1   # Bridging the gap between impact assessment methods and climate science

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32 **Abstract**

33 Life-cycle assessment and carbon footprint studies are widely used by decision makers to

34 identify climate change mitigation options and priorities at corporate and public levels.

35 These applications, including the vast majority of emission accounting schemes and policy

36 frameworks, traditionally quantify climate impacts of human activities by aggregating

37 greenhouse gas emissions into the so-called CO_2-equivalents using the 100-year Global

38 Warming Potential (GWP100) as the default emission metric. The practice was established

39 in the early nineties and has not been coupled with progress in climate science, other than

40 simply updating numerical values for GWP100. We review the key insights from the

41 literature surrounding climate science that are at odds with existing climate impact methods

42 and we identify possible improvement options. Issues with the existing approach lie in the

43 use of a single metric that cannot represent the climate system complexity for all possible

44 research and policy contexts, and in the default exclusion of near-term climate forcers such

45 as aerosols or ozone precursors and changes in the Earth's energy balance associated with

46 land cover changes. Failure to acknowledge the complexity of climate change drivers and

47 the spatial and temporal heterogeneities of their climate system responses can lead to the

48 deployment of suboptimal, and potentially even counterproductive, mitigation strategies. We

49 argue for an active consideration of these aspects to bridge the gap between climate impact

50 methods used in environmental impact analysis and climate science.

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52 **Keywords**: climate change; emission metrics; life cycle assessment (LCA); global warming

53 potential (GWP).

1. Introduction

Human activities perturb the climate system through a variety of forcing agents. Over the industrial era, the total anthropogenic radiative forcing, a measure of the net energy imbalance of the Earth caused by a forcing agent, is 2.29 [1.13 to 3.33] W m^{-2} [1]. The major contributors are carbon dioxide (CO_2) and methane (CH_4) emissions, which are responsible for about 1.68 ± 0.17 W m^{-2} and 0.97 ± 0.17 W m^{-2}, respectively [1]. The net contribution from so-called Near-Term Climate Forcers (NTCFs), that is, species with an atmospheric lifetime of less than about one year, is estimated to be a slight negative forcing (cooling) of –0.06 W m^{-2} [1], with large uncertainty bounds largely due to the lack of scientific understanding of aerosol-cloud interactions [2]. The contributions from the direct forcing effect of single NTCFs range between –0.41 ± 0.20 W m^{-2} for sulphur oxides (SO_x) emissions and +0.64 [+0.25 to +1.09] W m^{-2} for black carbon (BC) emissions [1]. The radiative forcing values from historical land use changes for CO_2 and surface albedo (the ratio between reflected and incident solar radiation at the surface) are of the same order of magnitude but opposite sign, with a warming effect of 0.17 to 0.51 W m^{-2} for CO_2 (1850-2000) and a cooling effect of –0.15 ± 0.10 W m^{-2} for surface albedo changes (1750-2011) [1]. The net effect from changes in emissions of biogenic volatile organic compounds (BVOCs) associated with this land use change is estimated to be an additional cooling contribution of –0.11 ± 0.17 W m^{-2} (1850-2000) [3].

Life cycle assessment (LCA) and carbon footprints are largely used to attribute climate change impacts to specific human activities like products, technological systems, or sectors [4]. Decision and policy makers widely rely on the outcomes from comparative climate impact analyses to promote mitigation options, and to design strategies for sustainable production and consumption at a public or corporate level. The most common approach is to aggregate emissions of well-mixed greenhouse gases to so-called "CO_2-equivalents"

79   using the 100-year global warming potential (henceforth GWP100) as the default emission

80   metric. A similar procedure is frequently applied in international agreements, like the Kyoto

81   protocol, the Intended Nationally Determined Contributions (INDCs) for mitigation

82   obligations to 2030 and climate-oriented policy directives, such as those regulating the

83   climate impacts of specific sectors. This practice does not take into account the impacts from

84   emissions of NTCFs or biophysical factors arising from changes in land cover. It also

85   overlooks the temporal and spatial heterogeneities of the climate system response to

86   different forcing agents, and the consideration of emission metrics alternative to GWP100.

87   Studies that have explored the influence of NTCFs [5, 6], of changes in surface albedo [7, 8],

88   of temporal and spatial impact dynamics [9-11], and of metrics other than GWP100 [5, 12-

89   15] on the climate impacts attributed to a specific human activity usually conclude that an

90   international effort on improving existing methods is desirable to prevent the

91   implementation of suboptimal mitigation pathways.

92   The Life Cycle Initiative under the United Nations Environment Program (UNEP) and the

93   Society of Environmental Toxicology and Chemistry (SETAC) launched the Global Guidance

94   on Environmental Life Cycle Impact Assessment Indicators to revise existing standard

95   methodologies used in environmental impact categories of LCA and footprint studies [16,

96   17], including climate change. Here, as part of the activities from the Global Warming Task

97   Force, we identify key insights from the climate science related literature that are of

98   relevance for advancing climate impact assessment frameworks.

99

100   ## 2. Life cycle impact assessment and emission metrics

101   The life cycle impact assessment phase consists in the conversion of different well-mixed

102   greenhouse gases (WMGHGs) to common units (kg CO_2-eq) after multiplication of each

103   emission flow by the respective emission metric, [4]. Emission metrics, which in LCA are

104   usually referred to as characterization factors, are typically simplified measures of the

105   climate system response to forcing agents and are mostly based on outcomes from physical

106   models of varying complexity linking emissions to impacts [1]. Metrics can be formulated in

107   absolute terms, for instance based on the temporal evolution of a temperature impact, or in

108   relative terms after normalization to a reference gas, usually CO_2 [5, 18]. Different

109   emissions have different climate system responses, and a metric that establishes equivalence

110   with regard to one effect does not usually result in equivalence with regard to other effects.

111   GWP is an integrative measure defined as the integrated radiative forcing of a gas between

112   the time of emission and a chosen time horizon (TH) relative to that of CO_2. The GWP was

113   introduced by the first IPCC assessment report in 1990 with illustrative purposes and, by its

114   own definition, it does not embed any climate system responses or direct link to policy goals

115   [1]. Despite the rather cautious introduction by the IPCC, the United Nations Framework

116   Convention on Climate Change, LCA and the majority of national and corporate emission

117   accounting frameworks started to use this metric without any substantial modifications,

118   with the exception of updating the GWP values according to the successive IPCC reports.

