New use of global warming potentials to compare cumulative and short-lived climate pollutants

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6 **A new use of Global Warming Potentials to relate the impacts of cumulative**
7 **and short-lived climate pollutants**
8
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11
12 **Parties to the United Nations Framework Convention on Climate Change**
13 **(UNFCCC) have requested guidance on common greenhouse gas metrics in**
14 **accounting for Nationally Determined Contributions (NDCs) to emission**
15 **reductions[1]. Metric choice can affect the relative emphasis placed on**
16 **reductions of 'cumulative climate pollutants' like carbon dioxide (CO_2)**
17 **versus 'Short-Lived Climate Pollutants' (SLCPs) including methane and**
18 **black carbon[2,3,4,5,6]. Here we show that the widely used 100-year Global**
19 **Warming Potential (GWP_{100}) effectively measures relative impact of both**
20 **cumulative pollutants and SLCPs on realised warming 20-40 years after the**
21 **time of emission. If the overall goal of climate policy is to limit peak**
22 **warming, GWP_{100} therefore overstates the importance of current SLCP**
23 **emissions unless stringent and immediate reductions of all climate**
24 **pollutants result in temperatures nearing their peak soon after mid-**
25 **century[7,8,9,10] which may be necessary to limit warming to "well below 2**
26 **ºC".[1] The GWP_{100} can be used to approximately equate a one-off pulse**
27 **emission of a cumulative pollutant and an indefinitely sustained change in**
28 **the rate of emission of an SLCP[11,12,13]. The climate implications of**
29 **traditional "CO_2-equivalent" targets are ambiguous unless contributions**
30 **from cumulative pollutants and SLCPs are specified separately.**
31
32 Establishing policy priorities and market-based emission reduction mechanisms
33 involving different climate forcing agents all require some way of measuring
34 what one forcing agent is 'worth' relative to another. The GWP_{100} metric has
35 been widely used for this purpose for over 20 years, notably within the UNFCCC
36 and its Kyoto Protocol. It represents the time-integrated climate forcing
37 (perturbation to the Earth's balance between incoming and outgoing energy)
38 due to a one-off pulse emission of one tonne of a greenhouse gas over the 100
39 years following its emission, relative to the corresponding impact of a one tonne
40 pulse emission of CO_2. The notion of a temporary emission pulse is itself a rather
41 artificial construct: it could also be interpreted as the impact of a delay in
42 reducing the rate of emission of a greenhouse gas (see Methods).
43
44 This focus on climate forcing and 100-year time-horizon in GWP_{100} has no
45 particular justification either for climate impacts or for the policy goals of the
46 UNFCCC, which focus on limiting peak warming, independent of timescale. While

