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### **► To cite this version:**

Francesco Cherubini, Jan Fuglestad, Thomas Gasser, Andy Reisinger, Otávio Cavalett, et al.. Bridging the gap between impact assessment methods and climate science. *Environmental Science & Policy*, 2016, 64, pp.129-40. 10.1016/j.envsci.2016.06.019 . hal-01425092

**HAL Id: hal-01425092**

**<https://enpc.hal.science/hal-01425092>**

Submitted on 6 Sep 2021

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# Bridging the gap between impact assessment methods and climate science

Francesco Cherubini<sup>a\*</sup>, Jan Fuglestad<sup>b</sup>, Thomas Gasser<sup>c,d</sup>, Andy Reisinger<sup>e</sup>, Otávio Cavalett<sup>f</sup>,  
Mark A. J. Huijbregts<sup>g,h</sup>, Daniel J.A. Johansson<sup>i</sup>, Susanne V. Jørgensen<sup>j</sup>, Marco Raugel<sup>k</sup>, Greg  
Schivley<sup>l</sup>, Anders Hammer Strømman<sup>a</sup>, Katsumasa Tanaka<sup>m</sup>, Annie Levasseur<sup>n</sup>

<sup>a</sup>Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of  
Science and Technology (NTNU), Trondheim, Norway

<sup>b</sup>Center for International Climate and Environmental Research – Oslo (CICERO), Oslo, Norway

<sup>c</sup>Laboratoire des Sciences du Climat et de l'Environnement (LSCE), Institut Pierre-Simon Laplace (IPSL), CEA-  
CNRS-UVSQ, 91191 Gif-sur-Yvette Cedex, France

<sup>d</sup>Centre International de Recherche sur l'Environnement et le Développement (CIRED), CNRS-PontsParisTech-  
EHESS-AgroParisTech-CIRAD, 94736 Nogent-sur-Marne Cedex, France

<sup>e</sup>New Zealand Agricultural Greenhouse Gas Research Centre, Palmerston North 4442, New Zealand

<sup>f</sup>Laboratório Nacional de Ciência e Tecnologia do Bioetanol (CTBE/CNPEN), Campinas, São Paulo, Brazil

<sup>g</sup>Department of Environmental Science, Institute for Water and Wetland Research, Radboud University,  
Nijmegen, The Netherlands

<sup>h</sup>Dutch Environmental Assessment Agency, Bilthoven, The Netherlands

<sup>i</sup>Division of Physical Resource Theory, Department of Energy and Environment, Chalmers University of  
Technology, Gothenburg, Sweden

<sup>j</sup>ALECTIA A/S, Virum, Denmark

<sup>k</sup>Faculty of Technology, Design and Environment, Oxford Brookes University, Wheatley, UK

<sup>l</sup>Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania, United States

<sup>m</sup>National Institute for Environmental Studies (NIES), Tsukuba, Japan

<sup>n</sup>Polytechnique Montréal, Department of Chemical Engineering, CIRAI, Montréal, Canada

\*Corresponding author: francesco.cherubini@ntnu.no

## 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<sub>2</sub>-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 forcings 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  $2.29 [1.13 \text{ to } 3.33] \text{ W m}^{-2}$  [1]. The major contributors are carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ) emissions, which are responsible for about  $1.68 \pm 0.17 \text{ W m}^{-2}$  and  $0.97 \pm 0.17 \text{ W m}^{-2}$ , 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  $-0.06 \text{ W m}^{-2}$  [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  $-0.41 \pm 0.20 \text{ W m}^{-2}$  for sulphur oxides ( $\text{SO}_x$ ) emissions and  $+0.64 [+0.25 \text{ to } +1.09] \text{ W m}^{-2}$  for black carbon (BC) emissions [1]. The radiative forcing values from historical land use changes for  $\text{CO}_2$  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  $0.17 \text{ to } 0.51 \text{ W m}^{-2}$  for  $\text{CO}_2$  (1850–2000) and a cooling effect of  $-0.15 \pm 0.10 \text{ W m}^{-2}$  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  $-0.11 \pm 0.17 \text{ W m}^{-2}$  (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 “ $\text{CO}_2$ -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<sub>2</sub>-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<sub>2</sub> [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<sub>2</sub>. 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<sub>2</sub> [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

model [25, 26], a temperature response function [24], or more sophisticated climate models [18, 24, 28, 42], and this generally makes results sensitive to the parameterization of the climate system [1]. Multi-model means are frequently used to mitigate these concerns [24] and to better understand uncertainties [42]. However, the subjective selection of a TH for the different metrics remain the most important factor that determines metrics variability [24], especially for the weight given to forcings with a relatively short lifetime, compared to forcings with long lifetimes [18]. This choice dependence introduces a strong, but often inadvertent and only implicit, value judgement that frequently makes results open to contrary outcomes [5, 15].

