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Climate change metrics: bridging IPCC AR6 updates and dynamic life cycle assessments

Vladimir Zieger[1], Thibaut Lecompte[1], Simon Guihéneuf[1], Yann Guevel[1], Manuel Bazzana[2], Thomas Gasser[3], Yue He[3]

[1]Univ. Bretagne-Sud, UMR CNRS 6027, IRDL, F-56100 Lorient,
[2]Centre Scientifique et Technique du Bâtiment, F-38400 Saint-Martin-d'Hères
[3]International Institute for Applied Systems Analysis, Laxenburg, Austria

Correspondence to: Vladimir Zieger (vladimir.zieger@univ-ubs.fr)

Abstract. Climate change metrics result from analytical simplification of complex and diverse climate models. Life Cycle Assessment (LCA) communities do not pay attention this complexity. We investigated the last IPCC report to properly gather updated metric equations, climate parameters and associated uncertainties. Metrics are mainly designed with a single gas pulse emission at t_0 whereas multi-gas and multi-time pulse emissions are mostly encountered in LCA modelling. Therefore, common static and relative metrics that aggregate emissions into one pulse of CO_2 at t_0 might not suit dynamic climate change assessments (dCCA) that differentiate pulse timing and gas contributions over time. This study focuses on absolute and dynamic metrics – cumulative radiative forcing (AGWP or ΔF) and global temperature change (AGTP or ΔT) – applied to well-mixed greenhouse gases. Common cumulative radiative forcing at 20, 100, 500 years appears sufficient. Global temperature change metrics have some advantages that offset their higher uncertainties. (1) Degree Celsius unit better suits peak warming targets. (2) Positive and negative peaks, as well as long-term temperature change, partly alleviate the time horizon decision issue. (3) Graphical representations are comparable to simultaneously depict short- and long-lived climate forcers. In future assessment reports, IPCC is invited to recall climate equations and updated parameters values in a pedagogical way and to adopt $AGTP_{peak}$ and $AGTP_{long\text{-}term}$. dCCA recommendations are to plot ΔF and ΔT temporal profiles of product systems up to 600 years and use suggested metrics. This should enable going towards climate neutrality with more clarity, transparency and understanding.

1 Introduction

Human activities have now clearly put the Earth system well beyond the safe operating space for humanity (Richardson et al., 2023). A systemic framework on the Earth system trends (Rockström et al., 2009; Steffen et al., 2015) is essential to capture levels of anthropogenic perturbation and develop a strategy in order to maintain stability and resilience of the Earth system as a whole. Global warming is one hidden cost of any human activity emitting greenhouse gases (GHGs). Recent changes are rapid, intensifying, and unprecedented over thousands of years (IPCC, 2021a).

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The study of Earth's climate considers complex interactions between Atmosphere, Biosphere, Cryosphere, Hydrosphere and Lithosphere. The number of forcing mechanisms (e.g. GHGs, aerosols) is large (Szopa et al., 2021), as are uncertainties. State-of-the-art of Earth system models used in Model Intercomparison Projects (MIPs) attempt to describe all climate system's components as accurately as possible. From MIPS, simplified parametric models are developed. In each new assessment report, the Intergovernmental Panel on Climate Change (IPCC) updates climate parameters and metrics based on recent modelling as well as on changes in background conditions. Lastly, IPCC gathers updated characterisation factors (CF)* (see definition in Appendix A) and associated uncertainties for several metrics.

Global Warming Potential (GWP) has been widely used since the Kyoto Protocol thanks to its ease of calculation and simple definition, kilogram CO_2-equivalent ($kgCO_2e$) at a 100-year time horizon (H) being now a common metric to assess carbon footprint of products and systems. GWP has also been largely criticised. 1) It does not explicitly represent the temperature response to a GHG emission (Shine et al., 2005), i.e. it is a poor indicator of peak warming and net-zero timing estimate (Allen et al., 2022; Fuglestvedt et al., 2018). 2) There is a nonlinear relationship between integrated radiative forcings of CO_2 and of the studied gas (O'Neill, 2000). 3) It is statically expressed, H being a value judgement that has a decisive influence on the metric values (Myhre et al., 2013a) from both GHG emissions and temporary biogenic carbon storage (Levasseur et al., 2012). Global Temperature change Potential (GTP) is a more policy-relevant metric (Shine et al., 2005) explicitly linked to temperature change. But it remains static and relative to CO_2.