119   GWP is a metric that aligns well with the general principles of LCA. LCA privileges impacts

120   integrated over time and space under the objective of avoiding burden shifting of impacts

121   [4]. LCA also typically follows a "marginal change" approach, in the sense that an additional

122   amount of a certain pollutant is assumed to introduce very small changes on top of a

123   constant background. This approach allows the assessment of environmental impacts

124   associated with the life cycle impacts of a single unit of a product, which gives only a small

125   contribution to the total impact [19]. Common critiques to GWP concern the fact that,

126   despite its name, it does not equate climate forcing agents on the basis of their effects on

127   surface temperature, nor does it consider them under a specific climate policy target, such

128   as the goal to limit warming to 2 degrees above pre-industrial levels [18, 20-22]. The use of

129   a TH of 100 years seems to be the result of an "inadvertent consensus" [23] and it is not

130   directly linked to any particular climate policy objective. There are many emission metrics

131   available from the climate science literature that focus on different characteristics of the

132   climate system response to emissions [12, 18, 20, 21, 24-28]. By targeting different aspects

133   of the climate impact cause-effect chain, such as radiative forcing [29], temperature [26,

134   27], sea level rise [30], precipitation changes [31], or economic dimensions [28], these

135   metrics compare emissions on the basis of their instantaneous [26] or time integrated

136   impacts [25, 27]. They are computed under a constant [1, 24] or changing [18, 32]

137   background climate and can be formulated around a fixed or a target-dependent TH [14,

138   18, 33, 34]. A common alternative to GWP is the Global Temperature Change Potential

139   (GTP), which is defined as the impact of a GHG emission pulse on global temperature at the

140   chosen TH, again relative to CO_2 [26]. With the exception of some gases with very short

141   lifetimes, values of GTP for a TH of about 40 years are usually similar to those of GWP100

142   [35]. Recently, GWP100 is shown to approximately equate a pulse emission of a cumulative

143   climate pollutant and an indefinitely sustained change in the rate of emission of short-lived

144   forcers, introducing a new application for GWP100 in comparing WMGHGs with different

145   lifetimes [36]. Within a context of emission accounting, some also argue against the practice

146   of aggregating all WMGHGs to common units [29, 37, 38] and instead explore a multi-

147   basket approach in which gases with similar lifetimes are grouped together [29, 37-41].

148   Metrics that are further down the cause effect chain produce outcomes that are more policy

149   relevant than those based on radiative forcing, but at the same time their embedded

150   uncertainties increase. For instance, uncertainties for GTP are larger than those for GWP,

151   because the latter does not embed the uncertainty of the climate system response.

152   Temperature-based metrics involve a climate model, which can be a simple energy balance

153   model [25, 26], a temperature response function [24], or more sophisticated climate models

154   [18, 24, 28, 42], and this generally makes results sensitive to the parameterization of the

155   climate system [1]. Multi-model means are frequently used to mitigate these concerns [24]

156   and to better understand uncertainties [42]. However, the subjective selection of a TH for the

157   different metrics remain the most important factor that determines metrics variability [24],

158   especially for the weight given to forcers with a relatively short lifetime, compared to forcers

159   with long lifetimes [18]. This choice dependence introduces a strong, but often inadvertent

160   and only implicit, value judgement that frequently makes results open to contrary outcomes

161   [5, 15].

162

3. Well-mixed GHGs (WMGHGs)

164   CO_2, CH_4, nitrous oxide (N_2O), and some groups of halogenated gases have atmospheric

165   lifetimes longer than the hemispheric mixing time (up to a few years). They are generally

166   considered well-mixed because their atmospheric concentration has sufficient time to

167   become nearly uniformly distributed in the troposphere and their radiative forcing patterns

168   are usually independent of the emission location [1]. Table 1 shows a classification of the

169   main WMGHGs grouped by lifetimes, with information about their atmospheric

170   concentration and radiative forcing in 2011, and their radiative efficiency per mass unit

171   atmospheric burden (W m^{-2} kg^{-1}). For the purpose of a simple classification, we consider as

172   "short-lived" those WMGHGs, like methane and most hydrofluorocarbons (HFCs) or

173   hydrofluoroethers (HFEs), with atmospheric lifetimes shorter than the response timescale of

174   the climate system, which is typically from two to four decades [20, 43]. Gases with lifetimes

175   longer than about 50 years are sufficiently long-lived that the climate system has time to

176 fully respond to the perturbation, and their impact on temperature is more strongly

177 controlled by the amount of cumulative emissions [35, 40, 44].

178 The atmospheric decay of non-CO_2 WMGHGs is governed by relatively well-known

179 chemical and physical processes and can be simply described with exponential decay

180 constants corresponding to the respective lifetimes of the gases [45]. The constant decay-

181 time, however, remains an approximation since the lifetime of some gases is actually

182 affected by their own atmospheric concentration, and sometimes by that of other gases. For

183 instance, the atmospheric concentration of CH_4 or N_2O feeds back on their own respective

184 lifetimes [46], CO_2 can be produced after oxidation of other carbon-containing gases [1,

185 47], or ozone can cause changes to the global land-carbon sinks [48]. Some short-lived

186 species are thus also responsible of long-term effects through the carbon cycle and climate

187 feedbacks [1, 47, 49, 50].

188 Table 1 WMGHGs grouped by atmospheric lifetimes. For atmospheric concentrations and radiative forcing

189 only the gas listed in Table 8.2 of the WGI 5th IPCC Assessment Report [1] are considered. Information on

190 lifetimes of the gases, atmospheric concentration, radiative forcing and radiative efficiencies are from the 5th

191 IPCC Assessment Report[1].

Group of lifetimes	Gases	Lifetime (years)	Atmospheric concentrations in 2011	Radiative forcing in 2011 (W m^{-2})	Radiative efficiency (W m^{-2} kg^{-1})
Years	Some HCFCs, HFCs, Halocarbons, and HFEs	Between 1 and 10	21.4 ± 0.1 ppt HCFC-141b	0.0034 HCFC-141b	2.05E-11 HCFC-141b
Decades	CH_4, CFC-11, CFC-113, CCl_4, some HCFCs, HFCs, and HFEs	Between 10 and 100	1803 ± 2 ppb CH_4, 238 ± 0.8 ppt CFC-11	0.48 ± 0.05 CH_4, 0.062 CFC-11	4.65E-14 CH_4, 3.84E-11, CFC-113
Centuries	N_2O, HFC-23, HFC-236fa, HFE-125, NF_3, some CFCs	Between 100 and 1,000	324 ± 0.1 ppb N_2O, 528 ppt CFC-12	0.17 ± 0.03 N_2O, 0.17 CFC-12	3.84E-13 N_2O, 4.10E-11 CFC-12
Millennials	Fluorinated	Between	79 ppt CF_4	0.0041 SF_6	7.3E-11 SF_6

	gases (SF_6, CF_4, etc.), CFC–115	1,000 and 50,000			
Indefinite	CO_2	n.a.	391 ppm	1.82 ± 0.19	1.81E–15

192

193   Among WMGHGs, CO_2 represents a special case. Unlike most other agents, it does not

194   decompose through atmospheric chemical reactions, nor it is deposited on the Earth surface,

195   but it is removed from the atmosphere by a variety of processes with different timescales

196   influenced by multiple nonlinear dependencies [24, 51, 52]. For a 100 GtC emission pulse

197   added to a constant CO_2 concentration of 389 ppm, 15–35% of the perturbation is still

198   found in the atmosphere after a thousand of years; the ocean has absorbed 59 ± 12% and the

199   land the remainder (16 ± 14%) [24]. Thereafter CO_2 concentration is only removed by

200   ocean–sediment interactions and the weathering cycle through timescales of hundreds of

201   thousands of years [51, 53].

