

1 A new use of Global Warming Potentials to relate the impacts of cumulative 2 and short-lived climate pollutants

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7 **Parties to the United Nations Framework Convention on Climate Change**
8 **(UNFCCC) have requested guidance on common greenhouse gas metrics in**
9 **accounting for Nationally Determined Contributions (NDCs) to emission**
10 **reductions¹. Metric choice can affect the relative emphasis placed on**
11 **reductions of ‘cumulative climate pollutants’ like carbon dioxide (CO₂)**
12 **versus ‘Short-Lived Climate Pollutants’ (SLCPs) including methane and**
13 **black carbon^{2,3,4,5,6}. Here we show that the widely used 100-year Global**
14 **Warming Potential (GWP₁₀₀) effectively measures relative impact of both**
15 **cumulative pollutants and SLCPs on realised warming 20-40 years after the**
16 **time of emission. If the overall goal of climate policy is to limit peak**
17 **warming, GWP₁₀₀ therefore overstates the importance of current SLCP**
18 **emissions unless stringent and immediate reductions of all climate**
19 **pollutants result in temperatures nearing their peak soon after mid-**
20 **century^{7,8,9,10} which may be necessary to limit warming to “well below 2**
21 **°C”.¹ The GWP₁₀₀ can be used to approximately equate a one-off pulse**
22 **emission of a cumulative pollutant and an indefinitely sustained change in**
23 **the rate of emission of an SLCP^{11,12,13}. The climate implications of**
24 **traditional “CO₂-equivalent” targets are ambiguous unless contributions**
25 **from cumulative pollutants and SLCPs are specified separately.**

26
27 Establishing policy priorities and market-based emission reduction mechanisms
28 involving different climate forcing agents all require some way of measuring
29 what one forcing agent is ‘worth’ relative to another. The GWP₁₀₀ metric has
30 been widely used for this purpose for over 20 years, notably within the UNFCCC
31 and its Kyoto Protocol. It represents the time-integrated climate forcing
32 (perturbation to the Earth’s balance between incoming and outgoing energy)
33 due to a one-off pulse emission of one tonne of a greenhouse gas over the 100
34 years following its emission, relative to the corresponding impact of a one tonne
35 pulse emission of CO₂. The notion of a temporary emission pulse is itself a rather
36 artificial construct: it could also be interpreted as the impact of a delay in
37 reducing the rate of emission of a greenhouse gas (see Methods).

38
39 This focus on climate forcing and 100-year time-horizon in GWP₁₀₀ has no
40 particular justification either for climate impacts or for the policy goals of the
41 UNFCCC, which focus on limiting peak warming, independent of timescale. While
42 it could be argued that, given current rates of warming, the goal of the Paris
43 Agreement¹ to limit warming to “well below 2 °C” focuses attention on mitigation
44 outcomes over the next few decades, this focus is only implicit and presupposes
45 that this goal will actually be met. Individual countries may also have goals to
46 limit climate impacts in the shorter term. These are acknowledged by the
47 UNFCCC, but not quantified in terms of, for example, a target maximum warming
48 rate. Metric choice is particularly important when comparing CO₂ emissions with

49 SLCPs such as methane and black carbon aerosols. Black carbon has only
50 recently been introduced into a few intended NDCs¹⁴ but may become
51 increasingly prominent as some early estimates¹⁵ assign it a very high GWP₁₀₀,
52 even though the net climatic impact of processes that generate black carbon
53 emissions remains uncertain¹⁶ and policy interventions to reduce black carbon
54 emissions are likely to impact⁶ other forms of pollution as well. Here we combine
55 the climatic impact of black carbon with that of reflective organic aerosols using
56 forcing estimates from ref. 16 (see Methods).