47 it could be argued that, given current rates of warming, the goal of the Paris
48 Agreement[1] to limit warming to "well below 2 °C" focuses attention on mitigation
49 outcomes over the next few decades, this focus is only implicit and presupposes
50 that this goal will actually be met. Individual countries may also have goals to
51 limit climate impacts in the shorter term. These are acknowledged by the
52 UNFCCC, but not quantified in terms of, for example, a target maximum warming
53 rate. Metric choice is particularly important when comparing CO_2 emissions with
54 SLCPs such as methane and black carbon aerosols. Black carbon has only
55 recently been introduced into a few intended NDCs[14] but may become
56 increasingly prominent as some early estimates[15] assign it a very high GWP_{100},
57 even though the net climatic impact of processes that generate black carbon
58 emissions remains uncertain[16] and policy interventions to reduce black carbon
59 emissions are likely to impact[6] other forms of pollution as well. Here we combine
60 the climatic impact of black carbon with that of reflective organic aerosols using
61 forcing estimates from ref. 16 (see Methods).
62
63 At least one party to the UNFCCC has argued[17] that using the alternative Global
64 Temperature-change Potential (GTP) metric would be more consistent with the
65 UNFCCC goal of limiting future warming. In its most widely used "pulse" variant[2],
66 the GTP represents the impact of the emission of one tonne of a greenhouse gas
67 on global average surface temperatures at a specified point in time after
68 emission[18], again relative to the corresponding impact of the emission of one
69 tonne of CO_2. Figure 1 shows how both GTP and GWP values for SLCPs like
70 methane and black carbon depend strongly on the time-horizon. For long time-
71 horizons, SLCP GTP values also depend on the response time of the climate
72 system, which is uncertain[19,20]. This latter uncertainty is a real feature of the
73 climate response that is not captured by GWP, and so is not itself a reason to
74 choose GWP over GTP. Other metrics and designs of multi-gas polices have been
75 proposed[21,22], some of which can be shown to be approximately equivalent to
76 GWP or GTP[23], but since only GWP and GTP have been discussed in the context of
77 the UNFCCC, we focus on these here.
78
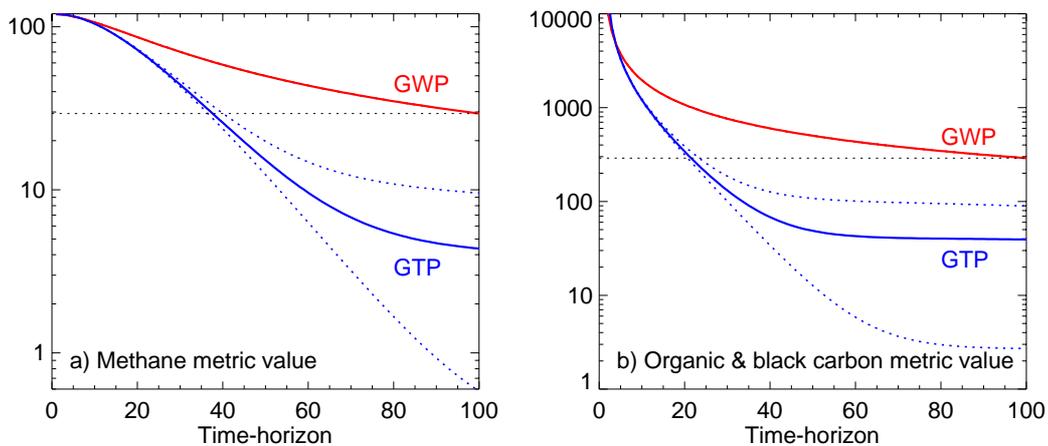
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80 Figure 1: Values of Global Warming Potential (red) and Global Temperature-
81 change Potential (blue) for methane and combined organic and black carbon as a
82 function of time-horizon. Solid lines show metrics calculated using current IPCC
83 response functions[16]; dotted blue lines show impact of varying the climate

