Bridging the gap between impact assessment methods and climate science

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Abstract

Life-cycle assessment and carbon footprint studies are widely used by decision makers to identify climate change mitigation options and priorities at corporate and public levels. These applications, including the vast majority of emission accounting schemes and policy frameworks, traditionally quantify climate impacts of human activities by aggregating greenhouse gas emissions into the so-called CO_2-equivalents using the 100-year Global Warming Potential (GWP100) as the default emission metric. The practice was established in the early nineties and has not been coupled with progress in climate science, other than simply updating numerical values for GWP100. We review the key insights from the literature surrounding climate science that are at odds with existing climate impact methods and we identify possible improvement options. Issues with the existing approach lie in the use of a single metric that cannot represent the climate system complexity for all possible research and policy contexts, and in the default exclusion of near-term climate forcers such as aerosols or ozone precursors and changes in the Earth's energy balance associated with land cover changes. Failure to acknowledge the complexity of climate change drivers and the spatial and temporal heterogeneities of their climate system responses can lead to the deployment of suboptimal, and potentially even counterproductive, mitigation strategies. We argue for an active consideration of these aspects to bridge the gap between climate impact methods used in environmental impact analysis and climate science.

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

using the 100-year global warming potential (henceforth GWP100) as the default emission metric. A similar procedure is frequently applied in international agreements, like the Kyoto protocol, the Intended Nationally Determined Contributions (INDCs) for mitigation obligations to 2030 and climate-oriented policy directives, such as those regulating the climate impacts of specific sectors. This practice does not take into account the impacts from emissions of NTCFs or biophysical factors arising from changes in land cover. It also overlooks the temporal and spatial heterogeneities of the climate system response to different forcing agents, and the consideration of emission metrics alternative to GWP100. Studies that have explored the influence of NTCFs [5, 6], of changes in surface albedo [7, 8], of temporal and spatial impact dynamics [9-11], and of metrics other than GWP100 [5, 12-15] on the climate impacts attributed to a specific human activity usually conclude that an international effort on improving existing methods is desirable to prevent the implementation of suboptimal mitigation pathways.

The Life Cycle Initiative under the United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC) launched the Global Guidance on Environmental Life Cycle Impact Assessment Indicators to revise existing standard methodologies used in environmental impact categories of LCA and footprint studies [16, 17], including climate change. Here, as part of the activities from the Global Warming Task Force, we identify key insights from the climate science related literature that are of relevance for advancing climate impact assessment frameworks.

2. Life cycle impact assessment and emission metrics

The life cycle impact assessment phase consists in the conversion of different well-mixed greenhouse gases (WMGHGs) to common units (kg CO_2-eq) after multiplication of each

emission flow by the respective emission metric, [4]. Emission metrics, which in LCA are usually referred to as characterization factors, are typically simplified measures of the climate system response to forcing agents and are mostly based on outcomes from physical models of varying complexity linking emissions to impacts [1]. Metrics can be formulated in absolute terms, for instance based on the temporal evolution of a temperature impact, or in relative terms after normalization to a reference gas, usually CO_2 [5, 18]. Different emissions have different climate system responses, and a metric that establishes equivalence with regard to one effect does not usually result in equivalence with regard to other effects.

GWP is an integrative measure defined as the integrated radiative forcing of a gas between the time of emission and a chosen time horizon (TH) relative to that of CO_2. The GWP was introduced by the first IPCC assessment report in 1990 with illustrative purposes and, by its own definition, it does not embed any climate system responses or direct link to policy goals [1]. Despite the rather cautious introduction by the IPCC, the United Nations Framework Convention on Climate Change, LCA and the majority of national and corporate emission accounting frameworks started to use this metric without any substantial modifications, with the exception of updating the GWP values according to the successive IPCC reports.