### 3. Well-mixed GHGs (WMGHGs)

CO<sub>2</sub>, CH<sub>4</sub>, nitrous oxide (N<sub>2</sub>O), and some groups of halogenated gases have atmospheric lifetimes longer than the hemispheric mixing time (up to a few years). They are generally considered well-mixed because their atmospheric concentration has sufficient time to become nearly uniformly distributed in the troposphere and their radiative forcing patterns are usually independent of the emission location [1]. Table 1 shows a classification of the main WMGHGs grouped by lifetimes, with information about their atmospheric concentration and radiative forcing in 2011, and their radiative efficiency per mass unit atmospheric burden (W m<sup>-2</sup> kg<sup>-1</sup>). For the purpose of a simple classification, we consider as “short-lived” those WMGHGs, like methane and most hydrofluorocarbons (HFCs) or hydrofluoroethers (HFEs), with atmospheric lifetimes shorter than the response timescale of the climate system, which is typically from two to four decades [20, 43]. Gases with lifetimes 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<sub>2</sub> 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<sub>4</sub> or N<sub>2</sub>O feeds back on their own respective lifetimes [46], CO<sub>2</sub> 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 5<sup>th</sup> IPCC Assessment Report [1] are considered. Information on lifetimes of the gases, atmospheric concentration, radiative forcing and radiative efficiencies are from the 5<sup>th</sup> IPCC Assessment Report[1].

Group of lifetimes	Gases	Lifetime (years)	Atmospheric concentrations in 2011	Radiative forcing in 2011 (W m <sup>-2</sup> )	Radiative efficiency (W m <sup>-2</sup> kg <sup>-1</sup> )
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 <sub>4</sub> , CFC-11, CFC-113, CCl <sub>4</sub> , some HCFCs, HFCs, and HFEs	Between 10 and 100	1803 ± 2 ppb CH <sub>4</sub> , 238 ± 0.8 ppt CFC-11	0.48 ± 0.05 CH <sub>4</sub> , 0.062 CFC-11	4.65E-14 CH <sub>4</sub> , 3.84E-11, CFC-113
Centuries	N <sub>2</sub> O, HFC-23, HFC-236fa, HFE-125, NF <sub>3</sub> , some CFCs	Between 100 and 1,000	324 ± 0.1 ppb N <sub>2</sub> O, 528 ppt CFC-12	0.17 ± 0.03 N <sub>2</sub> O, 0.17 CFC-12	3.84E-13 N <sub>2</sub> O, 4.10E-11 CFC-12
Millennials	Fluorinated	Between	79 ppt CF <sub>4</sub>	0.0041 SF <sub>6</sub>	7.3E-11 SF <sub>6</sub>

	gases (SF <sub>6</sub> , CF <sub>4</sub> , etc.), CFC-115	1,000 and 50,000			
Indefinite	CO <sub>2</sub>	n.a.	391 ppm	1.82 ± 0.19	1.81E-15

Among WMGHGs, CO<sub>2</sub> represents a special case. Unlike most other agents, it does not decompose through atmospheric chemical reactions, nor it is deposited on the Earth surface, but it is removed from the atmosphere by a variety of processes with different timescales influenced by multiple nonlinear dependencies [24, 51, 52]. For a 100 GtC emission pulse added to a constant CO<sub>2</sub> concentration of 389 ppm, 15–35% of the perturbation is still found in the atmosphere after a thousand of years; the ocean has absorbed 59 ± 12% and the land the remainder (16 ± 14%) [24]. Thereafter CO<sub>2</sub> concentration is only removed by ocean–sediment interactions and the weathering cycle through timescales of hundreds of thousands of years [51, 53].

We show the normalized temporal evolutions of the responses to emissions of selected WMGHGs in Figure 1. These responses, computed for both a pulse emission (Figure 1a,c) and constant sustained emissions (Figure 1b, d), are simulated following the approach used in the 5<sup>th</sup> IPCC assessment report [1] (see Methods in the Supplementary Information for details). The longer the lifetime of the gas, the higher the emission fraction remaining airborne over time (Figure 1a). Under constant sustained emissions (Figure 1b), the normalized increase in radiative forcing asymptotically tends towards a maximum that is proportional to the product of the atmospheric lifetime of the gas, its radiative efficiency, and the emission rate. The time taken to approach this maximum value is critically dependent on the lifetime, because it determines how soon atmospheric concentrations reach steady state. Short-lived species are near maximum within a few decades, while for others the steady state will not be reached for centuries or millennia. The temperature 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  $\text{CO}_2$ , the temperature does not  
 222 decrease significantly even if emissions cease entirely (Figure 1d). For extremely long-lived  
 223 gases like  $\text{CF}_4$ , 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].