Due to the variety of emitted components' physical properties and of applications, LCA studies would benefit from moving away from single metric studies towards a multi-metric perspective and sensitivity tests, combined with a careful exchange with the end-users of LCA (Levasseur et al., 2016a). Extensive efforts have been done in that sense through the UNEP/SETAC Life Cycle Initiative (Levasseur et al., 2016b). Levasseur et al. (2016a) summarized all issues one has to have in mind before choosing a climate metric. They offered the same relevant recommendations for static LCA as Cherubini et al. (2016), i.e. the use of GWP20 for short-term and GTP100 for long-term perspectives in order to complete the usual GWP100 mid-term results. Yet, these metrics incorrectly assess the impact of short-lived climate forcers* (SLCFs) and after Allen et al. (2018b) are a poor indicator of temperature stabilisation. Other approaches, such as the dynamic Life Cycle Analysis (dLCA) developed by Levasseur et al. (2010), consist in accounting for the timing of GHG storage and emission on a year-by-year basis, and assess them using dynamic climate metrics. As other impact categories than climate change are not considered here, dynamic climate change assessment (dCCA) will be used instead of dLCA throughout the rest of this paper.

Limitations for a broader use of dCCA have been identified. First, IPCC does not provide the needed information in its latest report to easily understand and use dynamic climate metrics. Second, such metrics have been ignored in recent LCA final recommendations (FAO, 2023; Jolliet et al., 2018; Levasseur et al., 2016b). More deeply, the way most climate metrics and CFs are designed, i.e. based on single gas emission at time zero (t_0), may not be suitable for dCCA applications. For instance, in assessments of long-lasting systems or materials containing biogenic carbon, multi-gas pulse emissions might happen several decades after t_0. Pros and cons of addressed dynamic metrics are discussed here to support the interpretation of dynamic assessments with several emission pulses spread over time.

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For that interdisciplinary research purpose, we found it useful to merge dynamic climate metrics, climate parameters and associated uncertainties, using updates from IPCC 6th Assessment Report (AR6). Special emphasis is given to two metrics: Absolute Global Warming Potential (AGWP) (or cumulative Radiative Forcing (ΔF)), an integrated metric, and Absolute Global Temperature change Potential (AGTP) (or Global Mean Temperature Change (ΔT)), an endpoint metric. According to AR6, carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are the three most important GHGs, responsible for 82% of positive effective radiative forcing (ERF) since the beginning of the industrial revolution (Szopa et al., 2021). The present study thus focus on them. Given the openness of the IPCC to revise emission metrics in future Assessment Reports (Abernethy and Jackson, 2022), the proposed framework could help in selecting more robust time-dependent emission metrics and new CF. To sum up, this article aims:

- to give an overview of what underpins climate metrics and associated uncertainties using AR6 ;
- to offer AGWP and AGTP for CO_2, CH_4 and N_2O to environmental assessment communities ;
- to discuss how helpful ΔF and ΔT, two absolute and dynamic metrics, are to design strong sustainability;
- to suggest clearer data presentation and new CFs in future IPCC reports that better suit single- and multi-time emission profiles for both short- and long-lived well-mixed GHGs;
- to make available an open-source dynamic climate change assessment tool that includes climate-carbon feedbacks.

2 Methodology

2.1 Climate change metrics – background information

Emission metrics aim to provide an 'exchange rate' in multi-component policies or in areas such as LCA (Aamaas et al., 2013; Myhre et al., 2013a). Among other attempts (Edwards and Trancik, 2022; Kandlikar, 1996), Eq. (1) gives a general formulation of an absolute emission metric (AM) (Forster et al., 2007). This proposal is suited to a wide range of metrics, but not all, e.g. cost-effective metrics (Tanaka et al., 2021).