GWP is a metric that aligns well with the general principles of LCA. LCA privileges impacts integrated over time and space under the objective of avoiding burden shifting of impacts [4]. LCA also typically follows a "marginal change" approach, in the sense that an additional amount of a certain pollutant is assumed to introduce very small changes on top of a constant background. This approach allows the assessment of environmental impacts associated with the life cycle impacts of a single unit of a product, which gives only a small contribution to the total impact [19]. Common critiques to GWP concern the fact that, despite its name, it does not equate climate forcing agents on the basis of their effects on surface temperature, nor does it consider them under a specific climate policy target, such

as the goal to limit warming to 2 degrees above pre-industrial levels [18, 20-22]. The use of a TH of 100 years seems to be the result of an "inadvertent consensus" [23] and it is not directly linked to any particular climate policy objective. There are many emission metrics available from the climate science literature that focus on different characteristics of the climate system response to emissions [12, 18, 20, 21, 24-28]. By targeting different aspects of the climate impact cause-effect chain, such as radiative forcing [29], temperature [26, 27], sea level rise [30], precipitation changes [31], or economic dimensions [28], these metrics compare emissions on the basis of their instantaneous [26] or time integrated impacts [25, 27]. They are computed under a constant [1, 24] or changing [18, 32] background climate and can be formulated around a fixed or a target-dependent TH [14, 18, 33, 34]. A common alternative to GWP is the Global Temperature Change Potential (GTP), which is defined as the impact of a GHG emission pulse on global temperature at the chosen TH, again relative to CO_2 [26]. With the exception of some gases with very short lifetimes, values of GTP for a TH of about 40 years are usually similar to those of GWP100 [35]. Recently, GWP100 is shown to approximately equate a pulse emission of a cumulative climate pollutant and an indefinitely sustained change in the rate of emission of short-lived forcers, introducing a new application for GWP100 in comparing WMGHGs with different lifetimes [36]. Within a context of emission accounting, some also argue against the practice of aggregating all WMGHGs to common units [29, 37, 38] and instead explore a multi-basket approach in which gases with similar lifetimes are grouped together [29, 37-41].

Metrics that are further down the cause effect chain produce outcomes that are more policy relevant than those based on radiative forcing, but at the same time their embedded uncertainties increase. For instance, uncertainties for GTP are larger than those for GWP, because the latter does not embed the uncertainty of the climate system response. 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

163 **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

fully respond to the perturbation, and their impact on temperature is more strongly controlled by the amount of cumulative emissions [35, 40, 44].

The atmospheric decay of non-CO_2 WMGHGs is governed by relatively well-known chemical and physical processes and can be simply described with exponential decay constants corresponding to the respective lifetimes of the gases [45]. The constant decay-time, however, remains an approximation since the lifetime of some gases is actually affected by their own atmospheric concentration, and sometimes by that of other gases. For instance, the atmospheric concentration of CH_4 or N_2O feeds back on their own respective lifetimes [46], CO_2 can be produced after oxidation of other carbon-containing gases [1, 47], or ozone can cause changes to the global land-carbon sinks [48]. Some short-lived species are thus also responsible of long-term effects through the carbon cycle and climate feedbacks [1, 47, 49, 50].

Table 1 WMGHGs grouped by atmospheric lifetimes. For atmospheric concentrations and radiative forcing only the gas listed in Table 8.2 of the WGI 5th IPCC Assessment Report [1] are considered. Information on lifetimes of the gases, atmospheric concentration, radiative forcing and radiative efficiencies are from the 5th 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

1c), because the climate system has insufficient time to fully respond before the perturbation has disappeared [20]. On the other hand, gases with longer lifetimes are persistent enough that the resulting long-term warming is governed by the equilibrium climate sensitivity [54] and some do not dissipate even on millennial time scales [45, 53]. The result is that the warming from long-lived GHGs remains almost constant or decreases only slowly after the temperature peak or a hypothetical cessation of emissions, and for some gases it is nearly irreversible over many human generations. In the case of CO_2, the temperature does not decrease significantly even if emissions cease entirely (Figure 1d). For extremely long-lived gases like CF_4, the temperature continues to rise for a century or more following cessation of emissions owing to the multi-century timescales of the ocean/atmosphere adjustments to constant warming [37, 45].