57
58 At least one party to the UNFCCC has argued¹⁷ that using the alternative Global
59 Temperature-change Potential (GTP) metric would be more consistent with the
60 UNFCCC goal of limiting future warming. In its most widely used “pulse” variant²,
61 the GTP represents the impact of the emission of one tonne of a greenhouse gas
62 on global average surface temperatures at a specified point in time after
63 emission¹⁸, again relative to the corresponding impact of the emission of one
64 tonne of CO₂. Figure 1 shows how both GTP and GWP values for SLCPs like
65 methane and black carbon depend strongly on the time-horizon. For long time-
66 horizons, SLCP GTP values also depend on the response time of the climate
67 system, which is uncertain^{19,20}. This latter uncertainty is a real feature of the
68 climate response that is not captured by GWP, and so is not itself a reason to
69 choose GWP over GTP. Other metrics and designs of multi-gas polices have been
70 proposed^{21,22}, some of which can be shown to be approximately equivalent to
71 GWP or GTP²³, but since only GWP and GTP have been discussed in the context of
72 the UNFCCC, we focus on these here.

73
74 For any time horizon longer than 10 years, values of the GTP are lower than
75 corresponding values of the GWP for SLCPs. The time-horizon has, however, a
76 different meaning between the two metrics: for GWP it represents the time over
77 which climate forcing is integrated, while for GTP it represents a future point in
78 time at which temperature change is measured. Hence there is no particular
79 reason to compare GWP and GTP values for the same time-horizon. Indeed,
80 figure 1 shows that the value of GWP₁₀₀ is equal to the GTP with a time-horizon
81 of about 40 years in the case of methane, and 20-30 years in the case of black
82 carbon, given the climate system response-times used in ref. 16, for reasons
83 given in the Methods.²⁴ Values of GWP and GTP for cumulative pollutants like
84 nitrous oxide (N₂O) or sulphur hexafluoride (SF₆) are determined primarily by
85 forcing efficiencies, not lifetimes, and are hence similar to each other and almost
86 constant over all these time-horizons.¹⁶ So for a wide range of both cumulative
87 and short-lived climate pollutants, GWP₁₀₀ is very roughly equivalent to GTP₂₀₋₄₀
88 when applied to an emission pulse, making it an approximate indicator of the
89 relative impact of a one-off pulse emission of a tonne of greenhouse gas or other
90 climate forcing agent on global temperatures 20-40 years after emission. The
91 inclusion of feedbacks between warming and the carbon cycle can substantially
92 increase GTP (and also, to a lesser degree, GWP) values, particularly on century
93 timescales²⁵. Here we follow the traditional approach, used for the most widely-
94 quoted metric values in ref. 16, of including these feedbacks in modelling CO₂ but
95 not other gases.

96

97 Figure 2, panel a, shows the impact on global average temperature of a pulse
98 emission of various climate pollutants, with the size of the pulse of each gas
99 being 'equivalent' (in terms of GWP₁₀₀) to total anthropogenic CO₂ emissions in
100 2011 (38 GtCO₂): hence the pulse size is 38/GWP₁₀₀ billion tonnes of each forcing
101 agent. SLCPs with high radiative efficiencies, like methane, black carbon and
102 some hydrofluorocarbons, have a more immediate impact on global
103 temperatures than notionally equivalent emissions of CO₂, and less impact after
104 20-40 years. Hence, if the primary goal of climate policy is to limit peak warming,
105 then given the time likely to be required to reduce net global CO₂ emissions to
106 zero to stabilise temperatures, the conventional use of GWP₁₀₀ to compare pulse
107 emissions of CO₂ and SLCPs is likely to overstate the importance of SLCPs for
108 peak warming until global CO₂ emissions are falling.^{7,8}

109
110 This is not an argument for delay in SLCP mitigation²⁶ – the benefits to human
111 health and agriculture alone would justify many proposed SLCP mitigation
112 measures⁴ – but it is an argument for clarity in what immediate SLCP reductions
113 may achieve for global climate. The use of GWP₁₀₀ to compare emission pulses
114 might still be appropriate to other policy goals, such as limiting the rate of
115 warming over the coming decades, although the impact of policies on warming
116 rates even over multi-decade timescales should always be considered in the
117 context of internal climate variability.²⁷ Some contributions to the rate of sea-
118 level-rise also scale with integrated climate forcing.²²