84 response time (see Methods Summary). Black dotted lines show the value of
85 GWP_{100}.
86
87 For any time horizon longer than 10 years, values of the GTP are lower than
88 corresponding values of the GWP for SLCPs. The time-horizon has, however, a
89 different meaning between the two metrics: for GWP it represents the time over
90 which climate forcing is integrated, while for GTP it represents a future point in
91 time at which temperature change is measured. Hence there is no particular
92 reason to compare GWP and GTP values for the same time-horizon. Indeed,
93 figure 1 shows that the value of GWP_{100} is equal to the GTP with a time-horizon
94 of about 40 years in the case of methane, and 20-30 years in the case of black
95 carbon, given the climate system response-times used in ref. 16, for reasons
96 given in the Methods.[24] Values of GWP and GTP for cumulative pollutants like
97 nitrous oxide (N_2O) or sulphur hexafluoride (SF_6) are determined primarily by
98 forcing efficiencies, not lifetimes, and are hence similar to each other and almost
99 constant over all these time-horizons.[16] So for a wide range of both cumulative
100 and short-lived climate pollutants, GWP_{100} is very roughly equivalent to GTP_{20-40}
101 when applied to an emission pulse, making it an approximate indicator of the
102 relative impact of a one-off pulse emission of a tonne of greenhouse gas or other
103 climate forcing agent on global temperatures 20-40 years after emission. The
104 inclusion of feedbacks between warming and the carbon cycle can substantially
105 increase GTP (and also, to a lesser degree, GWP) values, particularly on century
106 timescales[25]. Here we follow the traditional approach, used for the most widely-
107 quoted metric values in ref. 16, of including these feedbacks in modelling CO_2 but
108 not other gases.
109
110 Figure 2, panel a, shows the impact on global average temperature of a pulse
111 emission of various climate pollutants, with the size of the pulse of each gas
112 being 'equivalent' (in terms of GWP_{100}) to total anthropogenic CO_2 emissions in
113 2011 (38 $GtCO_2$): hence the pulse size is 38/GWP_{100} billion tonnes of each forcing
114 agent. SLCPs with high radiative efficiencies, like methane, black carbon and
115 some HFCs, have a more immediate impact on global temperatures than
116 notionally equivalent emissions of CO_2, and less impact after 20-40 years. Hence,
117 if the primary goal of climate policy is to limit peak warming, then given the time
118 likely to be required to reduce net global CO_2 emissions to zero to stabilise
119 temperatures, the conventional use of GWP_{100} to compare pulse emissions of CO_2
120 and SLCPs is likely to overstate the importance of SLCPs for peak warming until
121 global CO_2 emissions are falling.[7,8]
122
123 This is not an argument for delay in SLCP mitigation[26] – the benefits to human
124 health and agriculture alone would justify many proposed SLCP mitigation
125 measures[4] – but it is an argument for clarity in what immediate SLCP reductions
126 may achieve for global climate. The use of GWP_{100} to compare emission pulses
127 might still be appropriate to other policy goals, such as limiting the rate of
128 warming over the coming decades, although the impact of policies on warming
129 rates even over multi-decade timescales should always be considered in the
130 context of internal climate variability.[27] Some contributions to the rate of sea-
131 level-rise also scale with integrated climate forcing.[22]
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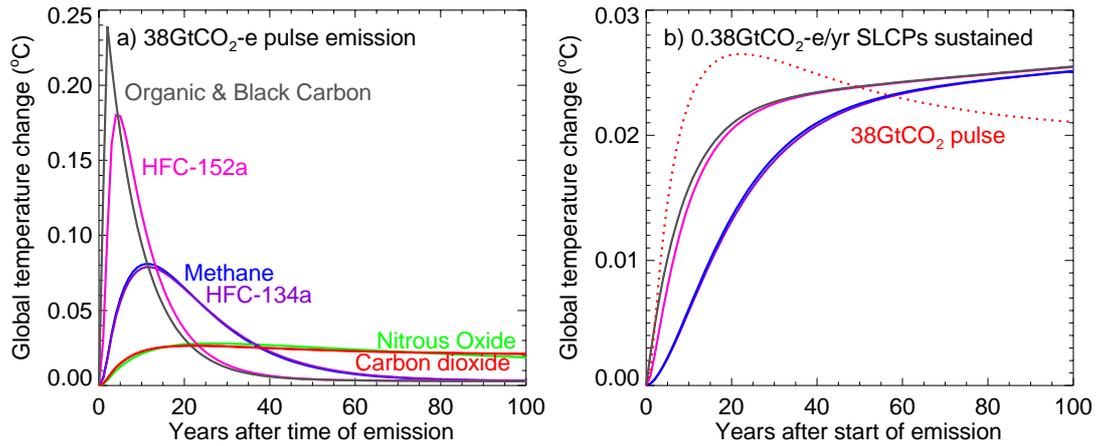
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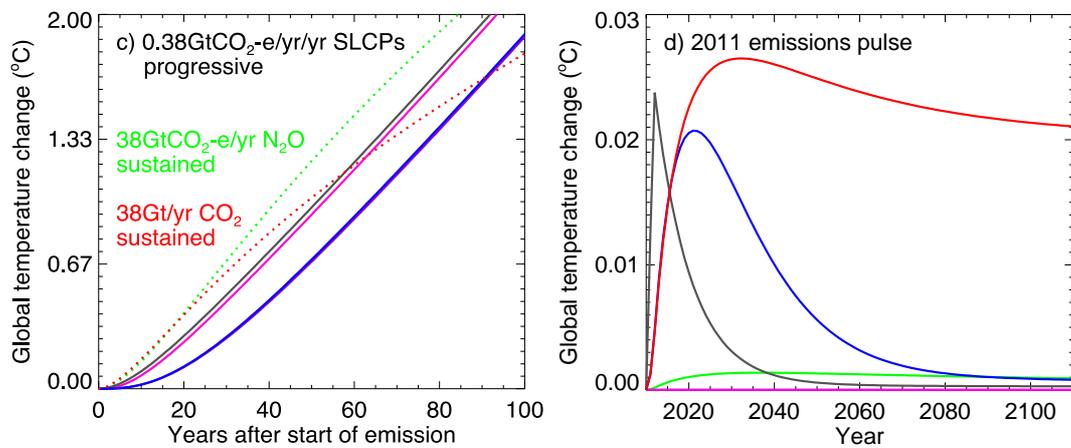
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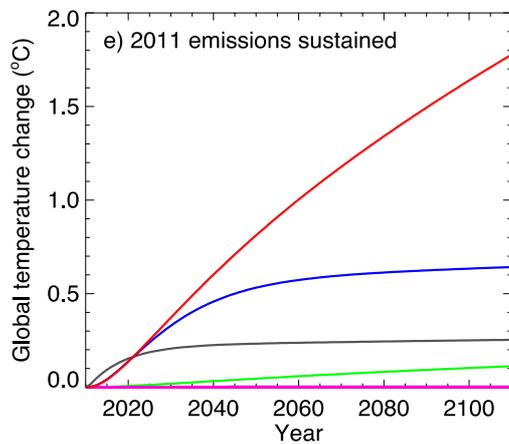
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136 Figure 2: Impact of pulse versus sustained emissions of various climate forcing
137 agents on global average temperatures. Colours indicate different greenhouse
138 gases, with grey line indicating combined impact of reflective organic and black
139 carbon aerosols (see Methods) a) Warming caused by a pulse emission in 2011
140 with each pulse size being nominally equivalent, using GWP_{100}, to 2011
141 emissions of CO_2. b) Solid lines: impact of sustained emissions of SLCPs at a rate
142 equivalent to 2011 emissions of CO_2 spread over the 100-year GWP_{100} time
143 horizon. Dotted line shows impact of pulse emission of CO_2 reproduced from (a).
144 c) Solid lines: impact of SLCP emissions progressively increasing from zero at
145 0.38 $GtCO_2$-e yr^{-2}. Dotted lines: impact of sustained emissions of CO_2 and N_2O at