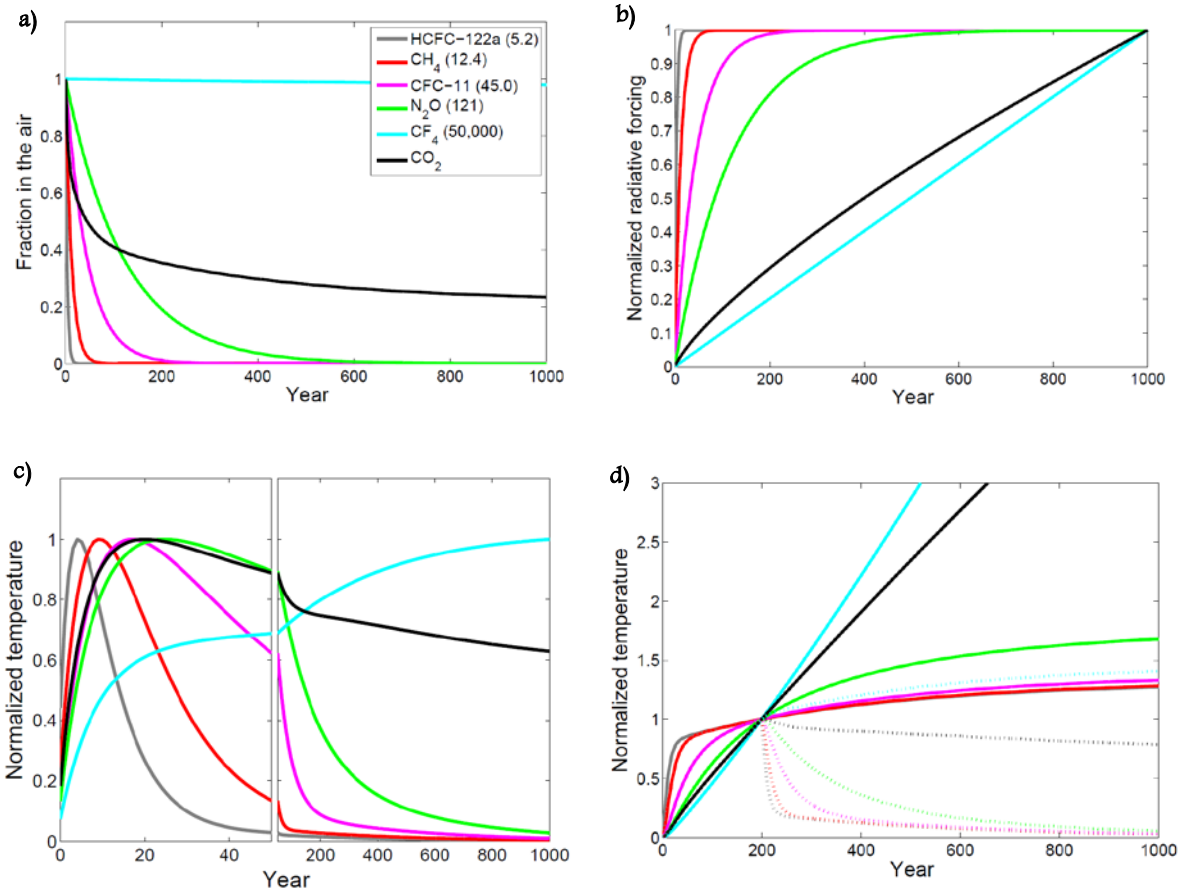


Figure 1 Temporal evolutions of the normalized responses of the climate system to some WMGHGs. a) Fraction of the gas remaining in the atmosphere following an emission pulse at year zero; b) normalized radiative forcing under constant emission rates; c) normalized global average surface temperature response to an emission pulse at year zero; d) normalized global average surface temperature response to constant emission rates (dotted lines show the response to a sudden cessation of emissions at year 200). Each curve is normalized to its maximum value in the one thousand year time interval in b) and c). The temperature responses are normalized to the respective value at year 200 in d). The selected gases are those found in IPCC AR5 Table 8.7 [1], with the replacement of HFC-134a (a gas with lifetime similar to methane) with a gas with lifetime of a few years (HCFC-122a).