202   We show the normalized temporal evolutions of the responses to emissions of selected

203   WMGHGs in Figure 1. These responses, computed for both a pulse emission (Figure 1a,c)

204   and constant sustained emissions (Figure 1b, d), are simulated following the approach used

205   in the 5th IPCC assessment report [1] (see Methods in the Supplementary Information for

206   details). The longer the lifetime of the gas, the higher the emission fraction remaining

207   airborne over time (Figure 1a). Under constant sustained emissions (Figure 1b), the

208   normalized increase in radiative forcing asymptotically tends towards a maximum that is

209   proportional to the product of the atmospheric lifetime of the gas, its radiative efficiency,

210   and the emission rate. The time taken to approach this maximum value is critically

211   dependent on the lifetime, because it determines how soon atmospheric concentrations

212   reach steady state. Short–lived species are near maximum within a few decades, while for

213   others the steady state will not be reached for centuries or millennia. The temperature

214   response to a pulse of short–lived emissions shows a roughly symmetric rise and fall (Figure

215   1c), because the climate system has insufficient time to fully respond before the perturbation

216   has disappeared [20]. On the other hand, gases with longer lifetimes are persistent enough

217   that the resulting long–term warming is governed by the equilibrium climate sensitivity [54]

218   and some do not dissipate even on millennial time scales [45, 53]. The result is that the

219   warming from long–lived GHGs remains almost constant or decreases only slowly after the

220   temperature peak or a hypothetical cessation of emissions, and for some gases it is nearly

221   irreversible over many human generations. In the case of CO_2, the temperature does not

222   decrease significantly even if emissions cease entirely (Figure 1d). For extremely long–lived

223   gases like CF_4, the temperature continues to rise for a century or more following cessation of

224   emissions owing to the multi–century timescales of the ocean/atmosphere adjustments to

225   constant warming [37, 45].
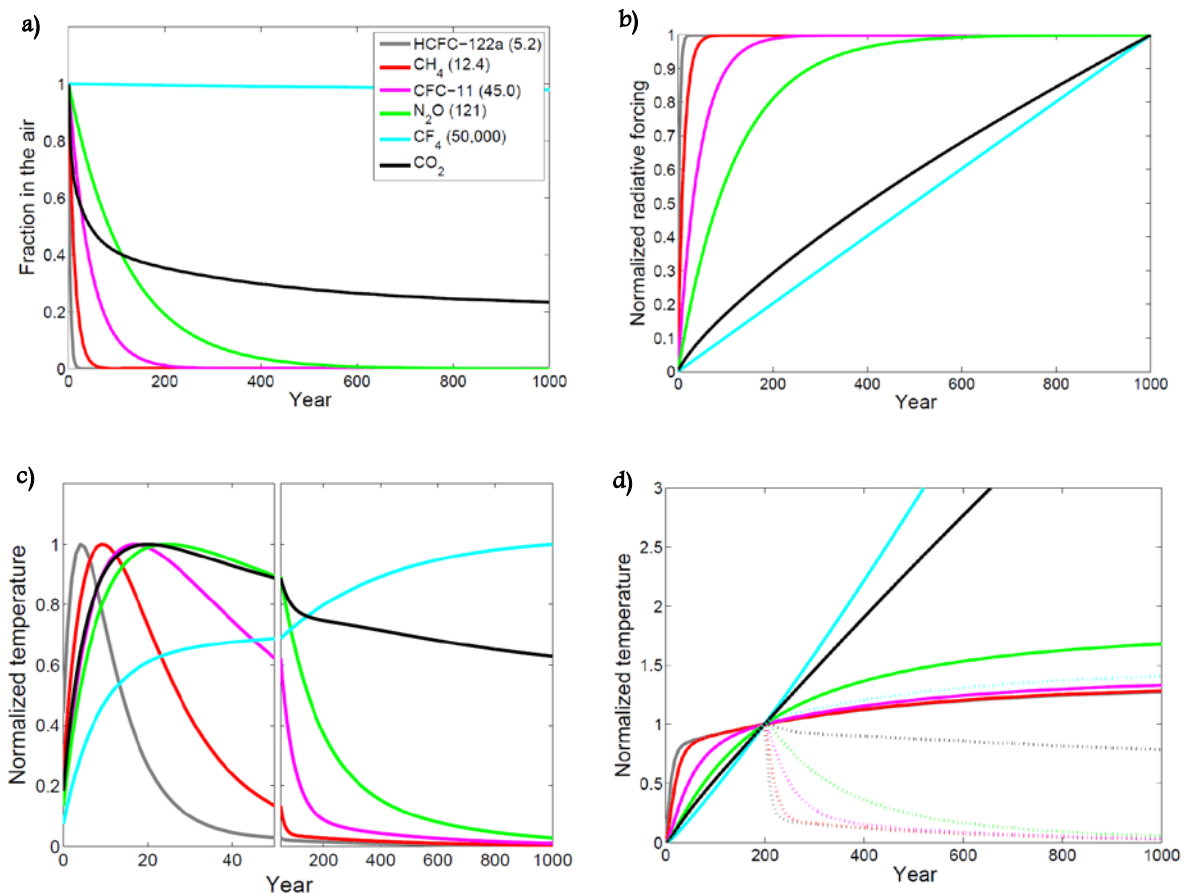
226 Figure 1 Temporal evolutions of the normalized responses of the climate system to some WMGHGs. a) Fraction

227 of the gas remaining in the atmosphere following an emission pulse at year zero; b) normalized radiative

228 forcing under constant emission rates; c) normalized global average surface temperature response to an

229 emission pulse at year zero; d) normalized global average surface temperature response to constant emission

230 rates (dotted lines show the response to a sudden cessation of emissions at year 200). Each curve is normalized

231 to its maximum value in the one thousand year time interval in b) and c). The temperature responses are

232 normalized to the respective value at year 200 in d). The selected gases are those found in IPCC AR5 Table 8.7

233 [1], with the replacement of HFC-134a (a gas with lifetime similar to methane) with a gas with lifetime of a

234 few years (HCFC-122a).

235

236 As pointed out in the climate science literature [20, 23, 33] and reiterated in the last IPCC

237 5th Assessment Report [1], the aggregation of WMGHGs to CO_2-equivalents is challenging

238 because it groups together gases with lifetimes ranging from a few years to several

239 thousands of years. Mitigation of either short-lived species or CO_2 achieves different goals

240 that are not equivalent in terms of climate system responses. For mitigation actions taking

241 place today, or several decades before a targeted temperature peak, metrics like GWP100

242 overestimate the importance of short-lived gases but underestimate their impact on near-

243 term change [18, 20, 33]. For example, HCFC-122a and N_2O have very different lifetimes (5

244 and 122 years, respectively) and temperature impact profiles. The temperature change from

245 N_2O is approximately 6.5 times larger than that from HCFC-122a 100 years after a pulse

246 emission, whereas the temperature change from HCFC-122a is about 1.5 times higher than

247 that from N_2O after 20 years from a pulse emission. Despite these differences, they are

248 considered as almost equal when converted to CO_2-equivalents because they have relatively

249 similar GWP100 values, 265 for N_2O and 258 for HCFC-122a [1]. This example underlines

250 the extent to which the choice of a metric can skew the apparent importance of different

251 gases, and why the use of a diverse array of metrics is desirable for matching specific policy

252   goals. The simple replacing of GWP100 with an alternative metric would not mitigate these

253   concerns because any choice that works for one dimension of the climate system, e.g. short–

254   term impacts, inevitably risks overlooking others, e.g. long–term impacts.