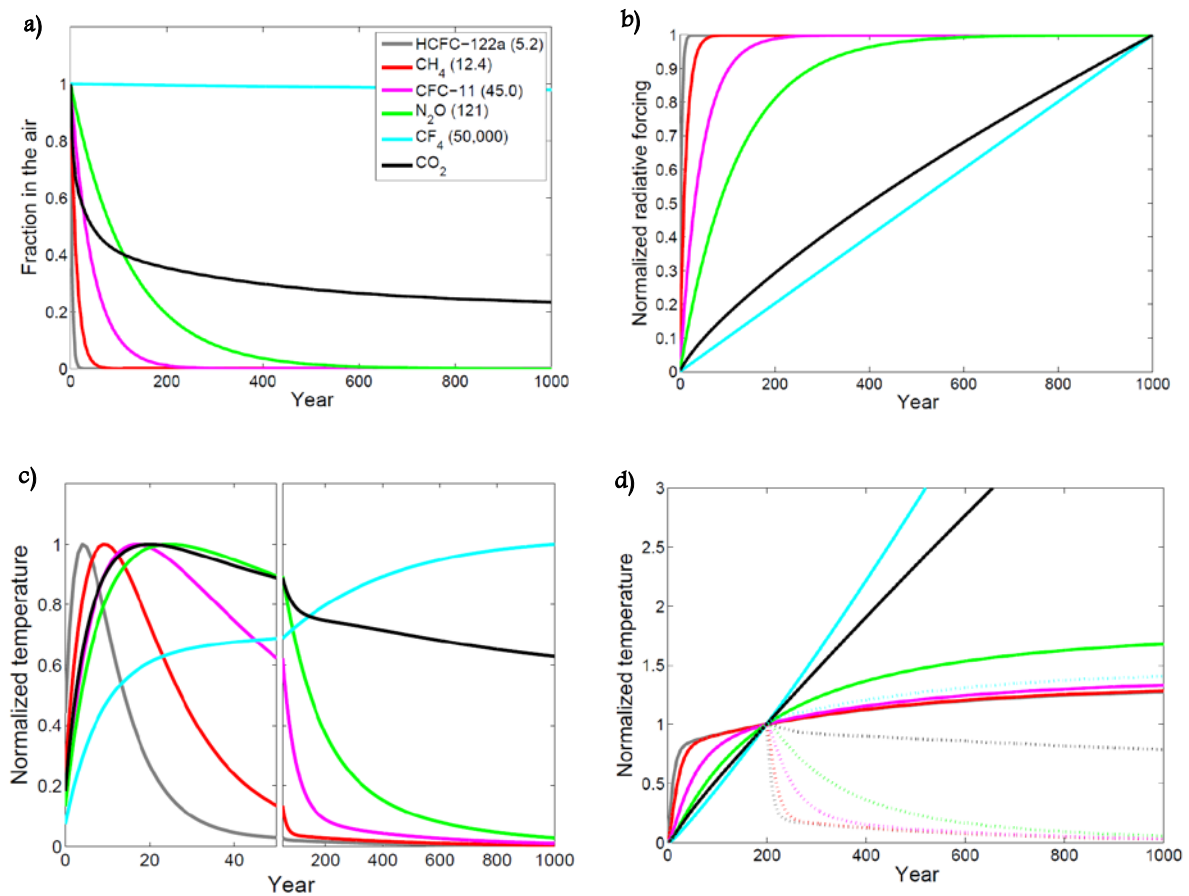


Figure 1 Temporal evolutions of the normalized responses of the climate system to some WMGHGs. a) Fraction of the gas remaining in the atmosphere following an emission pulse at year zero; b) normalized radiative forcing under constant emission rates; c) normalized global average surface temperature response 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 5<sup>th</sup> Assessment Report [1], the aggregation of WMGHGs to CO<sub>2</sub>-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<sub>2</sub> 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<sub>2</sub>O have very different lifetimes (5 and 122 years, respectively) and temperature impact profiles. The temperature change from N<sub>2</sub>O 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<sub>2</sub>O after 20 years from a pulse emission. Despite these differences, they are considered as almost equal when converted to CO<sub>2</sub>-equivalents because they have relatively similar GWP100 values, 265 for N<sub>2</sub>O 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

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

#### **4. Emissions and temperature peaks**

There is a growing interest in the climate science community to infer simplified metrics and climate policy frameworks from the relationships between temperature peaks and emissions [40, 55–57]. In Figure 2, we show the temperature peak dynamics of different WMGHGs following four idealized emission trajectories. These trajectories, modelled with a triangular temporal distribution (Figure 2a), have either the same cumulative emissions and different maximum emission rates (E1 and E2), or the same maximum emission rate and different total emissions (E3 and E4). When the temperature responses to E1 and E2 are compared (Figure 2b), gases with short lifetimes have different temperature peak values (e.g., up to 40% lower under E2 than E1 for HCFC-122a), whereas nearly identical maximum temperatures are achieved by gases with longer lifetimes. Under constant cumulative emissions, temperature changes from gases with short lifetimes are sensitive to the maximum rate at which emissions occur, and the sensitivity gradually decreases while the lifetime of the gas increases. Temperature changes from gases with longer lifetimes become more sensitive than short-lived species to specific emission trajectories if total cumulative emissions differ (Figure 2c). For instance, the temperature peak reached by CO<sub>2</sub> emissions is about 30% lower under E4 than E3. We compare the effect of emission rates and cumulative emissions on the temperature responses in Figure 2d, where the normalized temperature peak differences are plotted against the lifetime of the gases. Gases in the top right corner (CO<sub>2</sub> and CF<sub>4</sub>) have higher sensitivity to cumulative emissions, whereas if a gas lies in the