As pointed out in the climate science literature [20, 23, 33] and reiterated in the last IPCC 5th Assessment Report [1], the aggregation of WMGHGs to CO_2-equivalents is challenging because it groups together gases with lifetimes ranging from a few years to several thousands of years. Mitigation of either short-lived species or CO_2 achieves different goals that are not equivalent in terms of climate system responses. For mitigation actions taking place today, or several decades before a targeted temperature peak, metrics like GWP100 overestimate the importance of short-lived gases but underestimate their impact on near-term change [18, 20, 33]. For example, HCFC-122a and N_2O have very different lifetimes (5 and 122 years, respectively) and temperature impact profiles. The temperature change from N_2O is approximately 6.5 times larger than that from HCFC-122a 100 years after a pulse emission, whereas the temperature change from HCFC-122a is about 1.5 times higher than that from N_2O after 20 years from a pulse emission. Despite these differences, they are considered as almost equal when converted to CO_2-equivalents because they have relatively similar GWP100 values, 265 for N_2O and 258 for HCFC-122a [1]. This example underlines the extent to which the choice of a metric can skew the apparent importance of different gases, and why the use of a diverse array of metrics is desirable for matching specific policy

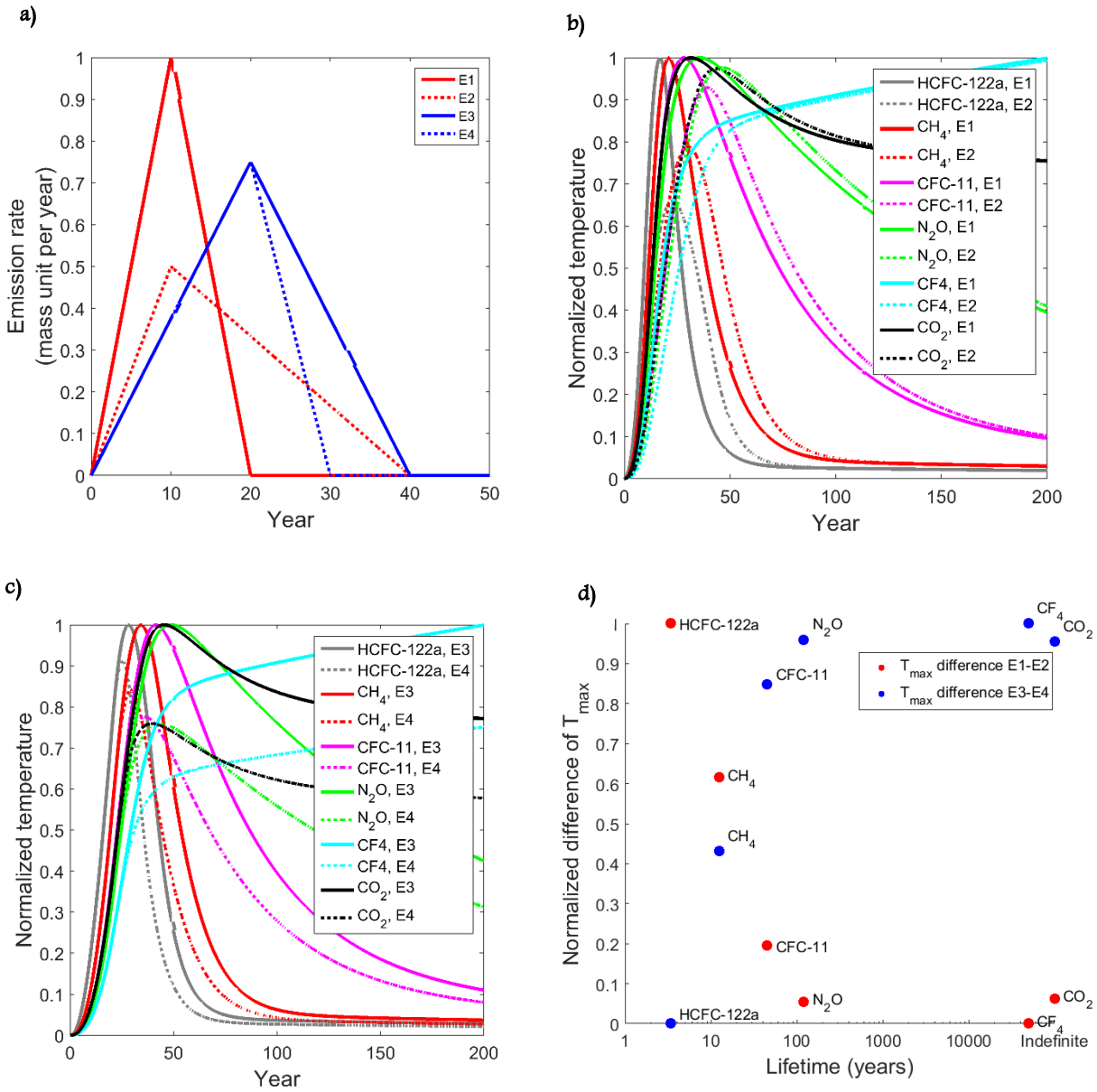
252 goals. The simple replacing of GWP100 with an alternative metric would not mitigate these
253 concerns because any choice that works for one dimension of the climate system, e.g. short-
254 term impacts, inevitably risks overlooking others, e.g. long-term impacts.