146   38 GtCO$_2$ (or equivalent) per year. d) Impact of actual 2011 emissions of each
147   climate forcing agent expressed as a pulse. e) Impact of emissions sustained
148   indefinitely at 2011 rates.
149
150   Simply adopting a different metric that assigns a lower weight to SLCP
151   emissions, such as GTP$_{100}$, does not solve this overstatement problem, since any
152   metric that correctly reflects the impact of SLCPs on temperatures 100 years in
153   the future would understate their impact, relative to notionally equivalent
154   quantities of CO$_2$, on all shorter timescales. Any choice of metric to compare
155   pulse emissions of cumulative and short-lived pollutants contains a choice of
156   time horizon[16,18]. It is, however, important for policy-makers to be clear about
157   the time-horizon they are focussing on. One problem with the GWP$_{100}$ metric is
158   that "warming" may be interpreted colloquially to mean "temperature rise by a
159   point in time", making the name misleading, because, in the case of SLCPs,
160   GWP$_{100}$ actually delineates impact on temperatures in 20-40 years, not 100
161   years.
162
163   Figure 2b suggests an alternative way of using GWP$_{100}$ to express equivalence
164   between cumulative and short-lived climate pollutants that is valid over a wider
165   range of time-scales, suggesting a way to use GWP$_{100}$ to reconcile the "emission
166   metrics" literature[2,3] with the "carbon budget" approach[9]. The solid lines show
167   the impact on global temperatures of a *sustained* emission of 38 GtCO$_2$-
168   equivalent (again computed using GWP$_{100}$) of the short-lived climate pollutants
169   shown in 2a, but now starting abruptly in year 1 and distributed evenly over the
170   GWP time-horizon: hence a sustained emission rate of $38/(H \times GWP_{100})$ billion
171   tonnes per year, where H=100 years. These cause temperatures to increase and
172   then approach stabilization after 20-40 years, depending on their lifetimes. The
173   dotted line shows the impact of a *pulse* emission of 38 GtCO$_2$ in year one,
174   reproduced from 2a. The correspondence between these temperature responses
175   is not exact, but much better than in 2a, at least over timescales from 30 to 100
176   years.