119
120 Simply adopting a different metric that assigns a lower weight to SLCP
121 emissions, such as GTP₁₀₀, does not solve this overstatement problem, since any
122 metric that correctly reflects the impact of SLCPs on temperatures 100 years in
123 the future would understate their impact, relative to notionally equivalent
124 quantities of CO₂, on all shorter timescales. Any choice of metric to compare
125 pulse emissions of cumulative and short-lived pollutants contains a choice of
126 time horizon^{16,18}. It is, however, important for policy-makers to be clear about
127 the time-horizon they are focussing on. One problem with the GWP₁₀₀ metric is
128 that “warming” may be interpreted colloquially to mean “temperature rise by a
129 point in time”, making the name misleading, because, in the case of SLCPs,
130 GWP₁₀₀ actually delineates impact on temperatures in 20-40 years, not 100
131 years.

132
133 Figure 2b suggests an alternative way of using GWP₁₀₀ to express equivalence
134 between cumulative and short-lived climate pollutants that is valid over a wider
135 range of time-scales, suggesting a way to use GWP₁₀₀ to reconcile the “emission
136 metrics” literature^{2,3} with the “carbon budget” approach⁹. The solid lines show
137 the impact on global temperatures of a *sustained* emission of 38 GtCO₂-
138 equivalent (again computed using GWP₁₀₀) of the short-lived climate pollutants
139 shown in 2a, but now starting abruptly in year 1 and distributed evenly over the
140 GWP time-horizon: hence a sustained emission rate of 38/(H×GWP₁₀₀) billion
141 tonnes per year, where H=100 years. These cause temperatures to increase and
142 then approach stabilization after 20-40 years, depending on their lifetimes. The
143 dotted line shows the impact of a *pulse* emission of 38 GtCO₂ in year one,
144 reproduced from 2a. The correspondence between these temperature responses

145 is not exact, but much better than in 2a, at least over timescales from 30 to 100
146 years.

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

158 A corollary is that a *sustained* step-change in the rate of emission of a cumulative
159 pollutant such as CO_2 is approximately equivalent to a *progressive* linear increase
160 or decrease in the rate of emission of an SLCP. This is illustrated in figure 2c,
161 which compares the impact of a sustained emission of 38 Gt per year of CO_2
162 emissions (red dotted line) with SLCP emissions increasing from zero at a rate of
163 0.38 Gt CO_2 -e per year per year (solid lines). Again, although the correspondence
164 is not exact, it is much better than the nominally equivalent emission pulses in
165 2a. The green dotted line shows that sustained emissions of cumulative
166 pollutants (N_2O and CO_2) have similar impacts on these timescales. Finally, a
167 *progressive* change in the rate of emission of CO_2 , necessary to reach net zero¹⁰
168 CO_2 emissions to stabilise temperatures, could only be equated to an *accelerating*
169 change in SLCP emissions. This last equivalence is somewhat moot because
170 attempting to match the rates of reduction of CO_2 emissions²⁸ required to limit
171 warming to 2 °C would result in SLCP emissions soon having to be reduced
172 below zero. In summary, therefore, a pulse (or sustained) emission of a
173 cumulative pollutant may be approximately equivalent to a sustained (or
174 progressively increasing) change in the rate of emission of an SLCP, but there is
175 no substitute for a progressive reduction in the rate of emission a cumulative
176 pollutant such as CO_2 , which remains the *sine qua non* of climate stabilisation.

177
178 This correspondence between pulse emissions of cumulative pollutants and
179 sustained emissions of short-lived pollutants (or the benefits of corresponding
180 emissions reductions) has been noted before^{7,8,11,12,13}, but previous studies
181 suggested that a new metric of sustained emission reductions would be required
182 to relate them. Figure 2b suggests that the familiar GWP_{100} might still be
183 adequate for this purpose, provided it is used to relate sustained reductions in
184 emission rates of SLCPs (agents with lifetimes much shorter than the GWP time-
185 horizon) with temporarily avoided emissions of cumulative climate pollutants
186 (any with lifetimes substantially longer than the GWP time-horizon).