$$AM_i = \int_0^{\infty} \{(\mathrm{I}(\Delta \mathrm{C}_{\mathrm{r+i}}\,(\mathrm{t})) - \mathrm{I}(\Delta \mathrm{C}_{\mathrm{r}}\,(\mathrm{t}))\mathrm{g}(\mathrm{t})\} dt\ , \quad (1)$$

where $I(\Delta C_r(t))$ is the function describing the "impact" of a change in climate ΔC (e.g., concentration, temperature) at time t, with a discount function, g(t), and compared to a reference system, r, on which the perturbation i occurs. In emission metrics, g(t) is mostly a step-function to represent a fixed time-horizon in integrated metrics, or a Dirac delta function that removes the integral of Eq. (1) to represent an instantaneous evaluation in endpoint metrics (Peters et al., 2011a). We can notice that the latter have nothing to do with LCA endpoint modelling (Bare et al., 2000): an endpoint climate metric is a midpoint LCA indicator. To get a common scale, metrics can be given in relative terms by normalising to a reference gas: $M_i = AM_i/AM_j$. For instance, GWP and GTP are defined by normalising respectively AGWP or AGTP from a pulse emission of a specific GHG to respectively AGWP or AGTP of 1kg of CO_2. All metrics require input parameters (Hodnebrog et al., 2013) influenced by changing background information (see Table 1).

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The present paper focuses on absolute metrics based on pulse emission. Integrated temperature change metrics (iAGTP, iΔT, iGTP) that reflect for instance sea-level rise (Sterner et al., 2014) were not considered here since they have similar behaviours as integrated radiative forcing metrics (AGWP, ΔF, GWP) for both short- and long-lived climate forcers (Collins et al., 2020; Levasseur et al., 2016a; Sterner et al., 2014). Recently developed step/pulse metrics have been proposed (Dhakal et al., 2022, Cross-chapter box 2) such as GWP* (Allen et al., 2018; Cain et al., 2019) that is a minimalistic dynamic model designed to properly include SLCFs, or CGTP (Collins et al., 2020) that is a relative metric comparing a step change in SLCF emissions with a pulse emission of CO_2. These metrics are suited for yearly monitored emissions, e.g. at country level. Sustained emissions are barely encountered in LCA of products. Therefore, these metrics are left out of the present study.

Table 1. Evolution of radiative efficiency (RE), perturbation lifetime (τ), GWP and GTP at 100 years between the First IPCC Assessment Report (FAR) (Shine et al., 1990), SAR (Houghton et al., 1995), TAR (Ramaswamy et al., 2001), AR4 (Forster et al., 2007), AR5 (Myhre et al., 2013a) and AR6 (Forster et al., 2021).

		FAR	SAR	TAR	AR4	AR5	AR6
CO_2	RE (W m^{-2} ppb^{-1}).10^{-5}	1.78[a]	1.75[a]	1.548	1.4	1.37	1.33
CH_4	RE (W m^{-2} ppb^{-1}).10^{-5}	37[a]	37[a]	37	34	36.3	38.9 (57[b])
	τ (year)	10	12	12	12	12.4	11.8
	GWP_{100}	21	21	23	25	28 – 30	27 – 29.8
	GTP_{100}	-	-	-	4 – 7[c]	4 – 6	4.7 – 7.5
N_2O	RE (W m^{-2} ppb^{-1}).10^{-5}	308[a]	307[a]	310	303	300	320 (280[b])
	τ (year)	150	120	114	114	121	109
	GWP_{100}	290	310	296	298	265	273
	GTP_{100}	-	-	-	270[c]	234	233

[a] Calculated after equations from (Shine et al., 1990, Table 2.2) and concentration indicated in the corresponding IPCC report.
[b] With chemical effects included. AR6 indicates this radiative efficiency value in its main report.
[c] Values from (Shine et al., 2005) cited in AR4.

2.2 Absolute and dynamic metrics

GHGs effective radiative forcing (ERF)* quantifies the energy gained by the Earth system following an imposed perturbation (Forster et al., 2021). The absolute global warming potential (AGWP) is the integrated ERF. Following Eq. (2), it describes the change in heat flux density caused by a pulse emission, i.e. a Dirac delta function, of a unit mass of gas at t_0. The AGWP framework can be extended to multi-pulse cumulative ERF calculations, ΔF, since product systems can be viewed as a series of pulse emissions and analysed through convolution (Eq. (3), Aamaas et al., 2013):

$$AGWP_i(H) = \int_0^H ERF_i(t)\,dt = A_i \int_0^H IRF_i(t)\,dt\,, \quad (2)$$

$$\Delta F_i(H) = A_i \int_0^H g_i(t).IRF_i(H-t)\,dt\,, \quad (3)$$

where H is the time horizon, i the studied gas, A_i is the radiative efficiency scaling factor in W.m^{-2}.kg^{-1}, g_i the temporal emission profile in kg, and IRF_i is the impulse response function*.

