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A new use of Global Warming Potentials to relate the impacts of cumulative and short-lived climate pollutants

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Parties to the United Nations Framework Convention on Climate Change (UNFCCC) have requested guidance on common greenhouse gas metrics in accounting for Nationally Determined Contributions (NDCs) to emission reductions[1]. Metric choice can affect the relative emphasis placed on reductions of 'cumulative climate pollutants' like carbon dioxide (CO_2) versus 'Short-Lived Climate Pollutants' (SLCPs) including methane and black carbon[2,3,4,5,6]. Here we show that the widely used 100-year Global Warming Potential (GWP_{100}) effectively measures relative impact of both cumulative pollutants and SLCPs on realised warming 20-40 years after the time of emission. If the overall goal of climate policy is to limit peak warming, GWP_{100} therefore overstates the importance of current SLCP emissions unless stringent and immediate reductions of all climate pollutants result in temperatures nearing their peak soon after mid-century[7,8,9,10] which may be necessary to limit warming to "well below 2 ^{o}C".[1] The GWP_{100} can be used to approximately equate a one-off pulse emission of a cumulative pollutant and an indefinitely sustained change in the rate of emission of an SLCP[11,12,13]. The climate implications of traditional "CO_2-equivalent" targets are ambiguous unless contributions from cumulative pollutants and SLCPs are specified separately.

Establishing policy priorities and market-based emission reduction mechanisms involving different climate forcing agents all require some way of measuring what one forcing agent is 'worth' relative to another. The GWP_{100} metric has been widely used for this purpose for over 20 years, notably within the UNFCCC and its Kyoto Protocol. It represents the time-integrated climate forcing (perturbation to the Earth's balance between incoming and outgoing energy) due to a one-off pulse emission of one tonne of a greenhouse gas over the 100 years following its emission, relative to the corresponding impact of a one tonne pulse emission of CO_2. The notion of a temporary emission pulse is itself a rather artificial construct: it could also be interpreted as the impact of a delay in reducing the rate of emission of a greenhouse gas (see Methods).

This focus on climate forcing and 100-year time-horizon in GWP_{100} has no particular justification either for climate impacts or for the policy goals of the UNFCCC, which focus on limiting peak warming, independent of timescale. While it could be argued that, given current rates of warming, the goal of the Paris Agreement[1] to limit warming to "well below 2 °C" focuses attention on mitigation outcomes over the next few decades, this focus is only implicit and presupposes that this goal will actually be met. Individual countries may also have goals to limit climate impacts in the shorter term. These are acknowledged by the UNFCCC, but not quantified in terms of, for example, a target maximum warming rate. Metric choice is particularly important when comparing CO_2 emissions with SLCPs such as methane and black carbon aerosols. Black carbon has only recently been introduced into a few intended NDCs[14] but may become increasingly prominent as some early estimates[15] assign it a very high GWP_{100}, even though the net climatic impact of processes that generate black carbon emissions remains uncertain[16] and policy interventions to reduce black carbon emissions are likely to impact[6] other forms of pollution as well. Here we combine the climatic impact of black carbon with that of reflective organic aerosols using forcing estimates from ref. 16 (see Methods).

At least one party to the UNFCCC has argued[17] that using the alternative Global Temperature-change Potential (GTP) metric would be more consistent with the UNFCCC goal of limiting future warming. In its most widely used "pulse" variant[2], the GTP represents the impact of the emission of one tonne of a greenhouse gas on global average surface temperatures at a specified point in time after emission[18], again relative to the corresponding impact of the emission of one tonne of CO_2. Figure 1 shows how both GTP and GWP values for SLCPs like methane and black carbon depend strongly on the time-horizon. For long time-horizons, SLCP GTP values also depend on the response time of the climate system, which is uncertain[19,20]. This latter uncertainty is a real feature of the climate response that is not captured by GWP, and so is not itself a reason to choose GWP over GTP. Other metrics and designs of multi-gas polices have been proposed[21,22], some of which can be shown to be approximately equivalent to GWP or GTP[23], but since only GWP and GTP have been discussed in the context of the UNFCCC, we focus on these here.