187
188 There are obvious challenges to incorporating this second use of GWP_{100} into the
189 UNFCCC process. The Kyoto Protocol and most emissions trading schemes are
190 predicated on emissions accounting over fixed commitment periods. Although
191 possible in the new, more flexible, NDC framework, equating an open-ended

192 commitment to a permanent reduction in an SLCP emission rate with actual
193 avoided emissions of a cumulative pollutant within a commitment period would
194 be a significant policy innovation. Nevertheless, this approximate equivalence
195 may be useful in setting national or corporate climate policy priorities,
196 particularly where decisions involve capital investments committing future
197 emissions¹³.

198
199 This second use of GWP₁₀₀ is also relevant to the long-term goal in the Paris
200 Agreement “to achieve a balance between anthropogenic emissions by sources
201 and removals by sinks” in order to hold the increase in the global average
202 temperature to well below 2°C above pre-industrial levels. Peak warming scales
203 approximately with cumulative CO₂ and N₂O emissions (expressed as GtCO₂-e
204 using GWP₁₀₀) between now and the time of peak warming plus the sustained
205 rate of emission of SLCPs (expressed in GtCO₂-e/*H* per year, with *H*=100 years if
206 GWP₁₀₀ is used to define GtCO₂-e) in the decades immediately prior to peak
207 warming. So a sustained emission rate of 0.01 tonnes per year of methane has
208 the same impact on peak warming as a pulse of 28 tonnes of CO₂ released at any
209 time between now and when temperatures peak, GWP₁₀₀ of methane being 28.
210 As NDCs are updated, it would be useful for countries to clarify how they
211 propose to balance (individually or collectively) cumulative emissions of CO₂ and
212 N₂O as these are reduced to zero or below with future emission rates of SLCPs.

213
214 Figure 2d shows the impact on global temperatures of actual 2011 emissions of
215 various climate pollutants, considered as a one-year emission pulse.¹⁶ Methane
216 and black carbon emissions in 2011 have a comparable or even larger impact on
217 global temperatures over the next couple of decades than 2011 CO₂ emissions,
218 but their impact rapidly decays, while the impact of current CO₂ emissions
219 persists throughout the 21st century and for many centuries beyond.

220
221 Figure 2e shows the impact of 2011 emissions of various climate pollutants,
222 assuming these emissions are maintained at the same level for the next 100
223 years. The warming impact of the cumulative pollutants, CO₂ and nitrous oxide,
224 increases steadily as long as these emissions persist, while sustained emissions
225 of methane and organic and black carbon aerosols cause temperatures to warm
226 rapidly at first and then stabilize. A permanent reduction of 50-75% in these
227 SLCPs could reduce global temperatures by over 0.5°C by mid-century⁴,
228 comparable to the impact on these timescales of similar-magnitude reductions of
229 CO₂ emissions and, it has been argued, at much lower cost^{4,5,29}. Stabilising global
230 temperatures, however, requires net emissions of cumulative pollutants,
231 predominantly CO₂, to be reduced to zero.

232
233 The notion of ‘CO₂-equivalent’ pulse emissions of cumulative and short-lived
234 climate pollutants will always be ambiguous because they act to warm the
235 climate system in fundamentally different ways. To date, this ambiguity may
236 have had only a limited impact, not least because emission reductions have so far
237 been relatively unambitious. As countries with relatively large agricultural
238 emissions of methane and significant black carbon emissions begin to quantify
239 their contributions to the UNFCCC, and as the stringency of commitments

240 increases consistent with the collective goal of limiting warming to “well below”
241 2°C, this situation may change^{21,30}.