255

4. Emissions and temperature peaks

257   There is a growing interest in the climate science community to infer simplified metrics and

258   climate policy frameworks from the relationships between temperature peaks and emissions

259   [40, 55–57]. In Figure 2, we show the temperature peak dynamics of different WMGHGs

260   following four idealized emission trajectories. These trajectories, modelled with a triangular

261   temporal distribution (Figure 2a), have either the same cumulative emissions and different

262   maximum emission rates (E1 and E2), or the same maximum emission rate and different

263   total emissions (E3 and E4). When the temperature responses to E1 and E2 are compared

264   (Figure 2b), gases with short lifetimes have different temperature peak values (e.g., up to

265   40% lower under E2 than E1 for HCFC–122a), whereas nearly identical maximum

266   temperatures are achieved by gases with longer lifetimes. Under constant cumulative

267   emissions, temperature changes from gases with short lifetimes are sensitive to the

268   maximum rate at which emissions occur, and the sensitivity gradually decreases while the

269   lifetime of the gas increases. Temperature changes from gases with longer lifetimes become

270   more sensitive than short–lived species to specific emission trajectories if total cumulative

271   emissions differ (Figure 2c). For instance, the temperature peak reached by CO_2 emissions is

272   about 30% lower under E4 than E3. We compare the effect of emission rates and cumulative

273   emissions on the temperature responses in Figure 2d, where the normalized temperature

274   peak differences are plotted against the lifetime of the gases. Gases in the top right corner

275   (CO_2 and CF_4) have higher sensitivity to cumulative emissions, whereas if a gas lies in the

top left corner (HCFC122a) has a strong sensitivity to emission rates. The temperature

increase from short-lived emissions thus primarily depends on today emissions, which

mainly affect the rate and magnitude of climate change over the next few decades [37, 38,

40, 58, 59]. On the other hand, the temperature impact from long-lived gases like CO_2 and

CF_4 gradually accumulates over time and, rather than with the rate and timing of emissions,

it scales with the cumulative amount of emissions, including those occurred in the past [40,

53, 55, 60, 61].
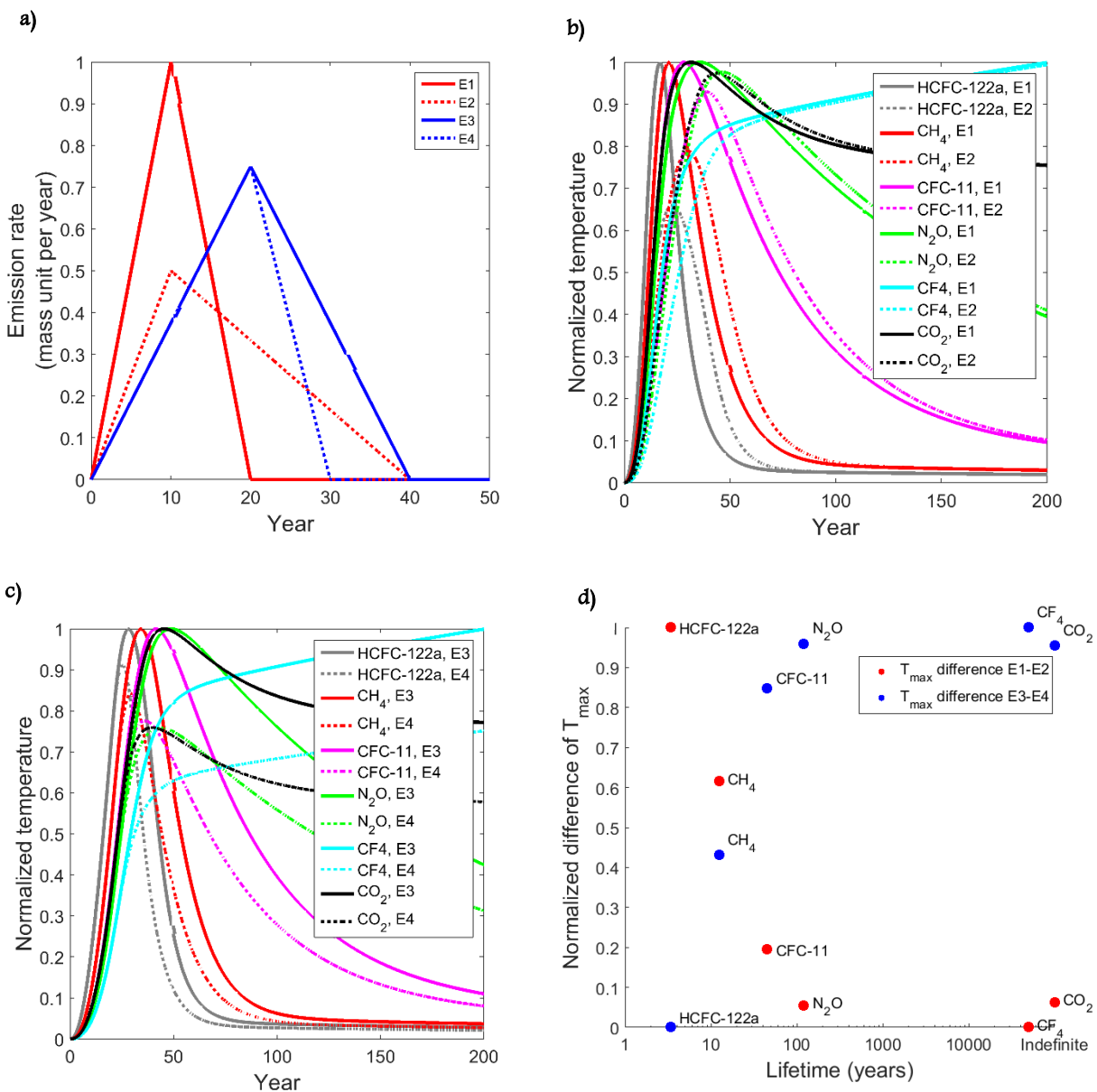
283 Figure 2: Sensitivity of the temperature response of WMGHGs to emission rates. a) idealized emission rates

284 peaking and declining. E1 and E2 have the same amount of cumulative emissions but different maximum

285 emission rates (E1 > E2); E3 and E4 have the same maximum emission rate but different cumulative emissions

286 (E3 > E4); b) normalized temperature responses to E1 and E2; c) normalized temperature responses to E3 and

287 E4; d) normalized difference of the temperature peak (T_{max}), computed from the responses in b) and c), for

288 each WMGHG as a function of the lifetime of the gas (logarithmic scale). The red dots indicate the normalized

289 differences in the temperature peak values of each WMGHG to emission scenarios E1 and E2 (Figure 2b). The

290 blue dots are for the normalized differences in T_{max} under emission scenarios E3 and E4 (Figure 2c). Values

291 close to 1 indicate high sensitivity of T_{max} to emission rates (red dots) or cumulative emissions (blue dots). The

292 profile for each gas in b) and c) is normalized to the respective maximum value from the emission scenario E1

293 and E3, respectively. For CF_4, the temperature at 200 years is taken as the normalizing factor.