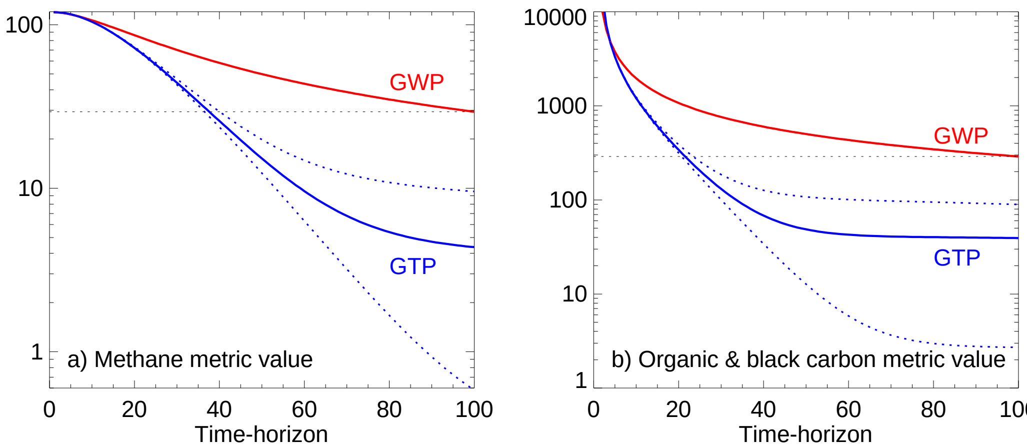

Figure 1: Values of Global Warming Potential (red) and Global Temperature-change Potential (blue) for methane and combined organic and black carbon as a function of time-horizon. Solid lines show metrics calculated using current IPCC response functions[16]; dotted blue lines show impact of varying the climate

response time (see Methods Summary). Black dotted lines show the value of GWP_{100}.

For any time horizon longer than 10 years, values of the GTP are lower than corresponding values of the GWP for SLCPs. The time-horizon has, however, a different meaning between the two metrics: for GWP it represents the time over which climate forcing is integrated, while for GTP it represents a future point in time at which temperature change is measured. Hence there is no particular reason to compare GWP and GTP values for the same time-horizon. Indeed, figure 1 shows that the value of GWP_{100} is equal to the GTP with a time-horizon of about 40 years in the case of methane, and 20-30 years in the case of black carbon, given the climate system response-times used in ref. 16, for reasons given in the Methods.[24] Values of GWP and GTP for cumulative pollutants like nitrous oxide (N_2O) or sulphur hexafluoride (SF_6) are determined primarily by forcing efficiencies, not lifetimes, and are hence similar to each other and almost constant over all these time-horizons.[16] So for a wide range of both cumulative and short-lived climate pollutants, GWP_{100} is very roughly equivalent to $GTP_{20\text{-}40}$ when applied to an emission pulse, making it an approximate indicator of the relative impact of a one-off pulse emission of a tonne of greenhouse gas or other climate forcing agent on global temperatures 20-40 years after emission. The inclusion of feedbacks between warming and the carbon cycle can substantially increase GTP (and also, to a lesser degree, GWP) values, particularly on century timescales[25]. Here we follow the traditional approach, used for the most widely-quoted metric values in ref. 16, of including these feedbacks in modelling CO_2 but not other gases.

Figure 2, panel a, shows the impact on global average temperature of a pulse emission of various climate pollutants, with the size of the pulse of each gas being 'equivalent' (in terms of GWP_{100}) to total anthropogenic CO_2 emissions in 2011 (38 $GtCO_2$): hence the pulse size is $38/GWP_{100}$ billion tonnes of each forcing agent. SLCPs with high radiative efficiencies, like methane, black carbon and some HFCs, have a more immediate impact on global temperatures than notionally equivalent emissions of CO_2, and less impact after 20-40 years. Hence, if the primary goal of climate policy is to limit peak warming, then given the time likely to be required to reduce net global CO_2 emissions to zero to stabilise temperatures, the conventional use of GWP_{100} to compare pulse emissions of CO_2 and SLCPs is likely to overstate the importance of SLCPs for peak warming until global CO_2 emissions are falling.[7,8]