276 top left corner (HCFC122a) has a strong sensitivity to emission rates. The temperature  
 277 increase from short-lived emissions thus primarily depends on today emissions, which  
 278 mainly affect the rate and magnitude of climate change over the next few decades [37, 38,  
 279 40, 58, 59]. On the other hand, the temperature impact from long-lived gases like  $\text{CO}_2$  and  
 280  $\text{CF}_4$  gradually accumulates over time and, rather than with the rate and timing of emissions,  
 281 it scales with the cumulative amount of emissions, including those occurred in the past [40,  
 282 53, 55, 60, 61].

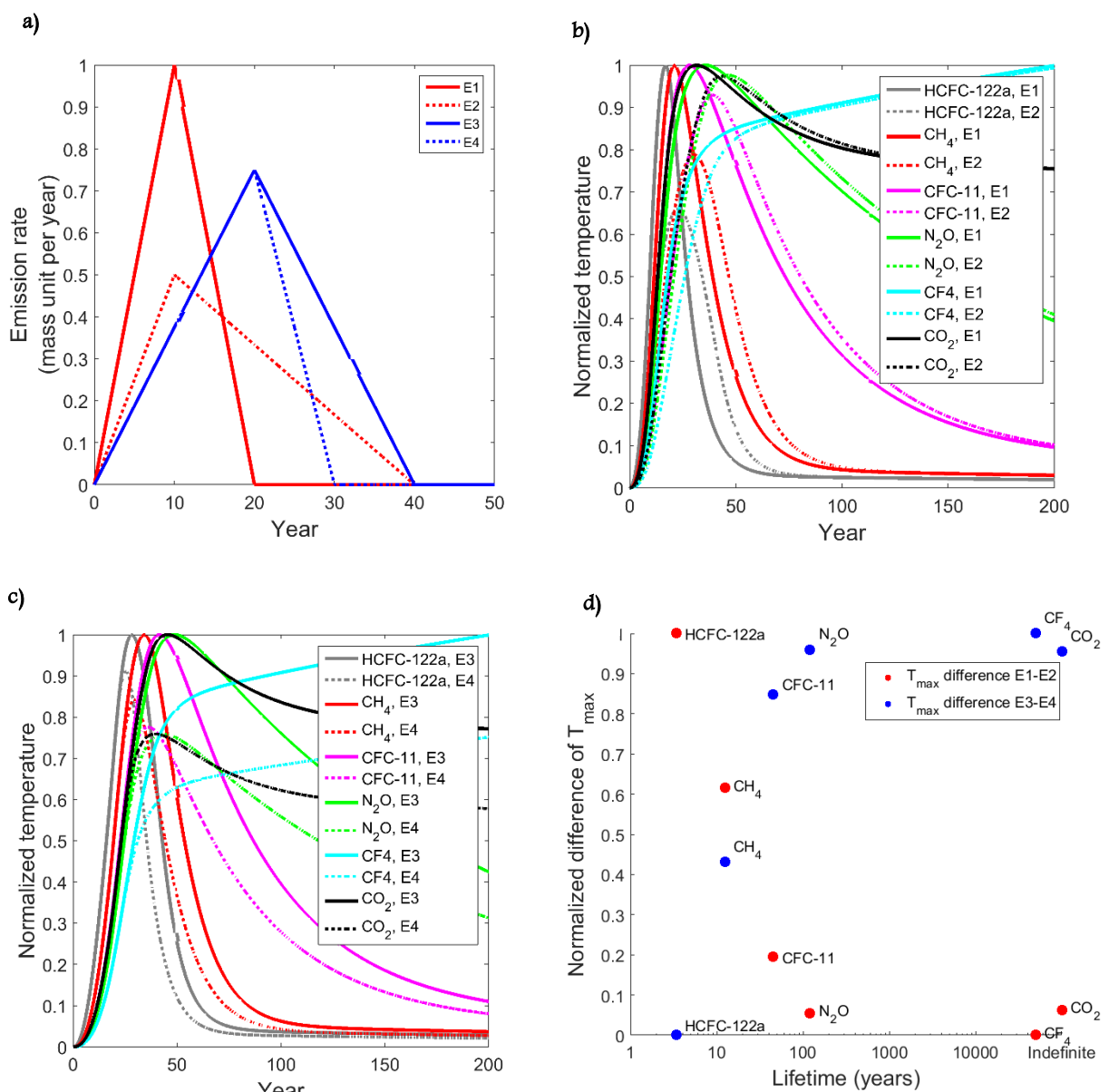


Figure 2: Sensitivity of the temperature response of WMGHGs to emission rates. a) idealized emission rates peaking and declining. E1 and E2 have the same amount of cumulative emissions but different maximum emission rates ( $E1 > E2$ ); E3 and E4 have the same maximum emission rate but different cumulative emissions ( $E3 > E4$ ); b) normalized temperature responses to E1 and E2; c) normalized temperature responses to E3 and E4; d) normalized difference of the temperature peak ( $T_{\max}$ ), computed from the responses in b) and c), for each WMGHG as a function of the lifetime of the gas (logarithmic scale). The red dots indicate the normalized differences in the temperature peak values of each WMGHG to emission scenarios E1 and E2 (Figure 2b). The blue dots are for the normalized differences in  $T_{\max}$  under emission scenarios E3 and E4 (Figure 2c). Values close to 1 indicate high sensitivity of  $T_{\max}$  to emission rates (red dots) or cumulative emissions (blue dots). The profile for each gas in b) and c) is normalized to the respective maximum value from the emission scenario E1 and E3, respectively. For  $CF_4$ , the temperature at 200 years is taken as the normalizing factor.

The relationship between emissions and temperature peaks is used to produce simplified emission metrics and approaches [37, 40, 55, 56]. If climate policy is focused on avoiding a specific temperature threshold, its achievement largely depends on the cumulative emissions of long-lived gases until the year of the peak, and on emission rates of short-lived species in the one or two decades preceding the peak [40, 62, 63]. In such a context, emissions of short-lived gases should be progressively more weighted as the temperature peak is approached, and less if it is more distant. There are options to link metric values to the gradual approaching of climate targets, such as time dependent formulations of GWP or GTP [18, 28, 33] and other metrics explicitly connected to a climatic threshold [14, 34]. Another option that is gathering increasing interest is the “transient climate response to cumulative carbon emissions” (TCRE) [60], which is formally defined as the warming due to one trillion ton of cumulative carbon emissions and is based on the linearity between