294

295 The relationship between emissions and temperature peaks is used to produce simplified

296 emission metrics and approaches [37, 40, 55, 56]. If climate policy is focused on avoiding a

297 specific temperature threshold, its achievement largely depends on the cumulative emissions

298 of long-lived gases until the year of the peak, and on emission rates of short-lived species in

299 the one or two decades preceding the peak [40, 62, 63]. In such a context, emissions of

300 short-lived gases should be progressively more weighted as the temperature peak is

301 approached, and less if it is more distant. There are options to link metric values to the

302 gradual approaching of climate targets, such as time dependent formulations of GWP or

303 GTP [18, 28, 33] and other metrics explicitly connected to a climatic threshold [14, 34].

304 Another option that is gathering increasing interest is the "transient climate response to

305 cumulative carbon emissions" (TCRE) [60], which is formally defined as the warming due to

306 one trillion ton of cumulative carbon emissions and is based on the linearity between

307 temperature peak and cumulative emissions [55, 61]. Earlier estimates of the TCRE

308 suggested an average value of 1.6 ± 0.5 °C per Tera ton carbon (TtonC) emitted [61], while

309 estimates from both observations and coupled models provide a wider range of 0.8–2.5 °C

14

310 per TtonC [60]. Although so far mainly validated for CO_2, the concept of TCRE can also be

311 extended to other long-lived GHGs [44]. Similarly, the temperature contribution from short-

312 lived gases can be approximated using scaling factors applied to the maximum emission

313 rates [37, 40, 58, 59]. The use of metrics based on temperature peak dependencies on either

314 emission rates or cumulative amounts within an LCA framework has not been explored yet.

315 On one hand, this approach would allow a multi-basket framework where the various

316 forcing agents are grouped together on the basis of their lifetimes, thus avoiding the practice

317 to group together species with very different lifetimes. On the other hand, different sets of

318 emission metrics would still be needed to aggregate emissions to common units, and the

319 selection of the metrics to be used in the different baskets would still remain based on value-

320 laden choices, as it would be dependent on the preferred policy goal [41]. Still open is also

321 the question on how to weight one basket with respect to the other, with some arguing that

322 any trading between the different baskets should not be allowed [37, 38].

324 ### 5. Near-term climate forcers (NTCFs)

325 In addition to emissions of WMGHGs, human activities perturb the climate system through

326 emissions of pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), volatile

327 organic compounds (VOCs), black carbon (BC), organic carbon (OC), sulphur oxides (SO_x),

328 and ammonia (NH_3). Some of these pollutants are precursors to the formation of

329 tropospheric ozone (NO_x, CO, VOCs), others are primary aerosols (BC, OC) or precursors to

330 secondary aerosols (NO_x, SO_x, NH_3). These species have lifetimes shorter than the

331 hemispheric mixing time and are usually called near-term climate forcers (NTCFs). The

332 atmospheric concentrations of NTCFs are very heterogeneous, with high concentrations

333 around the emission source, and therefore the resulting impact largely depends on the

334 source region [64–67]. Although short-lived GHGs like CH_4 are sometimes referred to as

335 NTCFs, we here restrict this definition to species with inhomogeneous atmospheric

336 concentrations that are not well-mixed.

337 The considerations above associated with the characteristics of the temperature response to

338 short-lived species also apply to NTCFs. Emissions of NTCFs may also have an effect on

339 precipitation patterns through changes in cloud formation processes and cover [2], which

340 have recently been quantified in terms of emission metrics [31]. In general, the confidence

341 level in the predicted climate impacts from NTCFs is lower than that for WMGHGs,

342 especially in the cases in which aerosol–cloud interactions are important (see section 8.5.1

343 in ref. [1] and the latest specific IPCC chapter on the matter [2]). These emissions are

344 coupled to the hydrological cycle and atmospheric chemistry and involve highly complex

345 processes that are challenging to validate. The net climate impacts of NTCFs are the result of

346 many opposing effects with different temporal evolutions at play. NO_x species are very

347 reactive and affect climate through many nonlinear chemical interactions with various

348 timescales [21, 46], including nitrate and ozone formation, changes in CH_4 concentration

349 and thereafter stratospheric water vapour [46, 50]. NO_x also influences CO_2 and the global

350 carbon cycle through the fertilization effect of nitrogen depositions. Other ozone precursors

351 are CO and VOCs, which increase the concentration of ozone on short time scales and by

352 affecting the levels of hydroxyl (OH) radical, and thereby of CH_4, they also initiate a net

353 positive long-term ozone effect [3, 65]. Aerosol species influence the climate mainly through

354 absorption (BC) or scattering (OC, sulphate and nitrate) of solar radiation and other indirect

355 effects, like deposition of BC on snow. Aerosols are either directly emitted from sources

356 (primary aerosols, like BC and OC), or they are formed in the atmosphere via several

357 processes (secondary aerosols, like sulphate after oxidation of SO_2, and OC from

358 condensation of organic compounds).
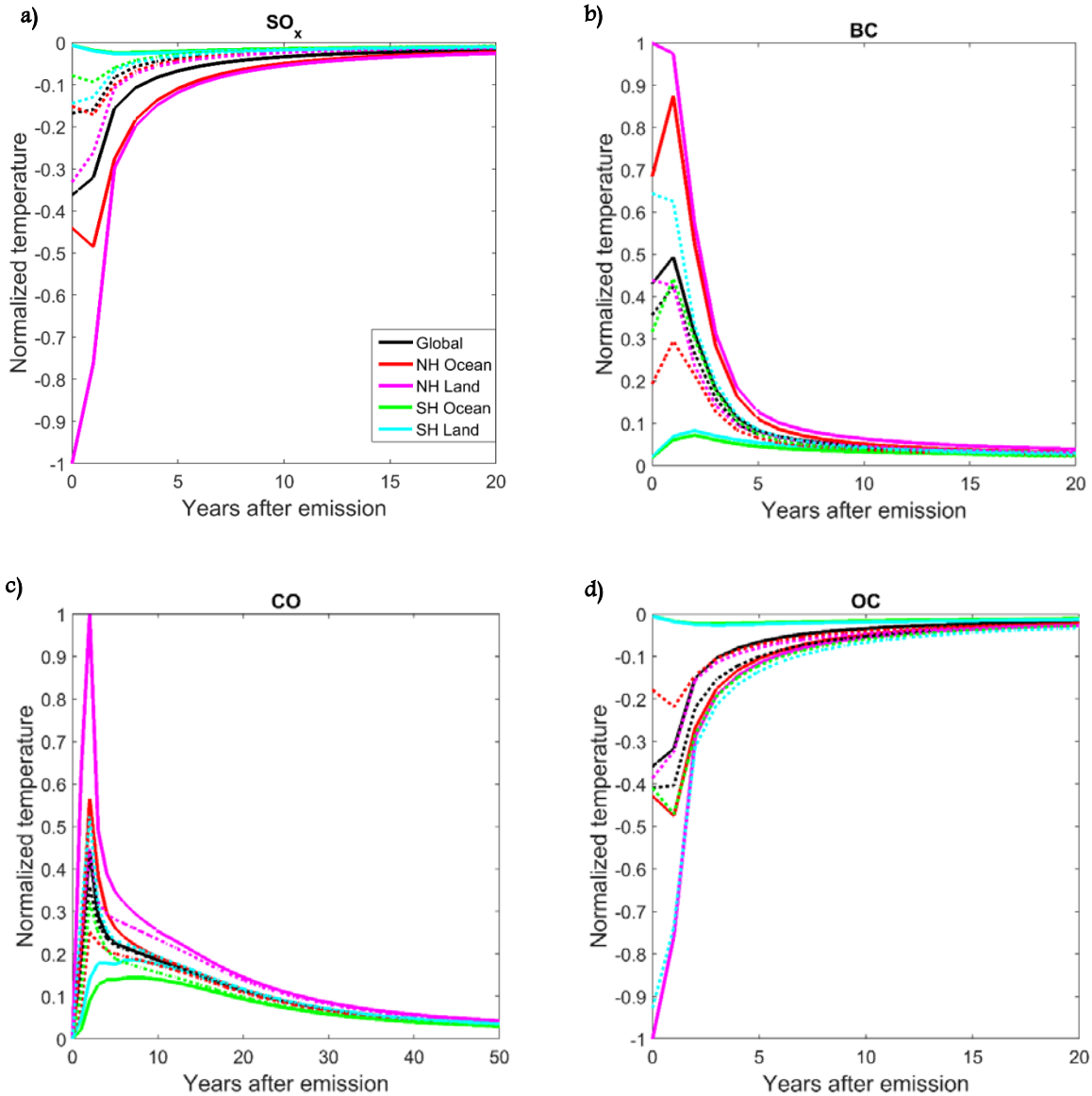
Figure 3 Global and regional normalized temperature responses to pulse emissions of selected NTCFs (SO$_x$, BC, CO and OC) located in the northern or southern hemisphere. The responses to emissions in the northern hemisphere (NH) are shown with solid lines, those to emissions from the southern hemisphere (SH) with dashed lines. The temperature response is averaged globally and over the land and oceans of NH and SH. For each specie, curves are normalized to the maximum (for BC and CO) or minimum (for SO$_x$ and OC) value of all the responses.