177   The reason is simple: a pulse emission of an infinite-lifetime gas and a sudden
178   step change in the sustained rate of emission of a very-short-lifetime gas both
179   give a near-constant radiative forcing. If the total quantities emitted of both
180   gases over the 100-year GWP time-horizon is the same in terms of GWP$_{100}$, then
181   the size of this radiative forcing, and hence the temperature response, will be
182   identical (see Methods for a more formal derivation). The solid and dotted lines
183   in figure 2b do not coincide exactly because CO$_2$ is not simply an infinite-lifetime
184   gas, nor are the lifetimes of methane or black carbon completely negligible,
185   although the effective residence times of CO$_2$ and these SLCPs are, crucially,
186   much longer and much shorter, respectively, than the 100-year GWP time
187   horizon.

188   A corollary is that a *sustained* step-change in the rate of emission of a cumulative
189   pollutant such as CO$_2$ is approximately equivalent to a *progressive* linear increase
190   or decrease in the rate of emission of an SLCP. This is illustrated in figure 2c,
191   which compares the impact of a sustained emission of 38 Gt per year of CO$_2$
192   emissions (red dotted line) with SLCP emissions increasing from zero at a rate of

193 0.38 $GtCO_2$-e per year per year (solid lines). Again, although the correspondence
194 is not exact, it is much better than the nominally equivalent emission pulses in
195 2a. The green dotted line shows that sustained emissions of cumulative
196 pollutants (N_2O and CO_2) have similar impacts on these timescales. Finally, a
197 *progressive* change in the rate of emission of CO_2, necessary to reach net zero[10]
198 CO_2 emissions to stabilise temperatures, could only be equated to an *accelerating*
199 change in SLCP emissions. This last equivalence is somewhat moot because
200 attempting to match the rates of reduction of CO_2 emissions[28] required to limit
201 warming to 2 °C would result in SLCP emissions soon having to be reduced
202 below zero. In summary, therefore, a pulse (or sustained) emission of a
203 cumulative pollutant may be approximately equivalent to a sustained (or
204 progressively increasing) change in the rate of emission of an SLCP, but there is
205 no substitute for a progressive reduction in the rate of emission a cumulative
206 pollutant such as CO_2, which remains the *sine qua non* of climate stabilisation.
207
208 This correspondence between pulse emissions of cumulative pollutants and
209 sustained emissions of short-lived pollutants (or the benefits of corresponding
210 emissions reductions) has been noted before[7,8,11,12,13], but previous studies
211 suggested that a new metric of sustained emission reductions would be required
212 to relate them. Figure 2b suggests that the familiar GWP_{100} might still be
213 adequate for this purpose, provided it is used to relate sustained reductions in
214 emission rates of SLCPs (agents with lifetimes much shorter than the GWP time-
215 horizon) with temporarily avoided emissions of cumulative climate pollutants
216 (any with lifetimes substantially longer than the GWP time-horizon).
217
218 There are obvious challenges to incorporating this second use of GWP_{100} into the
219 UNFCCC process. The Kyoto Protocol and most emissions trading schemes are
220 predicated on emissions accounting over fixed commitment periods. Although
221 possible in the new, more flexible, NDC framework, equating an open-ended
222 commitment to a permanent reduction in an SLCP emission rate with actual
223 avoided emissions of a cumulative pollutant within a commitment period would
224 be a significant policy innovation. Nevertheless, this approximate equivalence
225 may be useful in setting national or corporate climate policy priorities,
226 particularly where decisions involve capital investments committing future
227 emissions[13].
228
229 This second use of GWP_{100} is also relevant to the long-term goal in the Paris
230 Agreement "to achieve a balance between anthropogenic emissions by sources
231 and removals by sinks" in order to hold the increase in the global average
232 temperature to well below 2°C above pre-industrial levels. Peak warming scales
233 approximately with cumulative CO_2 and N_2O emissions (expressed as $GtCO_2$-e
234 using GWP_{100}) between now and the time of peak warming plus the sustained
235 rate of emission of SLCPs (expressed in $GtCO_2$-e/H per year, with H=100 years if
236 GWP_{100} is used to define $GtCO_2$-e) in the decades immediately prior to peak
237 warming. So a sustained emission rate of 0.01 tonnes per year of methane has
238 the same impact on peak warming as a pulse of 28 tonnes of CO_2 released at any
239 time between now and when temperatures peak, GWP_{100} of methane being 28.
240 As NDCs are updated, it would be useful for countries to clarify how they