255

256 **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

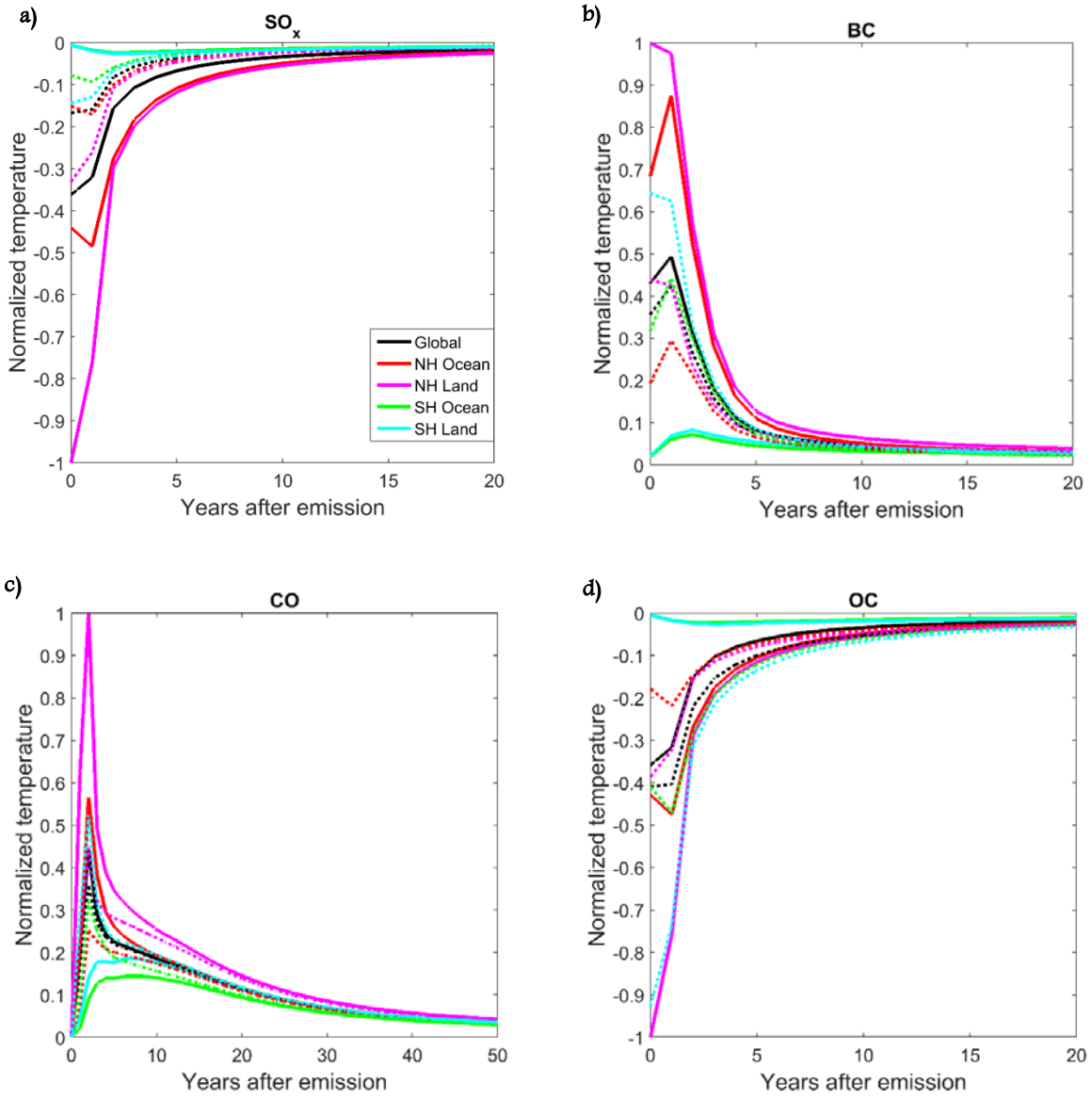
per TtonC [60]. Although so far mainly validated for CO_2, the concept of TCRE can also be extended to other long-lived GHGs [44]. Similarly, the temperature contribution from short-lived gases can be approximated using scaling factors applied to the maximum emission rates [37, 40, 58, 59]. The use of metrics based on temperature peak dependencies on either emission rates or cumulative amounts within an LCA framework has not been explored yet. On one hand, this approach would allow a multi-basket framework where the various forcing agents are grouped together on the basis of their lifetimes, thus avoiding the practice to group together species with very different lifetimes. On the other hand, different sets of emission metrics would still be needed to aggregate emissions to common units, and the selection of the metrics to be used in the different baskets would still remain based on value-laden choices, as it would be dependent on the preferred policy goal [41]. Still open is also the question on how to weight one basket with respect to the other, with some arguing that any trading between the different baskets should not be allowed [37, 38].