Figure 3 shows the normalized temperature effects from pulse emissions of three aerosol species (SO$_x$, BC and OC) and one ozone precursor (CO). Emissions are located in the

368   northern or southern hemisphere, and the temperature response is averaged both globally

369   and over macro regions like the land and oceans of the northern and southern hemispheres.

370   The responses, which merely have illustrative purposes, are computed using the simplified

371   climate model MAGICC6 [68], a model widely used in the climate science community (see

372   Methods in the Supplementary Information). Emissions from different regions have different

373   lifetimes and the responses are regionally dependent. The global averaged temperature has

374   significant variations with respect to the regional trends. The climate impact response to an

375   emission pulse is generally higher in the northern hemisphere, where there is the strongest

376   sensitivity to forcing, and over the land than the oceans, due to differences on evaporation

377   [69]. Emissions of BC have the largest impact on regional average temperature change when

378   located in the northern hemisphere, because BC can be easily transported to the white

379   surfaces of the arctic and thereby decrease albedo. The response to CO and VOCs are less

380   heterogeneous because they have longer lifetimes (from one to three months) and are

381   approximately well-mixed on a hemispheric spatial scale. As discussed elsewhere [20, 66,

382   70], they are less dependent on emission location and model configurations, although the

383   consideration of vegetation effects of ozone and aerosol responses can increase variability

384   [48].

385   Climate impacts from NTCFs are currently excluded from LCA studies, carbon footprints, or

386   international global climate agreements. Their possible inclusion has been debated [3, 5, 65,

387   70, 71] and, in some cases, explicitly argued [3, 5, 71]. However, the characterization of

388   NTCFs to CO_2 equivalents is even more difficult than it is for short-lived gases because of

389   the very short lifetime of the forcing, its spatial heterogeneity, and the larger uncertainty.

390   Global metrics like GWP normally use globally-averaged inputs to produce globally-

391   averaged measures and give no information about the spatial variability of the impact.

392   Global metrics available in the literature for NTCF emissions located in different regions are

393   presented and discussed in the 5th IPCC assessment report [1]. There is not a robust

394   relationship between the region of the emission and the metric value [20], and the inter-

395   model variability is sometimes larger than the variability between emission regions [50, 72].

396   Measures that rely on global averages or long integration times do not fully represent the

397   temporal and spatial characteristics of the responses [73, 74]. The application of a metric

398   that is first calculated locally and then averaged globally could be one way of capturing a

399   more complete and informative signal than one that uses global mean outputs [73].

400   Regional specific responses and emission metrics for NTCFs are also available [50, 64, 74,

401   75]. Absolute Regional Temperature Potentials (ARTP) are computed using fully coupled

402   atmosphere-ocean climate models and approximate the time-dependent temperature

403   response at four latitude bands as a function of the regional forcing imposed by various

404   climate pollutants in all bands [75]. These metrics allow the assessment of the climate effects

405   from NTCFs with some regional resolution without coupling the analysis with sophisticated

406   climate models. However, additional studies are required to determine the robustness of

407   ARTPs and explore their feasibility for life cycle impact assessment methods. Existing climate

408   impact frameworks rely on the assumption that the emission location does not affect the

409   response of the climate system and the climate change impact category has a global scale.

410   These assumptions hold for WMGHGs but not for all NTCFs. Species like NO_x, SO_x, BC and

411   OC would ideally require the formulation of sub-global emission locations and impact

412   categories for using the corresponding regional metrics.

413   There are other important caveats associated with the accounting of the climate impacts

414   from NTCFs. As they can have significant contributions to global warming, their inclusion in

415   LCA can make their mitigation an attractive proposition to achieve multiple environmental

416   goals at the same time [76], because these species have adverse effects in other

417   environmental impact categories than climate change, like human and ecosystem health .

418   On the other hand, some NTCFs have cooling effects, and their accounting may result in a

419   partial offsetting of the warming effect of the total aggregated emissions. This would result

420   in the attribution of climate benefits to species which are responsible of air pollution and

421   damage to ecosystems. LCA methodology includes many environmental impact categories

422   and is by definition well suited to inform about the possible shifts of impacts across

423   categories. However, risks of this type are higher in carbon footprint studies or other

424   applications where the goal is limited to the assessment of climate change impacts only.

425   Accounting for NTCFs using metrics like the GWP100 would bring to common unit species

426   with very different climate impact profiles and expand the abatement options available.

427   Decision-makers could for instance prioritize mitigation of NTCFs and delay reductions in

428   long-lived species like CO_2, thereby causing irreversible long-term warming for the sake of

429   reducing near-term rate of warming. Another important aspect is the consideration that

430   NTCFs are frequently co-emitted, and this has implications for the benefits that can be

431   achieved by their mitigation [62, 63]. For instance, with approximately 0.64 W m^{-2}, BC is

432   the third largest radiative forcing component for the period 1750-2011 after CO_2 and CH_4

433   [1]. One can therefore argue that a reduction in BC emissions will bring considerable

434   benefits for the climate. However, the benefits from a decrease in BC emissions are

435   dampened by the simultaneous reduction of emissions of species like SO_x and OC, which

436   have cooling contributions [62, 63].