According to simplified radiative forcing expressions of Etminan et al. (2016), RE of CO_2, CH_4 and N_2O depend on CO_2, CH_4 and N_2O background concentrations. The same applies for IRF_i. Decreasing RE_{CO2} with increasing CO_2 concentration is

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partially offset by an increase in climate-carbon cycle feedback (Reisinger et al., 2011) and by CO_2 sink saturation, mainly related to ocean (Raupach et al., 2014). Though, due to current rapid changes in background GHGs concentration and indirect chemical effects complexity, constant RE and IRF_i over time might be sources of uncertainty for mid- and long-term dCCA. Constant RE and IRF_i must at least be updated with each new IPCC assessment report. Following the AR6, RE and $IRF_{non\text{-}CO2}$ values are fixed with 2019-background concentrations (410 ppm CO_2, 1866 ppb CH_4 and 332 ppb N_2O). IRF_{CO2} is still calculated with 2010-background concentration of 389 ppm CO_2 (IPCC, 2021b; Joos et al., 2013), also similar to AR6. By contrast, 422 ppm CO_2 were measured on average in September 2024 (NOAA, 2024).

Further down the cause-effect chain of climate change, an additional radiative forcing implies a temperature change. Absolute Global Temperature change Potential (AGTP) is an endpoint metric. It is a well-established method that includes an energy balance climate model (Shine et al., 2005) to compute temperature change after a pulse emission (see Eq. (4)) (Boucher and Reddy, 2008; Fuglestvedt et al., 2010). Applying AGTP with the extended ΔF framework defined in Eq. (3) enables to estimate the global-mean temperature change, ΔT, to assess multi-pulse scenarios (see Eq. (5)):

$$AGTP_i(H) = A_i \int_0^H IRF_i(t).IRF_T(H-t)\,dt\,, \tag{4}$$

$$\Delta T_i(H) = \int_0^H \Delta F_i(t).IRF_T(H-t)\,dt\,, \tag{5}$$

$$IRF_T(t) = ECS * \sum_{j=1}^{J} \frac{c_j}{d_j} e^{-\frac{t}{d_j}} \tag{6}$$

where $IRF_T(t)$ is the temporally displaced temperature response function of the Earth system. The use of a two-layer energy balance emulator (Geoffroy et al., 2013) enables to simply reproduce the behaviour of a coupled atmosphere–ocean general circulation model. In this simple idealised framework, the heat-uptake temperature is a sum of two contributions (i.e. J = 2 in Eq. (6)): one quick mode representing the planetary surface's response to changes in forcing, and one mode with a much longer relaxation time that takes the large deep ocean inertia into account (Geoffroy et al., 2013).

AGTP is computed with IRF_T derived from a constrained ensemble from two emulators: FaIRv1.6.2 and MAGICC7.5.1, both in their AR6 calibration setups. Fast and slow response relaxation times are calculated to match the best-guess assessment of a 3.0°C equilibrium global surface air temperature response to a doubling of atmospheric CO_2 above its pre-industrial concentration (Smith et al., 2021). ECS, c_j and d_j mean values are given in Tab. 2.

Analytical resolution of AGWP and AGTP are shown in Supplementary Material (SM.1). Compared to AGWP, AGTP increases both the uncertainty and the policy relevance (Levasseur et al., 2016a; Myhre et al., 2013a; Peters et al., 2011b), as it requires an extra step for the climate response but directly gives easy-to-understand temperature changes.

2.3 Studied long-lived GHGs features

This study considers some long-lived climate forcers (LLCFs), GHGs whose lifetimes are greater than the time scales for inter-hemispheric mixing (1–2 years) (Szopa et al., 2021). As LLCFs have relatively homogeneous spatial climate influence in the troposphere, they are considered well mixed, i.e. local emissions impacts can be globally accounted for.

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To evaluate the total effect of a GHG, one needs to know its lifetime, its RE and its chemical interaction with other molecules. Components of complex models such as chemical adjustments* have to be accounted for in emissions-based ERF to provide transparency on climate metrics (Szopa et al., 2021).

