Kingdon C 2019 Social cost of carbon 101 resources for the future (available at: www.rff.org/publications/explainers/social-cost-carbon-101/)

[26] Interagency working group on social cost of greenhouse gases, US Government 2016 Addendum to technical support document on social cost of carbon for regulatory impact analysis under executive order 12866: application of the methodology to estimate the social cost of methane and the social cost of nitrous oxide (available at: www.whitehouse.gov/wp-content/uploads/2021/02/TechnicalSupportDocument_SocialCostOfCarbonMethaneNitrousOxide.pdf)

[27] Rennert K et al 2022 Comprehensive evidence implies a higher social cost of CO2 Nature 610 687–92

[28] Balcombe P, Heggo D A and Harrison M 2022 Total methane and CO2 emissions from liquefied natural gas carrier ships: the first primary measurements Environ. Sci. Technol. 56 9632–40

[29] Peters G, Aamaas B, Lund M, Solli C and Fuglestvedt J 2011 Alternative “global warming” metrics in life cycle assessment: a case study with existing transportation data Environ. Sci. Technol. 45 8633–41

[30] Neubauer S C and Megonigal J P 2015 Moving beyond global warming potentials to quantify the climatic role of ecosystems Ecosystems 18 1000–13

[31] Armstrong Mckay D I, Staal A, Abrams J F, Winkelmann R, Sakschewski B, Loriani S, Fetzer I, Cornell S E, Rockström J and Lenton T M 2022 Exceeding 1.5 °C global warming could trigger multiple climate tipping points Science 377 6611

[32] Dietz S, Rising J, Stoerk T and Wagner G 2021 Economic impacts of tipping points in the climate system Proc. Natl Acad. Sci. 118 e2103081118