temperature peak and cumulative emissions [55, 61]. Earlier estimates of the TCRE suggested an average value of  $1.6 \pm 0.5$  °C per Tera ton carbon (TtonC) emitted [61], while 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<sub>2</sub>, 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<sub>x</sub>), carbon monoxide (CO), volatile organic compounds (VOCs), black carbon (BC), organic carbon (OC), sulphur oxides (SO<sub>x</sub>), and ammonia (NH<sub>3</sub>). Some of these pollutants are precursors to the formation of tropospheric ozone (NO<sub>x</sub>, CO, VOCs), others are primary aerosols (BC, OC) or precursors to secondary aerosols (NO<sub>x</sub>, SO<sub>x</sub>, NH<sub>3</sub>). 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



source region [64–67]. Although short-lived GHGs like CH<sub>4</sub> are sometimes referred to as NTCFs, we here restrict this definition to species with inhomogeneous atmospheric concentrations that are not well-mixed.

The considerations above associated with the characteristics of the temperature response to short-lived species also apply to NTCFs. Emissions of NTCFs may also have an effect on precipitation patterns through changes in cloud formation processes and cover [2], which have recently been quantified in terms of emission metrics [31]. In general, the confidence level in the predicted climate impacts from NTCFs is lower than that for WMGHGs, especially in the cases in which aerosol–cloud interactions are important (see section 8.5.1 in ref. [1] and the latest specific IPCC chapter on the matter [2]). These emissions are coupled to the hydrological cycle and atmospheric chemistry and involve highly complex processes that are challenging to validate. The net climate impacts of NTCFs are the result of many opposing effects with different temporal evolutions at play. NO<sub>x</sub> species are very reactive and affect climate through many nonlinear chemical interactions with various timescales [21, 46], including nitrate and ozone formation, changes in CH<sub>4</sub> concentration and thereafter stratospheric water vapour [46, 50]. NO<sub>x</sub> also influences CO<sub>2</sub> and the global carbon cycle through the fertilization effect of nitrogen depositions. Other ozone precursors are CO and VOCs, which increase the concentration of ozone on short time scales and by affecting the levels of hydroxyl (OH) radical, and thereby of CH<sub>4</sub>, they also initiate a net positive long-term ozone effect [3, 65]. Aerosol species influence the climate mainly through absorption (BC) or scattering (OC, sulphate and nitrate) of solar radiation and other indirect effects, like deposition of BC on snow. Aerosols are either directly emitted from sources (primary aerosols, like BC and OC), or they are formed in the atmosphere via several processes (secondary aerosols, like sulphate after oxidation of SO<sub>2</sub>, and OC from condensation of organic compounds).