This is not an argument for delay in SLCP mitigation[26] – the benefits to human health and agriculture alone would justify many proposed SLCP mitigation measures[4] – but it is an argument for clarity in what immediate SLCP reductions may achieve for global climate. The use of GWP_{100} to compare emission pulses might still be appropriate to other policy goals, such as limiting the rate of warming over the coming decades, although the impact of policies on warming rates even over multi-decade timescales should always be considered in the context of internal climate variability.[27] Some contributions to the rate of sea-level-rise also scale with integrated climate forcing.[22]

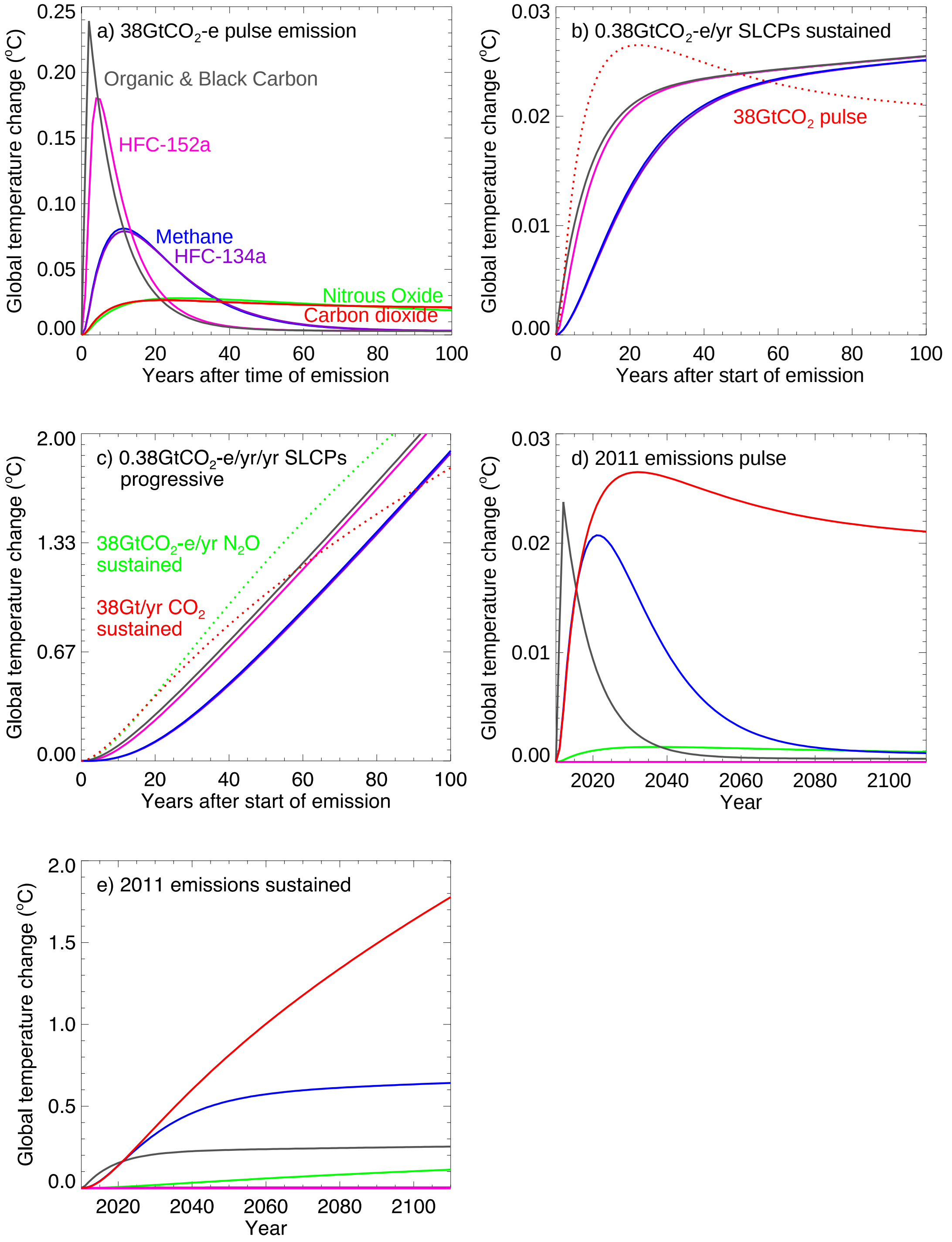

Figure 2: Impact of pulse versus sustained emissions of various climate forcing agents on global average temperatures. Colours indicate different greenhouse gases, with grey line indicating combined impact of reflective organic and black carbon aerosols (see Methods) a) Warming caused by a pulse emission in 2011 with each pulse size being nominally equivalent, using GWP_{100}, to 2011 emissions of CO_2. b) Solid lines: impact of sustained emissions of SLCPs at a rate equivalent to 2011 emissions of CO_2 spread over the 100-year GWP_{100} time horizon. Dotted line shows impact of pulse emission of CO_2 reproduced from (a). c) Solid lines: impact of SLCP emissions progressively increasing from zero at 0.38 $GtCO_2$-e yr^{-2}. Dotted lines: impact of sustained emissions of CO_2 and N_2O at

38 $GtCO_2$ (or equivalent) per year. d) Impact of actual 2011 emissions of each climate forcing agent expressed as a pulse. e) Impact of emissions sustained indefinitely at 2011 rates.

Simply adopting a different metric that assigns a lower weight to SLCP emissions, such as GTP_{100}, does not solve this overstatement problem, since any metric that correctly reflects the impact of SLCPs on temperatures 100 years in the future would understate their impact, relative to notionally equivalent quantities of CO_2, on all shorter timescales. Any choice of metric to compare pulse emissions of cumulative and short-lived pollutants contains a choice of time horizon[16,18]. It is, however, important for policy-makers to be clear about the time-horizon they are focussing on. One problem with the GWP_{100} metric is that "warming" may be interpreted colloquially to mean "temperature rise by a point in time", making the name misleading, because, in the case of SLCPs, GWP_{100} actually delineates impact on temperatures in 20-40 years, not 100 years.