242
243 For their long-term climate implications to be clear, policies and Nationally
244 Determined Contributions need to recognise these differences. GWP₁₀₀ can be
245 used in the traditional way, comparing pulse emissions of different greenhouse
246 gases, to specify how mitigation of both short-lived and cumulative climate
247 pollutants may reduce the rate and magnitude of climate change over the next
248 20-40 years, but only over that time. To achieve a balance between sources and
249 sinks of greenhouse gases in the very long term, net emissions of cumulative
250 pollutants such as CO₂ need to be reduced to zero, while emissions of SLCPs
251 simply need to be stabilised. GWP₁₀₀ can again be used, but in the second way
252 identified here, to relate cumulative (positive and negative) emissions of CO₂
253 until these reach zero with future emission rates of SLCPs, particularly around
254 the time of peak warming. Some NDCs are already providing a breakdown in
255 terms of cumulative and short-lived climate pollutants, or differential policy
256 instruments for different forcing agents³⁰ and different timescales, all of which is
257 needed for their climatic implications to be clear. The Paris Agreement proposes
258 that Parties will report emissions and removals using common metrics, but a
259 generic ‘CO₂-equivalent’ emission reduction target by a given year, defined in
260 terms of GWP₁₀₀ and containing a substantial element of SLCP mitigation,
261 represents an ambiguous commitment to future climate. The conventional use of
262 GWP₁₀₀ to compare pulse emissions of all gases is an effective metric to limit
263 peak warming if and only if emissions of all climate pollutants, most notably CO₂,
264 are being reduced such that temperatures are expected to stabilise within the
265 next 20-40 years. This expected time to peak warming will only become clear
266 when CO₂ emissions are falling fast enough to observe the response. Until such a
267 clear end-point is in sight, only a permanent change in the rate of emission of an
268 SLCP can be said to have a comparable impact on future temperatures as a one-
269 off pulse emission of CO₂, N₂O or other cumulative pollutant.

270
271 **Acknowledgements:** MRA was supported by the Oxford Martin Programme on
272 Resource Stewardship. MRA and KPS received support from the UK Department
273 of Energy and Climate Change under contract no. TRN/307/11/2011; JSF from
274 the Norwegian Research Council, project no. 235548; RTP from the Kung Carl
275 XVI Gustaf 50-års fond; PMdF from the UK Natural Environment Research
276 Council grant no. NE/N006038/1. The authors would like to thank three very
277 helpful anonymous reviewers who considerably clarified this work and
278 numerous colleagues, particularly among IPCC authors, for discussions of
279 metrics over recent years.

280 **Methods**

281 **The equality of GWP₁₀₀ and GTP₂₀₋₄₀** follows from the idealised expressions for
282 GWP and GTP for a pulse emission given in ref. 2 (equations A1 and 3 in ref. 2,
283 expressed as relative GWP and GTP respectively, and with decay-times replaced
284 by decay rates):

$$285 \text{GWP}_H = \frac{\frac{F_1}{k_1}(1-e^{-k_1H})}{\frac{F_0}{k_0}(1-e^{-k_0H})} \quad (1)$$

286 and

$$287 \quad \text{GTP}_{H'} = \frac{\frac{F_1}{(k_1 - k_T)}(e^{-k_T H'} - e^{-k_1 H'})}{\frac{F_0}{(k_T - k_0)}(e^{-k_0 H'} - e^{-k_T H'})} \quad (2)$$

288 where F_1 is the instantaneous forcing per unit emission and k_1 the concentration
 289 decay rate for a greenhouse gas, with F_0 and k_0 the corresponding parameters
 290 for a reference gas, k_T is a typical thermal adjustment rate of the ocean mixed
 291 layer in response to forcing, and H and H' are the GWP and GTP time-horizons.
 292 For a very short-lived greenhouse gas and very long-lived reference gas such
 293 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
 294 parentheses in the numerator and denominator of equations (1) and (2) are
 295 approximately unity, $k_0 H$, $e^{-k_T H'}$ and $(1 - e^{-k_T H'})$ respectively. Hence, using
 296 $k_1 - k_T \approx k_1$ and $k_T - k_0 \approx k_T$, we have

$$297 \quad \text{GWP}_H \approx \frac{F_1}{F_0 k_1 H} \quad \text{and} \quad \text{GTP}_{H'} \approx \frac{F_1 k_T}{F_0 k_1 (e^{k_T H'} - 1)}$$

298 so GWP_H equals $\text{GTP}_{H'}$ if $H' = \ln(1 + H k_T)/k_T$, or 21 years if $H = 100$ years and
 299 $k_T = (8.4 \text{ years})^{-1}$, as in ref. 16. Hence in the limit of a very short-lived gas and
 300 infinitely persistent reference gas, the GTP for a pulse emission evaluated at 21
 301 years will be equal to the GWP_{100} . The expression becomes more complicated if
 302 $k_1 H' \approx 1$ as is the case of methane, but this limiting case serves to show that the
 303 equality of GWP_{100} and GTP_{20-40} arises primarily from the thermal adjustment
 304 time of the climate system.