241   propose to balance (individually or collectively) cumulative emissions of CO_2 and
242   N_2O as these are reduced to zero or below with future emission rates of SLCPs.
243
244   Figure 2d shows the impact on global temperatures of actual 2011 emissions of
245   various climate pollutants, considered as a one-year emission pulse.[16] Methane
246   and black carbon emissions in 2011 have a comparable or even larger impact on
247   global temperatures over the next couple of decades than 2011 CO_2 emissions,
248   but their impact rapidly decays, while the impact of current CO_2 emissions
249   persists throughout the 21st century and for many centuries beyond.
250
251   Figure 2e shows the impact of 2011 emissions of various climate pollutants,
252   assuming these emissions are maintained at the same level for the next 100
253   years. The warming impact of the cumulative pollutants, CO_2 and nitrous oxide,
254   increases steadily as long as these emissions persist, while sustained emissions
255   of methane and organic and black carbon aerosols cause temperatures to warm
256   rapidly at first and then stabilize. A permanent reduction of 50-75% in these
257   SLCPs could reduce global temperatures by over 0.5°C by mid-century[4],
258   comparable to the impact on these timescales of similar-magnitude reductions of
259   CO_2 emissions and, it has been argued, at much lower cost[4,5,29]. Stabilising global
260   temperatures, however, requires net emissions of cumulative pollutants,
261   predominantly CO_2, to be reduced to zero.
262
263   The notion of 'CO$_2$-equivalent' pulse emissions of cumulative and short-lived
264   climate pollutants will always be ambiguous because they act to warm the
265   climate system in fundamentally different ways. To date, this ambiguity may
266   have had only a limited impact, not least because emission reductions have so far
267   been relatively unambitious. As countries with relatively large agricultural
268   emissions of methane and significant black carbon emissions begin to quantify
269   their contributions to the UNFCCC, and as the stringency of commitments
270   increases consistent with the collective goal of limiting warming to "well below"
271   2°C, this situation may change[21,30].
272
273   For their long-term climate implications to be clear, policies and Nationally
274   Determined Contributions need to recognise these differences. GWP$_{100}$ can be
275   used in the traditional way, comparing pulse emissions of different greenhouse
276   gases, to specify how mitigation of both short-lived and cumulative climate
277   pollutants may reduce the rate and magnitude of climate change over the next
278   20-40 years, but only over that time. To achieve a balance between sources and
279   sinks of greenhouse gases in the very long term, net emissions of cumulative
280   pollutants such as CO_2 need to be reduced to zero, while emissions of SLCPs
281   simply need to be stabilised. GWP$_{100}$ can again be used, but in the second way
282   identified here, to relate cumulative (positive and negative) emissions of CO_2
283   until these reach zero with future emission rates of SLCPs, particularly around
284   the time of peak warming. Some NDCs are already providing a breakdown in
285   terms of cumulative and short-lived climate pollutants, or differential policy
286   instruments for different forcing agents[30] and different timescales, all of which is
287   needed for their climatic implications to be clear. The Paris Agreement proposes
288   that Parties will report emissions and removals using common metrics, but a
289   generic 'CO$_2$-equivalent' emission reduction target by a given year, defined in