437

6. Land use and land cover change (LULCC)

439   Climate impacts from a change in land use or management are frequently associated to

440   emission or removal of WMGHGs like CO_2, N_2O and CH_4. Direct GHG emissions from land

441   use changes such as deforestation or afforestation, as well as those from changes in above-

ground or soil carbon content after a change in management, are usually accounted for in LCA, when data are available [4, 77]. The consideration of possible emissions associated with indirect land use changes via market-mediated effects, that is the change in land use in one place caused by a change in production in another place, is widely debated [78, 79]. Land use without land-cover change (e.g., managed or harvested forests) have traditionally been treated under a default carbon neutrality assumption [80], thus ignoring the temporal asymmetry between CO_2 emission and uptake fluxes, which can be rather significant for forests. Recent studies show how the climate forcing impact from this asymmetry can be assessed through site-specific emission metrics that embed post-disturbance carbon dynamics [81]. Emission metrics or temporally differentiated emission inventories are also used to compute the climate change implications of anthropogenic carbon sequestration and storage in products [11, 82-84].

Relatively more challenging and less common is the quantification of the biogeophysical effects following a change in land use or land cover. Modifications of the surface energy balance through changes in surface albedo, evapotranspiration (the fluxes of heat and water between the vegetation and the atmosphere), and surface roughness (the aerodynamics of the vegetation cover), can have implications for the local [85-87] and global [88-90] climate, either directly or indirectly [89, 91]. The global temperature impact from these effects can be of the same order of magnitude as the impact associated with CO_2 emission or removal fluxes [88, 90, 92, 93], whether or not the land cover change is long lasting, such as in afforestation or deforestation [90, 94], or transient, such as in forest management or post-fire forest recovery [7, 95]. Nevertheless, accounting for changes in albedo and other biogeophysical properties is not currently required in the formal rules for quantifying the climate effects of land use activities [96]. This is despite the large evidence from climate simulation studies [88, 90, 96-98] or empirical observations [86, 99], where the importance

467   to go beyond a simple carbon accounting framework when assessing the impacts of LULCC

468   activities on climate is frequently highlighted [7, 92, 96-98]. It has been explicitly argued

469   that "ignoring biophysical interactions could result in millions of dollars being invested in

470   some mitigation projects that provide little climate benefit or, worse, are counter-

471   productive" [96].

472   Biogeophysical properties vary with surface cover and have high spatial and seasonal

473   variations. There are differences between summer and winter, especially in areas affected by

474   seasonal snow cover. For instance, forests usually have lower albedo than open lands such as

475   grassland or cropland, especially during snow covered periods. Biogeochemical effects

476   following a change in forest cover usually dominate at low latitudes, while biogeophysical

477   contributions are stronger at high latitudes [88-90, 100]. Biogeophysical effects are

478   significant also when changes in management occur on the same land use type, such as

479   irrigation, crop rotation, and forestry [7, 98, 99]. In general, climate impacts vary in spatial

480   scale and depend on complex, and often nonlinear, mechanisms. Compared to grass, trees

481   are generally more efficient in transferring water from the soil to the atmosphere because of

482   their deeper roots and larger leaf area, and forests thus tend to maintain a cooler local

483   surface temperature by releasing more energy in the form of latent heat than sensible heat.

484   Hence, conversion from forest to grassland tends to warm the local surface, and it also tends

485   to reduce the roughness of the landscape and thus to reduce the turbulence in the boundary

486   layer. However, it is difficult to predict the effect that this reduction may have on surface

487   temperature, because the reduction of heat and water vapour transport associated with

488   reduced turbulence may be compensated by greater gradients of humidity and temperature

489   between the surface and the atmosphere [89, 96].

490   Biogeophysical effects differ in nature. Changes in surface albedo and emissivity modifies

491   global temperature by directly altering the Earth's radiative balance, while changes in

492   evapotranspiration and surface aerodynamics do not imply any direct perturbation to the

493   earth's radiative balance [89]. The quantification of the climate change effects from

494   evapotranspiration and surface roughness is complex. The attribution of regional and global

495   climate change effects to these forcing agents is highly uncertain and limited in evidence,

496   owing to a wide spread in model estimates and differences between observations and model

497   results [87, 91, 101]. Modelling changes in evapotranspiration and surface roughness also

498   requires knowledge of numerous vegetation structural, physiological, and environmental

499   parameters [97, 101], posing formidable challenges for the accounting of these effects in

500   climate impact assessment studies. On the other hand, changes in surface albedo are rather

501   more certain and less challenging to quantify. The 5th IPCC assessment report classified the

502   radiative forcing estimates from surface albedo changes with a *high* confidence level, as it

503   has robust evidence with well documented high precision measurements [1]. Surface albedo

504   is also the most important biogeophysical mechanism influencing the global climate in

505   extra-tropical regions, especially in areas experiencing seasonal snow cover [88, 90, 98].

506   Because they can be measured in terms of radiative forcing, impacts from changes in

507   surface albedo are frequently converted to CO_2 equivalents using either carbon equivalent

508   factors [97, 102] or more conventional emission metrics like GWP or GTP [13]. However,

509   because of the non-linear and high spatial heterogeneity of the climate forcings from land-

510   atmosphere perturbations as well as the different temporal behaviour, the development and

511   possible routine applications of climate metrics for LULCC in LCA need to be land cover-

512   and location-specific. Like for NTCFs, radiative forcing from albedo changes located in

513   different regions affect climate heterogeneously [89, 90], with radiative forcings at high

514   latitudes being more effective in changing global temperature than radiative forcing at low

515   latitudes [103]. Because changes in land surface aerodynamic and physiological properties

516   often dampen the radiative temperature change at the local surface [89], global radiative

forcings from WMGHGs, like CO_2, and LULCC do not produce the same global mean

temperature response when added together, and more accurate estimates are achieved when

the individual climate responses are used [104]. However, the lack of regional temperature

response functions and metrics for radiative forcings originated from changes in

biogeophysical effects at various locations has so far limited the possibilities to perform

temperature–based analyses without coupling the study with global climate models.

In addition to WMGHGs and surface albedo, changes in land cover have a third direct effect

on the global radiation balance by altering emissions of biogenic VOCs (BVOCs), which

rapidly oxidize in the atmosphere generating multiple warming and cooling climate

pollutants like ozone and biogenic secondary organic aerosols [3, 105]. The photochemical

processing of BVOC emissions influences the oxidation capacity of the atmosphere, which

affects the lifetime of CH_4 and the production of other secondary aerosols (sulphate and

nitrates). Even if BVOC emissions are formally quantified as a terrestrial biogeochemical

feedback that responds to anthropogenic climate change [52], we briefly discuss them here

given the strict link they have with LULCC. As for the other NTCFs, the net radiative patterns

are highly spatially inhomogeneous. The net radiative forcing from historical BVOC

emission reductions from expansion of agricultural areas is estimated in a negative (cooling)

contribution [3]. Conversely, increasing BVOC emissions following LULCC involving

reforestation or afforestation strategies cause a positive radiative forcing [71]. Despite

relevant recent progress, important uncertainties still persist. Current generation models

underestimate the amount of organic aerosols in the atmosphere and are unable to fully

reproduce the variability found in the measurements [1]. As NTCFs, BVOC oxidation

products are also important for the growth of newly formed particles up to cloud

condensation, so they indirectly influence climate through changes in cloud albedo [106].