5. Near-term climate forcers (NTCFs)

In addition to emissions of WMGHGs, human activities perturb the climate system through emissions of pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOCs), black carbon (BC), organic carbon (OC), sulphur oxides (SO_x), and ammonia (NH_3). Some of these pollutants are precursors to the formation of tropospheric ozone (NO_x, CO, VOCs), others are primary aerosols (BC, OC) or precursors to secondary aerosols (NO_x, SO_x, NH_3). These species have lifetimes shorter than the hemispheric mixing time and are usually called near-term climate forcers (NTCFs). The atmospheric concentrations of NTCFs are very heterogeneous, with high concentrations 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).



359 Figure 3 Global and regional normalized temperature responses to pulse emissions of selected NTCFs (SO_x, BC,
360 CO and OC) located in the northern or southern hemisphere. The responses to emissions in the northern
361 hemisphere (NH) are shown with solid lines, those to emissions from the southern hemisphere (SH) with
362 dashed lines. The temperature response is averaged globally and over the land and oceans of NH and SH. For
363 each specie, curves are normalized to the maximum (for BC and CO) or minimum (for SO_x and OC) value of
364 all the responses.

365

366 Figure 3 shows the normalized temperature effects from pulse emissions of three aerosol
367 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

438 **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-

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

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

to go beyond a simple carbon accounting framework when assessing the impacts of LULCC activities on climate is frequently highlighted [7, 92, 96–98]. It has been explicitly argued that "ignoring biophysical interactions could result in millions of dollars being invested in some mitigation projects that provide little climate benefit or, worse, are counter-productive" [96].

Biogeophysical properties vary with surface cover and have high spatial and seasonal variations. There are differences between summer and winter, especially in areas affected by seasonal snow cover. For instance, forests usually have lower albedo than open lands such as grassland or cropland, especially during snow covered periods. Biogeochemical effects following a change in forest cover usually dominate at low latitudes, while biogeophysical contributions are stronger at high latitudes [88–90, 100]. Biogeophysical effects are significant also when changes in management occur on the same land use type, such as irrigation, crop rotation, and forestry [7, 98, 99]. In general, climate impacts vary in spatial scale and depend on complex, and often nonlinear, mechanisms. Compared to grass, trees are generally more efficient in transferring water from the soil to the atmosphere because of their deeper roots and larger leaf area, and forests thus tend to maintain a cooler local surface temperature by releasing more energy in the form of latent heat than sensible heat. Hence, conversion from forest to grassland tends to warm the local surface, and it also tends to reduce the roughness of the landscape and thus to reduce the turbulence in the boundary layer. However, it is difficult to predict the effect that this reduction may have on surface temperature, because the reduction of heat and water vapour transport associated with reduced turbulence may be compensated by greater gradients of humidity and temperature between the surface and the atmosphere [89, 96].

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

517 forcings from WMGHGs, like CO_2, and LULCC do not produce the same global mean
518 temperature response when added together, and more accurate estimates are achieved when
519 the individual climate responses are used [104]. However, the lack of regional temperature
520 response functions and metrics for radiative forcings originated from changes in
521 biogeophysical effects at various locations has so far limited the possibilities to perform
522 temperature-based analyses without coupling the study with global climate models.