290   terms of GWP_{100} and containing a substantial element of SLCP mitigation,
291   represents an ambiguous commitment to future climate. The conventional use of
292   GWP_{100} to compare pulse emissions of all gases is an effective metric to limit
293   peak warming if and only if emissions of all climate pollutants, most notably CO_2,
294   are being reduced such that temperatures are expected to stabilise within the
295   next 20-40 years. This expected time to peak warming will only become clear
296   when CO_2 emissions are falling fast enough to observe the response. Until that
297   time, the only coherent comparison is between pulse emissions of CO_2, N_2O and
298   other cumulative pollutants and permanent changes in the rates of emissions of
299   SLCPs.
300

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

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

313   and

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

315   where F_1 is the instantaneous forcing per unit emission and k_1 the concentration
316   decay rate for a greenhouse gas, with F_0 and k_0 the corresponding parameters
317   for a reference gas, k_T is a typical thermal adjustment rate of the ocean mixed
318   layer in response to forcing, and H and H' are the GWP and GTP time-horizons.
319   For a very short-lived greenhouse gas and very long-lived reference gas such
320   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
321   parentheses in the numerator and denominator of equations (1) and (2) are
322   approximately unity, $k_0 H$, $e^{-k_T H'}$ and $\left(1-e^{-k_T H'}\right)$ respectively. Hence, using
323    $k_1 - k_T \approx k_1$ and $k_T - k_0 \approx k_T$, we have

$$GWP_H \approx \frac{F_1}{F_0 k_1 H} \quad \text{and} \quad GTP_{H'} \approx \frac{F_1 k_T}{F_0 k_1 \left(e^{k_T H'}-1\right)}$$

324   so GWP_H equals $GTP_{H'}$ if $H' = \ln(1+H k_T)/k_T$, or 21 years if $H = 100$ years and
325    $k_T = (8.4 \text{ years})^{-1}$, as in ref. 16. Hence in the limit of a very short-lived gas and
326   infinitely persistent reference gas, the GTP for a pulse emission evaluated at 21
327   years will be equal to the GWP_{100}. The expression becomes more complicated if
328    $k_1 H' \approx 1$ as is the case of methane, but this limiting case serves to show that the
329   equality of GWP_{100} and $GTP_{20\text{-}40}$ arises primarily from the thermal adjustment
330   time of the climate system.
331