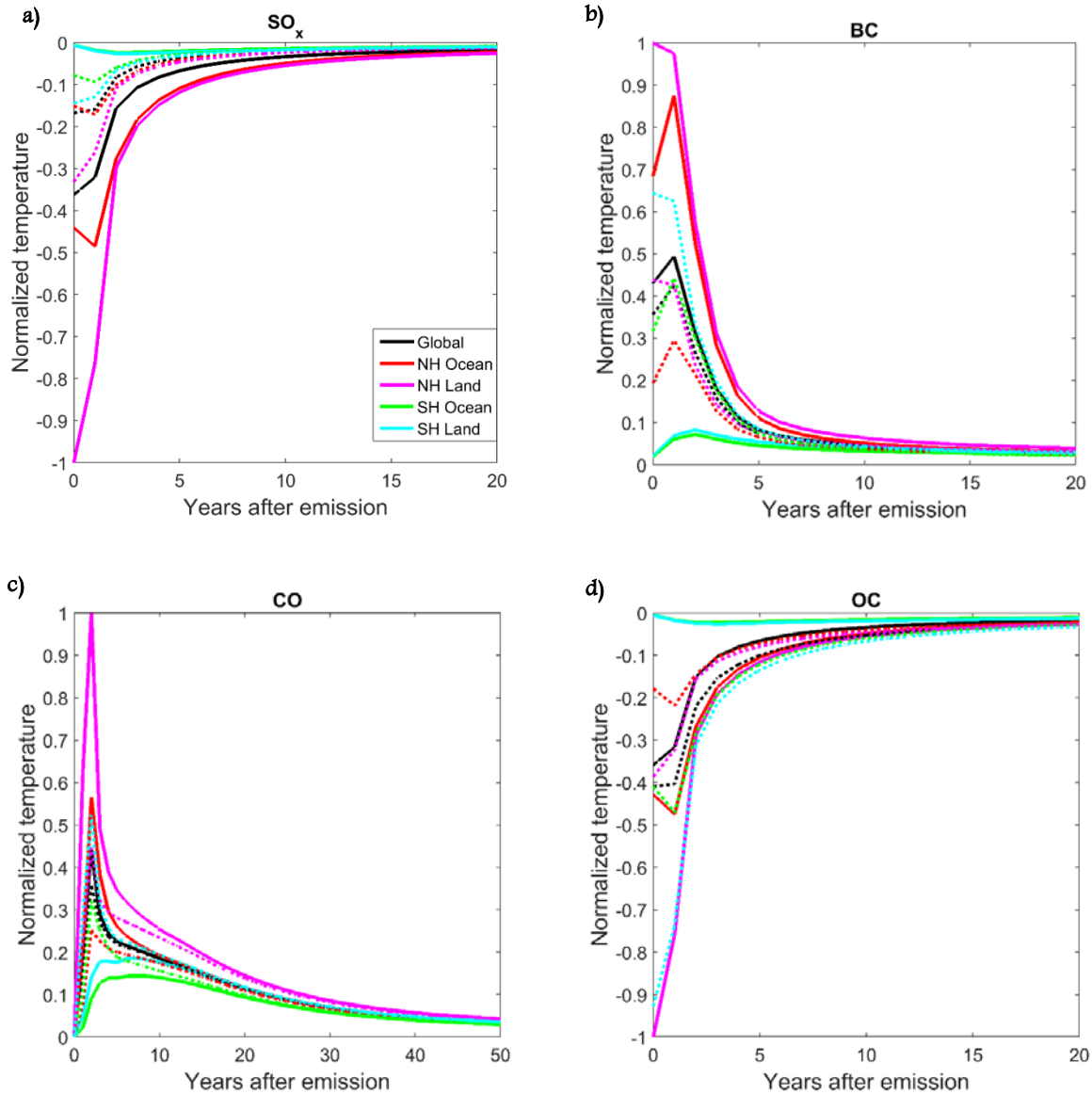


Figure 3 Global and regional normalized temperature responses to pulse emissions of selected NTCFs ( $\text{SO}_x$ , BC, CO and OC) located in the northern or southern hemisphere. The responses to emissions in the northern hemisphere (NH) are shown with solid lines, those to emissions from the southern 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  $\text{SO}_x$  and OC) value of all the responses.