Figure 2b suggests an alternative way of using GWP_{100} to express equivalence between cumulative and short-lived climate pollutants that is valid over a wider range of time-scales, suggesting a way to use GWP_{100} to reconcile the "emission metrics" literature[2,3] with the "carbon budget" approach[9]. The solid lines show the impact on global temperatures of a *sustained* emission of 38 $GtCO_2$-equivalent (again computed using GWP_{100}) of the short-lived climate pollutants shown in 2a, but now starting abruptly in year 1 and distributed evenly over the GWP time-horizon: hence a sustained emission rate of $38/(H\times GWP_{100})$ billion tonnes per year, where H=100 years. These cause temperatures to increase and then approach stabilization after 20-40 years, depending on their lifetimes. The dotted line shows the impact of a *pulse* emission of 38 $GtCO_2$ in year one, reproduced from 2a. The correspondence between these temperature responses is not exact, but much better than in 2a, at least over timescales from 30 to 100 years.

The reason is simple: a pulse emission of an infinite-lifetime gas and a sudden step change in the sustained rate of emission of a very-short-lifetime gas both give a near-constant radiative forcing. If the total quantities emitted of both gases over the 100-year GWP time-horizon is the same in terms of GWP_{100}, then the size of this radiative forcing, and hence the temperature response, will be identical (see Methods for a more formal derivation). The solid and dotted lines in figure 2b do not coincide exactly because CO_2 is not simply an infinite-lifetime gas, nor are the lifetimes of methane or black carbon completely negligible, although the effective residence times of CO_2 and these SLCPs are, crucially, much longer and much shorter, respectively, than the 100-year GWP time horizon.

A corollary is that a *sustained* step-change in the rate of emission of a cumulative pollutant such as CO_2 is approximately equivalent to a *progressive* linear increase or decrease in the rate of emission of an SLCP. This is illustrated in figure 2c, which compares the impact of a sustained emission of 38 Gt per year of CO_2 emissions (red dotted line) with SLCP emissions increasing from zero at a rate of

0.38 $GtCO_2$-e per year per year (solid lines). Again, although the correspondence is not exact, it is much better than the nominally equivalent emission pulses in 2a. The green dotted line shows that sustained emissions of cumulative pollutants (N_2O and CO_2) have similar impacts on these timescales. Finally, a *progressive* change in the rate of emission of CO_2, necessary to reach net zero[10] CO_2 emissions to stabilise temperatures, could only be equated to an *accelerating* change in SLCP emissions. This last equivalence is somewhat moot because attempting to match the rates of reduction of CO_2 emissions[28] required to limit warming to 2 °C would result in SLCP emissions soon having to be reduced below zero. In summary, therefore, a pulse (or sustained) emission of a cumulative pollutant may be approximately equivalent to a sustained (or progressively increasing) change in the rate of emission of an SLCP, but there is no substitute for a progressive reduction in the rate of emission a cumulative pollutant such as CO_2, which remains the *sine qua non* of climate stabilisation.