332 **The approximate equivalence** of the temperature response to a one-tonne
333 transitory pulse emission of a cumulative pollutant to sustained step-change in
334 the rate of emission of an SLCP by $1/(H \times \text{GWP}_H)$ tonnes per year, where H is the
335 GWP time horizon, follows from the cumulative impact of CO_2 emissions on
336 global temperatures. This means that the temperature response at a time H after
337 a unit pulse emission of CO_2 ($\text{AGTP}_P(CO_2)$ in ref. 2), multiplied by H, is
338 approximately equal to the response after time H to a one-unit-per-year
339 sustained emission of CO_2 ($\text{AGTP}_S(CO_2)$), provided H is shorter than the effective
340 atmospheric residence time of CO_2, which is of order millennia This is consistent
341 with the concept of the "trillionth tonne" – that it is the cumulative amount of
342 CO_2 that is emitted, rather than when it is emitted, that matters most for future
343 climate[9]. Ref. 2 also notes that the ratio $\text{AGTP}_S(x)/\text{AGTP}_S(CO_2)$ is approximately
344 equal to $\text{GWP}_H(x)$ for time horizons H much longer than the lifetime of an agent x.
345 Hence:
346
347 $$\text{AGTP}_S(x) \approx \text{GWP}_H(x) \times \text{AGTP}_S(CO_2) \approx \text{GWP}_H(x) \times H \times \text{AGTP}_P(CO_2) \qquad (3)$$
348
349 provided H is shorter than the effective residence time of CO_2 and longer than
350 the lifetime of the agent x, as is the case when $H=100$ years and x is an SLCP.
351
352 **The interpretation of an "avoided emission pulse"**, although central most
353 emission trading schemes, may be ambiguous in the context of many mitigation
354 decisions, which may involve policies resulting in permanent changes in
355 emission rates. Another way of expressing this notion of an 'avoided pulse' is in
356 terms of the impact of delay in reducing emissions of cumulative pollutants: a
357 five year delay in implementing a one-tonne-per-year reduction of CO_2 emissions
358 would need to be compensated for by a permanent reduction of
359 $5/(100 \times 28) = 1.8 \times 10^{-3}$ tonnes-per-year of methane (GWP_{100} of methane
360 being 28). This would only compensate for the direct impact of the delay in CO_2
361 emission reductions, not for additional committed future CO_2 emissions that
362 might also result from that delay.[28]
363
364 **Treatment of Black Carbon emissions:** Focusing solely on absorbing aerosols
365 gives a high estimated 'radiative efficiency' (impact on the global energy budget
366 per unit change in atmospheric concentration) for black carbon, a strong positive
367 global climate forcing[15] (1.1 W m^{-2} in 2011) and a GWP_{100} of 910. This figure has
368 been argued[16] to be too high, and the actual radiative impact of individual black
369 carbon emissions depends strongly on the circumstances (location, season and
370 weather conditions) at the time of emission. Many processes that generate black
371 carbon also generate reflective organic aerosols, which have a cooling effect on
372 global climate. Although ratios vary considerably across sources, policy
373 interventions to limit black carbon emissions are likely also to affect these other
374 aerosols, so it might be more relevant to consider their combined impact: the
375 current best estimate[16] net global radiative forcing of organic and black carbon
376 aerosols in 2011 was 0.35 W m^{-2}, giving a combined GWP_{100} of 290, used in the
377 figures. Combined emissions of organic and black carbon aerosols are inferred
378 from this GWP_{100} value assuming all radiative forcing resulting from these
379 emissions is concentrated in the first year (i.e. a lifetime much shorter than one
380 year). This is only one estimate of a very uncertain quantity: when both

381 reflection and absorption are taken into account, including interactions between
382 aerosols and clouds and surface albedo, even the sign of the net radiative impact
383 of the processes that generate black carbon aerosols remains uncertain.
384
385 **Modelling details:** Figure 1: GWP values calculated using current IPCC methane
386 and CO_2 impulse response functions without carbon cycle feedbacks.[16] Radiative
387 forcing (RF) of a pulse emission of organic and black carbon aerosols
388 concentrated in year 1, scaled to give a net GWP_{100} of 290, consistent with ratio
389 of 2011 RF values given in refs. 15 and 16. GTP values calculated using the
390 standard IPCC AR5 thermal response model (solid blue lines) with coefficients
391 adjusted (dotted blue lines) to give Realised Warming Fractions[24] (ratio of
392 Transient Climate Response, TCR, to Equilibrium Climate Sensitivity, ECS) of 0.35
393 and 0.85, spanning the range of uncertainty around the best-estimate value of
394 0.56. Figure 2: As figure 1 with radiative efficiencies and lifetimes provided in
395 Table A.8.1 of ref. 16 and representative mid-range values of TCR=1.5^{o}C and
396 ECS=2.7^{o}C.

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