523 In addition to WMGHGs and surface albedo, changes in land cover have a third direct effect
524 on the global radiation balance by altering emissions of biogenic VOCs (BVOCs), which
525 rapidly oxidize in the atmosphere generating multiple warming and cooling climate
526 pollutants like ozone and biogenic secondary organic aerosols [3, 105]. The photochemical
527 processing of BVOC emissions influences the oxidation capacity of the atmosphere, which
528 affects the lifetime of CH_4 and the production of other secondary aerosols (sulphate and
529 nitrates). Even if BVOC emissions are formally quantified as a terrestrial biogeochemical
530 feedback that responds to anthropogenic climate change [52], we briefly discuss them here
531 given the strict link they have with LULCC. As for the other NTCFs, the net radiative patterns
532 are highly spatially inhomogeneous. The net radiative forcing from historical BVOC
533 emission reductions from expansion of agricultural areas is estimated in a negative (cooling)
534 contribution [3]. Conversely, increasing BVOC emissions following LULCC involving
535 reforestation or afforestation strategies cause a positive radiative forcing [71]. Despite
536 relevant recent progress, important uncertainties still persist. Current generation models
537 underestimate the amount of organic aerosols in the atmosphere and are unable to fully
538 reproduce the variability found in the measurements [1]. As NTCFs, BVOC oxidation
539 products are also important for the growth of newly formed particles up to cloud
540 condensation, so they indirectly influence climate through changes in cloud albedo [106].
541 These atmospheric aerosol processes changing cloud droplet concentrations and radiative

properties are among the least understood in climate research, and their contributions to the global radiation budget are considered as one of the largest source of uncertainty in the estimation of radiative forcing over the industrial period [106]. Results are not consistent across models, with estimates ranging between +0.23 W m^{-2} and -0.77 W m^{-2} [3]. All these aspects make a possible consideration of the contributions from aerosol-cloud effects in LCA and similar studies unrealistic for the short and medium term.

7. The way forward

Anthropogenic global warming is caused by a variety of forcing agents with different physical properties and lifetimes ranging from few days, like black carbon, to several thousands of years, like CF_4. Climate impact methods used in LCA are challenged when it comes to dealing with aspects like the various timescales of the responses to different GHGs, impacts from NTCFs and LULCC, and their temporal and spatial variability. Emissions can also be aggregated by metrics other than GWP100. Alternative metrics would allow the representation of different dimensions of climate change impacts, but would not sidestep the value-laden considerations of the relative weighting. Value judgements are embedded in metric formulations, most notably through the choice of time horizon, of climate impact parameters, and by whether the indicator refers to a time-integrated or instantaneous quantity. Any preference of one metric over another arguably favours the representation of some aspects of the climate system response and at the same time discount others.

There are considerable uncertainties in the attribution of climate impacts to specific forcing agents. Scientific uncertainties are larger for temperature-based metrics than for those based on radiative forcing, and for NTCFs, BVOCs, or non-radiative LULCC mechanisms 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

matter, their explicit inclusion in emission inventories is desirable to facilitate applications. Characterization of their impacts on climate should consider the higher level of uncertainties associated with metrics for NTCFs, and ideally consider the range of possible metric values summarized in the latest IPCC report. The LCA community should closely follow updates on quantification of impacts from NTCFs as the climate science community is continuously improving the robustness of characterization factors for NTCFs.

Regional climate change categories can also be formulated in the future when robust estimates of metric values for regional responses to NTCFs become available. Inventory databases should already be adapted by elaborating spatial-explicit emission inventories that keep track of emission regions.

The time is ripe for the LCA community to consider the complexity of climate science and gain insights on the implications associated with the selection of emission metrics for the intended goal of the analysis. Rather than using a single default metric for WMGHGs in all applications, analysts should acknowledge the various forcing agents and the caveats associated with the aggregation of species with different lifetimes to common units. The sensitivity of the results to the type of metric used should be explored. When a choice is to be made, this can be done consistently with the aspects of climate change that are most relevant for the particular application. In any case, it is important to be aware and transparent about the choice of metric, its meaning, and the inherent value judgments it entails when interpreting and communicating results. A continuous bridge between the two communities is desirable in the future to keep LCA methods up-to-date with the latest developments in climate science, and simultaneously engage climate scientists to shape emission metrics and approaches to fit environmental impact assessment frameworks.

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