2.3.1 Carbon dioxide

As the atmospheric CO_2 concentration is governed by a diversity of physical and biogeochemical processes (Joos et al., 2013), IRF_{CO2} is usually approximated by a sum of exponentials (see Eq. (7)). Joos et al. (2013) is still the latest multi-model quantification of the response of oceanic and terrestrial carbon sinks to an instantaneous pulse of CO_2 emission (Forster et al., 2021). Coefficients to fit their multi-model mean responses to a pulse emission of 100 GtC are used (see Tab. 2). These coefficients cannot be used to assess impacts on time horizons longer than 1000 years:

$$IRF_{CO2}(t) = \alpha_0 + \sum_{k=1}^{K} \alpha_k \, e^{-\frac{t}{\tau_k}} , \quad \text{for } 0 < t < 1000 , \tag{7}$$

where α_k represent a CO_2 fraction associated to a nominal timescale τ_k, with K = 3, and α_0 is the fraction of emissions that remains permanently in the atmosphere according to this multi-model fit.

2.3.2 Climate-carbon feedbacks

A carbon cycle response happens after the emission of CO_2 and non-CO_2 GHGs: a GHG emission warms the climate, which in turn reduces the carbon sinks uptake efficiency. According to Gasser et al. (2017), Climate–Carbon feedbacks (CCf) are for instance the effect of temperature and precipitation change on net primary productivity and heterotrophic respiration of land ecosystems, or changes in the surface ocean's chemistry. IRF_{CO2} from Joos et al. (2013) includes CCf. AR5's attempt to include CCf for non-CO_2 species (Myhre et al., 2013a) was inconsistent (Gasser et al., 2017). AR6 restored consistency by adding CCf to all GHGs after the framework developed by Gasser et al. (2017). Equation (8) indicates the increase in absolute climate metrics $\Delta AGxx_i$ of a gas i due to CCf (Smith et al., 2021) :

$$\Delta AGxx_i = \gamma \int_{t=0}^{H} AGTP_i(H-t) \int_{t'=0}^{t} AGxx_{CO2}(t') r_F(t-t') dt' dt , \tag{8}$$

with $r_F(t) = \delta(t) - \sum_{i=1}^{3} \frac{\beta_i}{\kappa_i} e^{-t/\kappa_i}$ and $\gamma r_F(t)$ the CO_2 flux perturbation following a unit temperature pulse in $kgCO_2\ yr^{-1}\ K^{-1}$. r_F parameter values and CCf analytical solution are indicated in SM.2.

2.3.2 Methane

Oxidation by tropospheric hydroxyl (OH) radical is the major sink of methane followed by other chemical losses – stratospheric and tropospheric halogen losses – and soil uptake (Boucher et al., 2009; Lelieveld et al., 1998; Stevenson et al., 2020). All these sinks lead to a total CH_4 atmospheric lifetime, $\tau_{atm,CH4}$, of 9.1 years (Szopa et al., 2021). Methane atmospheric lifetime is shorter than its perturbation lifetime τ_{CH4} since an increase in CH_4 emissions decreases tropospheric

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OH, which in turn enhances its own lifetime and therefore the methane burden (Szopa et al., 2021). Hence a CH_4-OH feedback factor, *f*, is applied: $\tau_{CH4} = \tau_{atm,CH4}$*f (see SM.2). IRF_{CH4} is then described with K = 1 and $\alpha_0 = 0$ (see Eq. (7)). Methane has a direct radiative effect through absorption of both shortwave and longwave radiation and indirect effects due to its reactivity. CH_4 emissions cause tropospheric ozone production as well as stratospheric water vapour increase (Szopa et al., 2021). Hence a positive chemical adjustment is attributed to methane and considerably increases the direct effect of CH_4 by a factor of 1.463 (see SM.2). As in Myhre et al. (2013b), methane influence on aerosols is not included here since these effects have not been confidently quantified to date (Forster et al., 2021). This might change in the future if findings on aerosol-cloud-interaction radiative forcing of O'Connor et al. (2022) are confirmed by future works.