305

306 **The approximate equivalence** of the temperature response to a one-tonne
 307 transitory pulse emission of a cumulative pollutant to sustained step-change in
 308 the rate of emission of an SLCP by $1/(H \times \text{GWP}_H)$ tonnes per year, where H is the
 309 GWP time horizon, follows from the cumulative impact of CO_2 emissions on
 310 global temperatures. This means that the temperature response at a time H after
 311 a unit pulse emission of CO_2 ($\text{AGTP}_P(\text{CO}_2)$ in ref. 2), multiplied by H , is
 312 approximately equal to the response after time H to a one-unit-per-year
 313 sustained emission of CO_2 ($\text{AGTP}_S(\text{CO}_2)$), provided H is shorter than the effective
 314 atmospheric residence time of CO_2 , which is of order millennia. This is consistent
 315 with the concept of the “trillionth tonne” – that it is the cumulative amount of
 316 CO_2 that is emitted, rather than when it is emitted, that matters most for future
 317 climate⁹. Ref. 2 also notes that the ratio $\text{AGTP}_S(x)/\text{AGTP}_S(\text{CO}_2)$ is approximately
 318 equal to $\text{GWP}_H(x)$ for time horizons H much longer than the lifetime of an agent x .
 319 Hence:

320

$$321 \quad \text{AGTP}_S(x) \approx \text{GWP}_H(x) \times \text{AGTP}_S(\text{CO}_2) \approx \text{GWP}_H(x) \times H \times \text{AGTP}_P(\text{CO}_2) \quad (3)$$

322

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

325

326 **The interpretation of an “avoided emission pulse”**, although central to most
 327 emission trading schemes, may be ambiguous in the context of many mitigation
 328 decisions, which may involve policies resulting in permanent changes in
 329 emission rates. Another way of expressing this notion of an ‘avoided pulse’ is in
 330 terms of the impact of delay in reducing emissions of cumulative pollutants: a
 331 five year delay in implementing a one-tonne-per-year reduction of CO_2 emissions
 332 would need to be compensated for by a permanent reduction of

333 $5/(100 \times 28) = 1.8 \times 10^{-3}$ tonnes-per-year of methane (GWP₁₀₀ of methane
334 being 28). This would only compensate for the direct impact of the delay in CO₂
335 emission reductions, not for additional committed future CO₂ emissions that
336 might also result from that delay.²⁸