This correspondence between pulse emissions of cumulative pollutants and sustained emissions of short-lived pollutants (or the benefits of corresponding emissions reductions) has been noted before[7,8,11,12,13], but previous studies suggested that a new metric of sustained emission reductions would be required to relate them. Figure 2b suggests that the familiar GWP_{100} might still be adequate for this purpose, provided it is used to relate sustained reductions in emission rates of SLCPs (agents with lifetimes much shorter than the GWP time-horizon) with temporarily avoided emissions of cumulative climate pollutants (any with lifetimes substantially longer than the GWP time-horizon).

There are obvious challenges to incorporating this second use of GWP_{100} into the UNFCCC process. The Kyoto Protocol and most emissions trading schemes are predicated on emissions accounting over fixed commitment periods. Although possible in the new, more flexible, NDC framework, equating an open-ended commitment to a permanent reduction in an SLCP emission rate with actual avoided emissions of a cumulative pollutant within a commitment period would be a significant policy innovation. Nevertheless, this approximate equivalence may be useful in setting national or corporate climate policy priorities, particularly where decisions involve capital investments committing future emissions[13].

This second use of GWP_{100} is also relevant to the long-term goal in the Paris Agreement "to achieve a balance between anthropogenic emissions by sources and removals by sinks" in order to hold the increase in the global average temperature to well below 2°C above pre-industrial levels. Peak warming scales approximately with cumulative CO_2 and N_2O emissions (expressed as $GtCO_2$-e using GWP_{100}) between now and the time of peak warming plus the sustained rate of emission of SLCPs (expressed in $GtCO_2$-e/H per year, with H=100 years if GWP_{100} is used to define $GtCO_2$-e) in the decades immediately prior to peak warming. So a sustained emission rate of 0.01 tonnes per year of methane has the same impact on peak warming as a pulse of 28 tonnes of CO_2 released at any time between now and when temperatures peak, GWP_{100} of methane being 28. As NDCs are updated, it would be useful for countries to clarify how they propose to balance (individually or collectively) cumulative emissions of CO_2 and N_2O as these are reduced to zero or below with future emission rates of SLCPs.

Figure 2d shows the impact on global temperatures of actual 2011 emissions of various climate pollutants, considered as a one-year emission pulse.[16] Methane and black carbon emissions in 2011 have a comparable or even larger impact on global temperatures over the next couple of decades than 2011 CO_2 emissions, but their impact rapidly decays, while the impact of current CO_2 emissions persists throughout the 21st century and for many centuries beyond.

Figure 2e shows the impact of 2011 emissions of various climate pollutants, assuming these emissions are maintained at the same level for the next 100 years. The warming impact of the cumulative pollutants, CO_2 and nitrous oxide, increases steadily as long as these emissions persist, while sustained emissions of methane and organic and black carbon aerosols cause temperatures to warm rapidly at first and then stabilize. A permanent reduction of 50-75% in these SLCPs could reduce global temperatures by over 0.5°C by mid-century[4], comparable to the impact on these timescales of similar-magnitude reductions of CO_2 emissions and, it has been argued, at much lower cost[4,5,29]. Stabilising global temperatures, however, requires net emissions of cumulative pollutants, predominantly CO_2, to be reduced to zero.

The notion of 'CO_2-equivalent' pulse emissions of cumulative and short-lived climate pollutants will always be ambiguous because they act to warm the climate system in fundamentally different ways. To date, this ambiguity may have had only a limited impact, not least because emission reductions have so far been relatively unambitious. As countries with relatively large agricultural emissions of methane and significant black carbon emissions begin to quantify their contributions to the UNFCCC, and as the stringency of commitments increases consistent with the collective goal of limiting warming to "well below" 2°C, this situation may change[21,30].