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

northern or southern hemisphere, and the temperature response is averaged both globally and over macro regions like the land and oceans of the northern and southern hemispheres. The responses, which merely have illustrative purposes, are computed using the simplified climate model MAGICC6 [68], a model widely used in the climate science community (see Methods in the Supplementary Information). Emissions from different regions have different lifetimes and the responses are regionally dependent. The global averaged temperature has significant variations with respect to the regional trends. The climate impact response to an emission pulse is generally higher in the northern hemisphere, where there is the strongest sensitivity to forcing, and over the land than the oceans, due to differences on evaporation [69]. Emissions of BC have the largest impact on regional average temperature change when located in the northern hemisphere, because BC can be easily transported to the white surfaces of the arctic and thereby decrease albedo. The response to CO and VOCs are less heterogeneous because they have longer lifetimes (from one to three months) and are approximately well-mixed on a hemispheric spatial scale. As discussed elsewhere [20, 66, 70], they are less dependent on emission location and model configurations, although the consideration of vegetation effects of ozone and aerosol responses can increase variability [48].

Climate impacts from NTCFs are currently excluded from LCA studies, carbon footprints, or international global climate agreements. Their possible inclusion has been debated [3, 5, 65, 70, 71] and, in some cases, explicitly argued [3, 5, 71]. However, the characterization of NTCFs to CO<sub>2</sub> equivalents is even more difficult than it is for short-lived gases because of the very short lifetime of the forcing, its spatial heterogeneity, and the larger uncertainty. Global metrics like GWP normally use globally-averaged inputs to produce globally-averaged measures and give no information about the spatial variability of the impact. Global metrics available in the literature for NTCF emissions located in different regions are

presented and discussed in the 5<sup>th</sup> IPCC assessment report [1]. There is not a robust relationship between the region of the emission and the metric value [20], and the inter-model variability is sometimes larger than the variability between emission regions [50, 72]. Measures that rely on global averages or long integration times do not fully represent the temporal and spatial characteristics of the responses [73, 74]. The application of a metric that is first calculated locally and then averaged globally could be one way of capturing a more complete and informative signal than one that uses global mean outputs [73].

Regional specific responses and emission metrics for NTCFs are also available [50, 64, 74, 75]. Absolute Regional Temperature Potentials (ARTP) are computed using fully coupled atmosphere-ocean climate models and approximate the time-dependent temperature response at four latitude bands as a function of the regional forcing imposed by various climate pollutants in all bands [75]. These metrics allow the assessment of the climate effects from NTCFs with some regional resolution without coupling the analysis with sophisticated climate models. However, additional studies are required to determine the robustness of ARTPs and explore their feasibility for life cycle impact assessment methods. Existing climate impact frameworks rely on the assumption that the emission location does not affect the response of the climate system and the climate change impact category has a global scale. These assumptions hold for WMGHGs but not for all NTCFs. Species like NO<sub>x</sub>, SO<sub>x</sub>, BC and OC would ideally require the formulation of sub-global emission locations and impact categories for using the corresponding regional metrics.

There are other important caveats associated with the accounting of the climate impacts from NTCFs. As they can have significant contributions to global warming, their inclusion in LCA can make their mitigation an attractive proposition to achieve multiple environmental goals at the same time [76], because these species have adverse effects in other environmental impact categories than climate change, like human and ecosystem health .

On the other hand, some NTCFs have cooling effects, and their accounting may result in a partial offsetting of the warming effect of the total aggregated emissions. This would result in the attribution of climate benefits to species which are responsible of air pollution and damage to ecosystems. LCA methodology includes many environmental impact categories and is by definition well suited to inform about the possible shifts of impacts across categories. However, risks of this type are higher in carbon footprint studies or other applications where the goal is limited to the assessment of climate change impacts only. Accounting for NTCFs using metrics like the GWP100 would bring to common unit species with very different climate impact profiles and expand the abatement options available. Decision-makers could for instance prioritize mitigation of NTCFs and delay reductions in long-lived species like CO<sub>2</sub>, thereby causing irreversible long-term warming for the sake of reducing near-term rate of warming. Another important aspect is the consideration that NTCFs are frequently co-emitted, and this has implications for the benefits that can be achieved by their mitigation [62, 63]. For instance, with approximately 0.64 W m<sup>-2</sup>, BC is the third largest radiative forcing component for the period 1750–2011 after CO<sub>2</sub> and CH<sub>4</sub> [1]. One can therefore argue that a reduction in BC emissions will bring considerable benefits for the climate. However, the benefits from a decrease in BC emissions are dampened by the simultaneous reduction of emissions of species like SO<sub>x</sub> and OC, which have cooling contributions [62, 63].