337

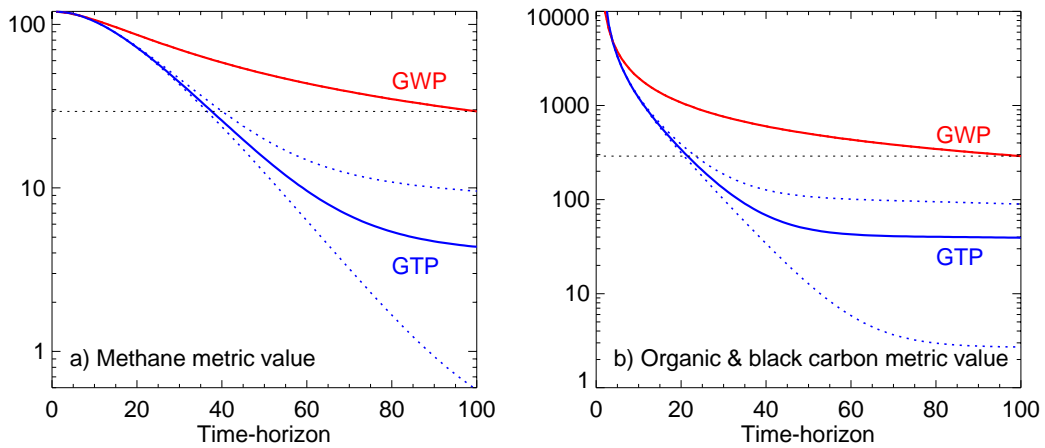
338 **Treatment of Black Carbon emissions:** Focusing solely on absorbing aerosols
339 gives a high estimated 'radiative efficiency' (impact on the global energy budget
340 per unit change in atmospheric concentration) for black carbon, a strong positive
341 global climate forcing¹⁵ (1.1 W m⁻² in 2011) and a GWP₁₀₀ of 910. This figure has
342 been argued¹⁶ to be too high, and the actual radiative impact of individual black
343 carbon emissions depends strongly on the circumstances (location, season and
344 weather conditions) at the time of emission. Many processes that generate black
345 carbon also generate reflective organic aerosols, which have a cooling effect on
346 global climate. Although ratios vary considerably across sources, policy
347 interventions to limit black carbon emissions are likely also to affect these other
348 aerosols, so it might be more relevant to consider their combined impact: the
349 current best estimate¹⁶ net global radiative forcing of organic and black carbon
350 aerosols in 2011 was 0.35 W m⁻², giving a combined GWP₁₀₀ of 290, used in the
351 figures. Combined emissions of organic and black carbon aerosols are inferred
352 from this GWP₁₀₀ value assuming all radiative forcing resulting from these
353 emissions is concentrated in the first year (i.e. a lifetime much shorter than one
354 year). This is only one estimate of a very uncertain quantity: when both
355 reflection and absorption are taken into account, including interactions between
356 aerosols and clouds and surface albedo, even the sign of the net radiative impact
357 of the processes that generate black carbon aerosols remains uncertain.