These atmospheric aerosol processes changing cloud droplet concentrations and radiative

542   properties are among the least understood in climate research, and their contributions to the

543   global radiation budget are considered as one of the largest source of uncertainty in the

544   estimation of radiative forcing over the industrial period [106]. Results are not consistent

545   across models, with estimates ranging between +0.23 W m^{-2} and -0.77 W m^{-2} [3]. All these

546   aspects make a possible consideration of the contributions from aerosol–cloud effects in LCA

547   and similar studies unrealistic for the short and medium term.

548

549   **7. The way forward**

550   Anthropogenic global warming is caused by a variety of forcing agents with different

551   physical properties and lifetimes ranging from few days, like black carbon, to several

552   thousands of years, like CF_4. Climate impact methods used in LCA are challenged when it

553   comes to dealing with aspects like the various timescales of the responses to different GHGs,

554   impacts from NTCFs and LULCC, and their temporal and spatial variability. Emissions can

555   also be aggregated by metrics other than GWP100. Alternative metrics would allow the

556   representation of different dimensions of climate change impacts, but would not sidestep the

557   value–laden considerations of the relative weighting. Value judgements are embedded in

558   metric formulations, most notably through the choice of time horizon, of climate impact

559   parameters, and by whether the indicator refers to a time–integrated or instantaneous

560   quantity. Any preference of one metric over another arguably favours the representation of

561   some aspects of the climate system response and at the same time discount others.

562   There are considerable uncertainties in the attribution of climate impacts to specific forcing

563   agents. Scientific uncertainties are larger for temperature–based metrics than for those

564   based on radiative forcing, and for NTCFs, BVOCs, or non–radiative LULCC mechanisms

565   than for WMGHGs or changes in surface albedo following LULCC. The presence of

566 uncertainties should not *per se* be an overriding constraint for using metrics and modelling

567 impacts [20]. If the main policy goal is to keep global temperature below a certain threshold,

568 the uncertainties and timing of political choices (i.e. a delay in action) are often those with

569 the largest cost-risk distributions, and may actually swamp the uncertainties associated with

570 the parameterization of the climate system [107].

571 Concerning the aggregation to common units, it is impossible to identify a single metric that

572 can produce a balanced representation of the overall climate impact from such a diversity of

573 forcing agents. Different climate policy goals may lead to different conclusions about what

574 is the most suitable metric to assess that policy. For instance, the use of GWP100 in LCA has

575 the inadvertent consequence of assessing emissions for their contributions to global

576 temperature over a timeframe of about four decades [35, 36], with no direct connections to

577 peak warming. GWP100 only becomes an indication of the contributions to peak warming

578 under the arguably optimistic assumption that global CO_2 emissions will approach zero

579 within about 40 years, so that the global temperature will approach stabilization. The

580 characterization of different emissions to CO_2-equivalents implicitly suggests that one can

581 freely choose which emissions to reduce in order to achieve the same improvement in the

582 climate system performance of a product. However, the same net reduction of the total

583 aggregated emissions in CO_2-equivalents will have different climate effects at different

584 times, depending on whether it is obtained through a reduction in long-lived or short-lived

585 species. If emissions of long-lived gases continue to rise, the mitigation of short-lived species

586 would temporarily reduce the rate of warming but cannot avoid the risk of passing

587 warming thresholds, because as long as the concentration of CO_2 is allowed to keep

588 growing, the reaching of those thresholds is only temporally postponed. Any delay in

589 mitigation of CO_2 emissions will lead to nearly irreversible warming. Within the global

590 policy goal of limiting warming to 2°C above pre-industrial levels, mitigation of CO_2

591 emissions is thus identified as a non-negotiable objective in strategies aiming at constraining

592 maximum temperature [35, 37, 44, 55, 57, 63], because any deferral in mitigating long-

593 lived emissions progressively closes the door for achieving ambitious peak temperature

594 targets.

595 Bridging life cycle impact assessment methods with climate science is essential to provide

596 decision makers with more robust climate change impact studies that acknowledge the

597 variety of forcing agents at play and the caveats of their aggregation. There are metrics other

598 than GWP100 and climate forcing agents other than WMGHGs. Explicit consideration of

599 alternative metrics by LCA practitioners would allow the characterization of climate change

600 impacts over multiple timescales and with regard to diverse and contrasting policy goals.

601 For instance, the use of metrics like GWP20 or GWP100 can provide information about the

602 time-integrated contributions to global warming in a short/medium term, whereas GTP100

603 provides information about the instantaneous contributions to global warming on a longer

604 timeframe. If GWP aligns well with the LCA ambition to prefer integrated impacts, GTP

605 provides the possibility to explicitly link global warming contributions to a climate target,

606 based on planetary boundary and/or policy considerations. In general, the utilization of

607 multiple metrics provides complementary information on the implications of mitigating

608 gases with varying lifetimes, and shows the extent to which results are sensitive to the

609 choice of metric or robust across a range of choices. The inclusion in existing LCA databases

610 and impact assessment methods of the spectrum of the metrics available in the latest IPCC

611 assessment report will facilitate their application by LCA practitioners.

612 The consideration of NTCFs in LCA presents challenges at an inventory and characterization

613 level. Most of the NTCFs are already tracked by the majority of the life-cycle inventory

614 databases, as they contribute to other environmental impact categories, except for BC and

615 OC emissions. Although they can be indirectly quantified from emissions of particulate

616   matter, their explicit inclusion in emission inventories is desirable to facilitate applications.

617   Characterization of their impacts on climate should consider the higher level of

618   uncertainties associated with metrics for NTCFs, and ideally consider the range of possible

619   metric values summarized in the latest IPCC report. The LCA community should closely

620   follow updates on quantification of impacts from NTCFs as the climate science community is

621   continuously improving the robustness of characterization factors for NTCFs.

622   Regional climate change categories can also be formulated in the future when robust

623   estimates of metric values for regional responses to NTCFs become available. Inventory

624   databases should already be adapted by elaborating spatial-explicit emission inventories

625   that keep track of emission regions.

626   The time is ripe for the LCA community to consider the complexity of climate science and

627   gain insights on the implications associated with the selection of emission metrics for the

628   intended goal of the analysis. Rather than using a single default metric for WMGHGs in all

629   applications, analysts should acknowledge the various forcing agents and the caveats

630   associated with the aggregation of species with different lifetimes to common units. The

631   sensitivity of the results to the type of metric used should be explored. When a choice is to

632   be made, this can be done consistently with the aspects of climate change that are most

633   relevant for the particular application. In any case, it is important to be aware and

634   transparent about the choice of metric, its meaning, and the inherent value judgments it

635   entails when interpreting and communicating results. A continuous bridge between the two

636   communities is desirable in the future to keep LCA methods up-to-date with the latest

637   developments in climate science, and simultaneously engage climate scientists to shape

638   emission metrics and approaches to fit environmental impact assessment frameworks.

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