## **6. Land use and land cover change (LULCC)**

Climate impacts from a change in land use or management are frequently associated to emission or removal of WMGHGs like CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>. Direct GHG emissions from land 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<sub>2</sub> 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<sub>2</sub> 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

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

evapotranspiration and surface aerodynamics do not imply any direct perturbation to the earth's radiative balance [89]. The quantification of the climate change effects from evapotranspiration and surface roughness is complex. The attribution of regional and global climate change effects to these forcing agents is highly uncertain and limited in evidence, owing to a wide spread in model estimates and differences between observations and model results [87, 91, 101]. Modelling changes in evapotranspiration and surface roughness also requires knowledge of numerous vegetation structural, physiological, and environmental parameters [97, 101], posing formidable challenges for the accounting of these effects in climate impact assessment studies. On the other hand, changes in surface albedo are rather more certain and less challenging to quantify. The 5<sup>th</sup> IPCC assessment report classified the radiative forcing estimates from surface albedo changes with a *high* confidence level, as it has robust evidence with well documented high precision measurements [1]. Surface albedo is also the most important biogeophysical mechanism influencing the global climate in extra-tropical regions, especially in areas experiencing seasonal snow cover [88, 90, 98]. Because they can be measured in terms of radiative forcing, impacts from changes in surface albedo are frequently converted to CO<sub>2</sub> equivalents using either carbon equivalent factors [97, 102] or more conventional emission metrics like GWP or GTP [13]. However, because of the non-linear and high spatial heterogeneity of the climate forcings from land-atmosphere perturbations as well as the different temporal behaviour, the development and possible routine applications of climate metrics for LULCC in LCA need to be land cover- and location-specific. Like for NTCFs, radiative forcing from albedo changes located in different regions affect climate heterogeneously [89, 90], with radiative forcings at high latitudes being more effective in changing global temperature than radiative forcing at low latitudes [103]. Because changes in land surface aerodynamic and physiological properties often dampen the radiative temperature change at the local surface [89], global radiative



forcings from WMGHGs, like CO<sub>2</sub>, 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<sub>4</sub> 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

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  $+0.23 \text{ W m}^{-2}$  and  $-0.77 \text{ W m}^{-2}$  [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  $\text{CF}_4$ . 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

uncertainties should not *per se* be an overriding constraint for using metrics and modelling impacts [20]. If the main policy goal is to keep global temperature below a certain threshold, the uncertainties and timing of political choices (i.e. a delay in action) are often those with the largest cost–risk distributions, and may actually swamp the uncertainties associated with the parameterization of the climate system [107].

Concerning the aggregation to common units, it is impossible to identify a single metric that can produce a balanced representation of the overall climate impact from such a diversity of forcing agents. Different climate policy goals may lead to different conclusions about what is the most suitable metric to assess that policy. For instance, the use of GWP100 in LCA has the inadvertent consequence of assessing emissions for their contributions to global temperature over a timeframe of about four decades [35, 36], with no direct connections to peak warming. GWP100 only becomes an indication of the contributions to peak warming under the arguably optimistic assumption that global CO<sub>2</sub> emissions will approach zero within about 40 years, so that the global temperature will approach stabilization. The characterization of different emissions to CO<sub>2</sub>-equivalents implicitly suggests that one can freely choose which emissions to reduce in order to achieve the same improvement in the climate system performance of a product. However, the same net reduction of the total aggregated emissions in CO<sub>2</sub>-equivalents will have different climate effects at different times, depending on whether it is obtained through a reduction in long-lived or short-lived species. If emissions of long-lived gases continue to rise, the mitigation of short-lived species would temporarily reduce the rate of warming but cannot avoid the risk of passing warming thresholds, because as long as the concentration of CO<sub>2</sub> is allowed to keep growing, the reaching of those thresholds is only temporally postponed. Any delay in mitigation of CO<sub>2</sub> emissions will lead to nearly irreversible warming. Within the global policy goal of limiting warming to 2°C above pre-industrial levels, mitigation of CO<sub>2</sub>

emissions is thus identified as a non-negotiable objective in strategies aiming at constraining maximum temperature [35, 37, 44, 55, 57, 63], because any deferral in mitigating long-lived emissions progressively closes the door for achieving ambitious peak temperature targets.

Bridging life cycle impact assessment methods with climate science is essential to provide decision makers with more robust climate change impact studies that acknowledge the variety of forcing agents at play and the caveats of their aggregation. There are metrics other than GWP100 and climate forcing agents other than WMGHGs. Explicit consideration of alternative metrics by LCA practitioners would allow the characterization of climate change impacts over multiple timescales and with regard to diverse and contrasting policy goals. For instance, the use of metrics like GWP20 or GWP100 can provide information about the time-integrated contributions to global warming in a short/medium term, whereas GTP100 provides information about the instantaneous contributions to global warming on a longer timeframe. If GWP aligns well with the LCA ambition to prefer integrated impacts, GTP provides the possibility to explicitly link global warming contributions to a climate target, based on planetary boundary and/or policy considerations. In general, the utilization of multiple metrics provides complementary information on the implications of mitigating gases with varying lifetimes, and shows the extent to which results are sensitive to the choice of metric or robust across a range of choices. The inclusion in existing LCA databases and impact assessment methods of the spectrum of the metrics available in the latest IPCC assessment report will facilitate their application by LCA practitioners.

The consideration of NTCFs in LCA presents challenges at an inventory and characterization level. Most of the NTCFs are already tracked by the majority of the life-cycle inventory databases, as they contribute to other environmental impact categories, except for BC and 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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