358

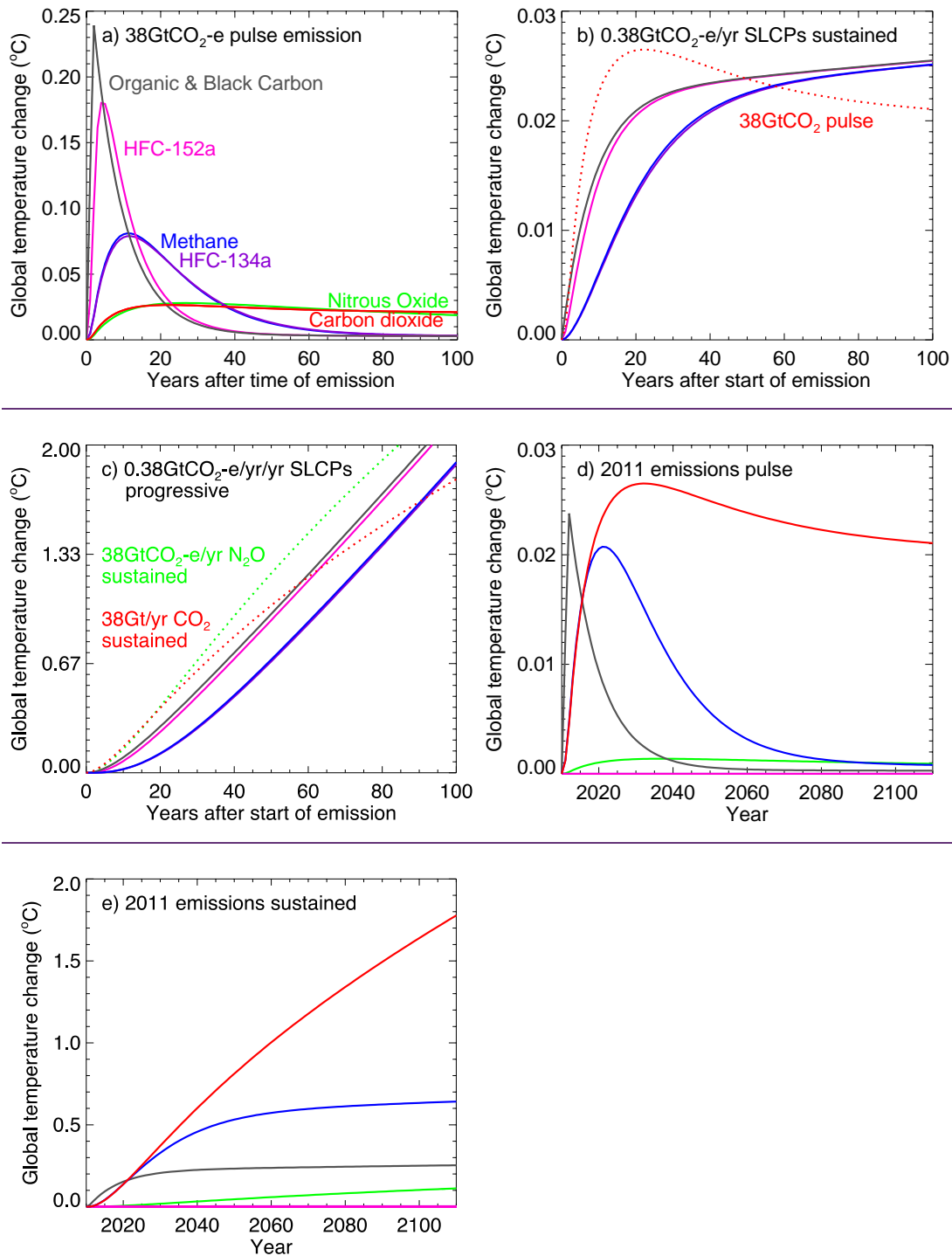
359 **Modelling details:** Figure 1: GWP values calculated using current IPCC methane
360 and CO₂ impulse response functions without carbon cycle feedbacks.¹⁶ Radiative
361 forcing (RF) of a pulse emission of organic and black carbon aerosols
362 concentrated in year 1, scaled to give a net GWP₁₀₀ of 290, consistent with ratio
363 of 2011 RF values given in refs. 15 and 16. GTP values calculated using the
364 standard IPCC AR5 thermal response model (solid blue lines) with coefficients
365 adjusted (dotted blue lines) to give Realised Warming Fractions²⁴ (ratio of
366 Transient Climate Response, TCR, to Equilibrium Climate Sensitivity, ECS) of 0.35
367 and 0.85, spanning the range of uncertainty around the best-estimate value of
368 0.56. Figure 2: As figure 1 with radiative efficiencies and lifetimes provided in
369 Table A.8.1 of ref. 16 and representative mid-range values of TCR=1.5°C and
370 ECS=2.7°C.

371

372 **Figures**
373



374
375 **Figure 1:** Values of Global Warming Potential (red) and Global Temperature-
376 change Potential (blue) for methane and combined organic and black carbon as a
377 function of time-horizon. Solid lines show metrics calculated using current IPCC
378 response functions¹⁶; dotted blue lines show impact of varying the climate
379 response time (see Methods). Black dotted lines show the value of GWP₁₀₀.
380



381

382

383

384 Figure 2: Impact of pulse versus sustained emissions of various climate forcing
 385 agents on global average temperatures. Colours indicate different greenhouse
 386 gases, with grey lines indicating combined impact of reflective organic and black
 387 carbon aerosols (see Methods) a) Warming caused by a pulse emission in 2011
 388 with each pulse size being nominally equivalent, using GWP₁₀₀, to 2011
 389 emissions of CO₂. b) Solid lines: impact of sustained emissions of SLCPs at a rate
 390 equivalent to 2011 emissions of CO₂ spread over the 100-year GWP₁₀₀ time
 391 horizon. Dotted line shows impact of pulse emission of CO₂ reproduced from (a).
 392 c) Solid lines: impact of SLCP emissions progressively increasing from zero at

393 0.38 GtCO₂-e yr⁻². Dotted lines: impact of sustained emissions of CO₂ and N₂O at
394 38 GtCO₂ (or equivalent) per year. d) Impact of actual 2011 emissions of each
395 climate forcing agent expressed as a pulse. e) Impact of emissions sustained
396 indefinitely at 2011 rates.
397

398 **References:**

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