For their long-term climate implications to be clear, policies and Nationally Determined Contributions need to recognise these differences. GWP_{100} can be used in the traditional way, comparing pulse emissions of different greenhouse gases, to specify how mitigation of both short-lived and cumulative climate pollutants may reduce the rate and magnitude of climate change over the next 20-40 years, but only over that time. To achieve a balance between sources and sinks of greenhouse gases in the very long term, net emissions of cumulative pollutants such as CO_2 need to be reduced to zero, while emissions of SLCPs simply need to be stabilised. GWP_{100} can again be used, but in the second way identified here, to relate cumulative (positive and negative) emissions of CO_2 until these reach zero with future emission rates of SLCPs, particularly around the time of peak warming. Some NDCs are already providing a breakdown in terms of cumulative and short-lived climate pollutants, or differential policy instruments for different forcing agents[30] and different timescales, all of which is needed for their climatic implications to be clear. The Paris Agreement proposes that Parties will report emissions and removals using common metrics, but a generic 'CO_2-equivalent' emission reduction target by a given year, defined in terms of GWP_{100} and containing a substantial element of SLCP mitigation, represents an ambiguous commitment to future climate. The conventional use of GWP_{100} to compare pulse emissions of all gases is an effective metric to limit peak warming if and only if emissions of all climate pollutants, most notably CO_2, are being reduced such that temperatures are expected to stabilise within the next 20-40 years. This expected time to peak warming will only become clear when CO_2 emissions are falling fast enough to observe the response. Until that time, the only coherent comparison is between pulse emissions of CO_2, N_2O and other cumulative pollutants and permanent changes in the rates of emissions of SLCPs.

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Methods

The equality of GWP_{100} and $GTP_{20\text{-}40}$ follows from the idealised expressions for GWP and GTP for a pulse emission given in ref. 2 (equations A1 and 3 in ref. 2, expressed as relative GWP and GTP respectively, and with decay-times replaced by decay rates):

$$\mathrm{GWP}_H = \frac{\frac{F_1}{k_1}\left(1-e^{-k_1 H}\right)}{\frac{F_0}{k_0}\left(1-e^{-k_0 H}\right)} \tag{1}$$

and

$$\mathrm{GTP}_{H'} = \frac{\frac{F_1}{(k_1-k_T)}\left(e^{-k_T H'}-e^{-k_1 H'}\right)}{\frac{F_0}{(k_T-k_0)}\left(e^{-k_0 H'}-e^{-k_T H'}\right)} \tag{2}$$

where F_1 is the instantaneous forcing per unit emission and k_1 the concentration decay rate for a greenhouse gas, with F_0 and k_0 the corresponding parameters for a reference gas, k_T is a typical thermal adjustment rate of the ocean mixed layer in response to forcing, and H and H' are the GWP and GTP time-horizons. For a very short-lived greenhouse gas and very long-lived reference gas such that $k_1 H \gg 1$, $k_1 H' \gg 1$, $k_0 H \ll 1$, $k_0 H' \ll 1$ and $k_1 \gg k_T \gg k_0$, the terms in parentheses in the numerator and denominator of equations (1) and (2) are approximately unity, $k_0 H$, $e^{-k_T H'}$ and $\left(1-e^{-k_T H'}\right)$respectively. Hence, using $k_1 - k_T \approx k_1$ and $k_T - k_0 \approx k_T$, we have

$$\mathrm{GWP}_H \approx \frac{F_1}{F_0 k_1 H} \quad \text{and} \quad \mathrm{GTP}_{H'} \approx \frac{F_1 k_T}{F_0 k_1\left(e^{k_T H'}-1\right)}$$

so GWP_H equals $\mathrm{GTP}_{H'}$ if $H' = \ln(1 + H k_T)/k_T$, or 21 years if $H = 100$ years and $k_T = (8.4\ \text{years})^{-1}$, as in ref. 16. Hence in the limit of a very short-lived gas and infinitely persistent reference gas, the GTP for a pulse emission evaluated at 21 years will be equal to the GWP_{100}. The expression becomes more complicated if $k_1 H' \approx 1$ as is the case of methane, but this limiting case serves to show that the equality of GWP_{100} and $GTP_{20\text{-}40}$ arises primarily from the thermal adjustment time of the climate system.

The approximate equivalence of the temperature response to a one-tonne transitory pulse emission of a cumulative pollutant to sustained step-change in the rate of emission of an SLCP by $1/(H \times \mathrm{GWP}_H)$ tonnes per year, where H is the GWP time horizon, follows from the cumulative impact of CO_2 emissions on global temperatures. This means that the temperature response at a time H after a unit pulse emission of CO_2 ($\mathrm{AGTP_P}(CO_2)$ in ref. 2), multiplied by H, is approximately equal to the response after time H to a one-unit-per-year sustained emission of CO_2 ($\mathrm{AGTP_S}(CO_2)$), provided H is shorter than the effective atmospheric residence time of CO_2, which is of order millennia This is consistent with the concept of the "trillionth tonne" – that it is the cumulative amount of CO_2 that is emitted, rather than when it is emitted, that matters most for future climate[9]. Ref. 2 also notes that the ratio $\mathrm{AGTP_S}(x)/\mathrm{AGTP_S}(CO_2)$ is approximately equal to $\mathrm{GWP}_H(x)$ for time horizons H much longer than the lifetime of an agent x. Hence:

$$\mathrm{AGTP_S}(x) \approx \mathrm{GWP}_H(x) \times \mathrm{AGTP_S}(\mathrm{CO_2}) \approx \mathrm{GWP}_H(x) \times H \times \mathrm{AGTP_P}(\mathrm{CO_2}) \qquad (3)$$

provided H is shorter than the effective residence time of CO_2 and longer than the lifetime of the agent x, as is the case when H=100 years and x is an SLCP.

The interpretation of an "avoided emission pulse", although central most emission trading schemes, may be ambiguous in the context of many mitigation decisions, which may involve policies resulting in permanent changes in emission rates. Another way of expressing this notion of an 'avoided pulse' is in terms of the impact of delay in reducing emissions of cumulative pollutants: a five year delay in implementing a one-tonne-per-year reduction of CO_2 emissions would need to be compensated for by a permanent reduction of $5/(100 \times 28) = 1.8 \times 10^{-3}$ tonnes-per-year of methane (GWP_{100} of methane being 28). This would only compensate for the direct impact of the delay in CO_2 emission reductions, not for additional committed future CO_2 emissions that might also result from that delay.[28]

Treatment of Black Carbon emissions: Focusing solely on absorbing aerosols gives a high estimated 'radiative efficiency' (impact on the global energy budget per unit change in atmospheric concentration) for black carbon, a strong positive global climate forcing[15] (1.1 W m^{-2} in 2011) and a GWP_{100} of 910. This figure has been argued[16] to be too high, and the actual radiative impact of individual black carbon emissions depends strongly on the circumstances (location, season and weather conditions) at the time of emission. Many processes that generate black carbon also generate reflective organic aerosols, which have a cooling effect on global climate. Although ratios vary considerably across sources, policy interventions to limit black carbon emissions are likely also to affect these other aerosols, so it might be more relevant to consider their combined impact: the current best estimate[16] net global radiative forcing of organic and black carbon aerosols in 2011 was 0.35 W m^{-2}, giving a combined GWP_{100} of 290, used in the figures. Combined emissions of organic and black carbon aerosols are inferred from this GWP_{100} value assuming all radiative forcing resulting from these emissions is concentrated in the first year (i.e. a lifetime much shorter than one year). This is only one estimate of a very uncertain quantity: when both reflection and absorption are taken into account, including interactions between aerosols and clouds and surface albedo, even the sign of the net radiative impact of the processes that generate black carbon aerosols remains uncertain.

Modelling details: Figure 1: GWP values calculated using current IPCC methane and CO_2 impulse response functions without carbon cycle feedbacks.[16] Radiative forcing (RF) of a pulse emission of organic and black carbon aerosols concentrated in year 1, scaled to give a net GWP_{100} of 290, consistent with ratio of 2011 RF values given in refs. 15 and 16. GTP values calculated using the standard IPCC AR5 thermal response model (solid blue lines) with coefficients adjusted (dotted blue lines) to give Realised Warming Fractions[24] (ratio of Transient Climate Response, TCR, to Equilibrium Climate Sensitivity, ECS) of 0.35 and 0.85, spanning the range of uncertainty around the best-estimate value of 0.56. Figure 2: As figure 1 with radiative efficiencies and lifetimes provided in Table A.8.1 of ref. 16 and representative mid-range values of TCR=1.5^{o}C and ECS=2.7^{o}C.

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