Lastly, oxidation of methane from fossil sources leads to additional fossil CO_2 (Forster et al., 2021). Not all CH_4 oxidises since other sinks as OH radical exist. With a yield of 75%, 1 kg of fossil methane yields the emission of 2.1 kgCO_2, and 1kg of anthropogenic biogenic methane yields to a sink of 0.33 kg atmospheric CO_2 (Boucher et al., 2009; Forster et al., 2021). However, dCCA enables accounting for CO_2 uptake, i.e. negative values, for instance for bio-based materials. Hence, along with Muñoz and Schmidt (2016), we do not recommend to apply the biogenic correction to avoid double counting. Equation (9) with no chemical distinction between released carbon from biogenic and fossil sources is then used. One can see that CO_2 is emitted slowly as methane decays, i.e. there is a convolution between IRF_{CH4} and $AGxx_{CO2}$ or ΔX_{CO2}. The analytical resolution of the convolution is in SM.3. All these chemical effects significantly impact the radiative forcing of CH_4 (Szopa et al., 2021, Figure 6.12), inducing adapted AGxx formulas.

$$AGWP_{CH4,fossil}(H) = (1 + f_1 + f_2)\mathrm{A'_{CH4}}\tau_{\mathrm{CH4}}\left(1 - e^{-\frac{H}{\tau_{\mathrm{CH4}}}}\right) + Y\frac{M_{CO2}}{M_{CH4}}\frac{1}{\tau^{\mathrm{OH}}_{\mathrm{CH4}}}\int_0^H e^{-\frac{H-t}{\tau^{OH}_{CH4}}} AGWP_{CO2}(t)dt + \Delta\mathrm{AGWP}_{CH4}(H)\ , \quad (9)$$

where f_1 and f_2 are respectively the ozone and the stratospheric water vapour indirect effects, $\mathrm{A'}$ is the radiative efficiency scaling factor without indirect effects with $(1+f_1+f_2)A'_{CH4} = A_{CH4}$, *Y* is the reaction yield from CH_4 to CO_2 molecules, M_i the molar mass of a gas *i*, τ^{OH}_{CH4} the chemical lifetime of methane and $\Delta AGWP_{CH4}$ is the climate–carbon feedback. $AGTP_{CH4}$, ΔF_{CH4} and ΔT_{CH4} are affected the same way. All mentioned climate parameters values are in SM.2.

2.3.2 Nitrous oxide

Anthropogenic emissions of N_2O are driven primarily by fertiliser use and the handling of animal waste (Prather et al., 2015). Nitrous oxides loss mainly occurs through photolysis and oxidation by $O(^1D)$ radicals in the stratosphere, the critical region for N_2O loss being the tropical middle stratosphere (Canadell, 2021; Prather et al., 2015). The rates of reactions are defined by O_3 and temperature stratospheric vertical profile (Prather et al., 2015). The mean atmospheric lifetime of N_2O is 116 ± 9 years. A small negative lifetime sensitivity of N_2O to its own burden leads to an effective residence time perturbation of 109 ± 10 years (Canadell, 2021). IRF_{N2O} is modelled with K = 1 and $\alpha_0 = 0$ (see Eq. (7)). The indirect contributions of nitrogen oxides (NO and NO_2) push the OH/HO_2 ratio in the other direction than methane through the reaction $NO+HO_2 \rightarrow NO_2+OH$, inducing a negative effect on CH_4 lifetime (Stevenson et al., 2020). A positive effect is due to stratospheric ozone depletion (Forster et al., 2021; Szopa et al., 2021). They are relatively minor since they nearly

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compensate each other. A_{N2O} is thus scaled with updated value from Forster et al. (2021) so that the AGWP formulae of Eq. (10) evolves from Myhre et al. (2013b):

$$AGWP_{N2O}(H) = A'_{N2O}\left\{1 - 1.7 \times (1 + f_1 + f_2)\frac{RE_{CH4}}{RE_{N2O}} + RE^{03}_{N2O}C_f\right\} \times \tau_{N2O}\left(1 - e^{-\frac{H}{\tau_{N2O}}}\right) + \Delta AGWP_{N2O}(H)$$

$$= A_{N2O} \times \tau_{N2O}\left(1 - e^{-\frac{H}{\tau_{N2O}}}\right) + \Delta AGWP_{N2O}(H) \quad (10)$$

where A'_{N20} and A_{N20} are radiative efficiency scaling factors in W.m^{-2}.kg^{-1} respectively without and with indirect effects, RE^{03}_{N20} the radiative efficiency through ozone in W.m^{-2}.ppb^{-1} and C_f the conversion factor to convert RE from per ppb(N_2O) to per kgN_2O. $AGTP_{N2O}$, ΔF_{N2O} and ΔT_{N2O} are affected the same way.

Table 2. Climate parameters and associated uncertainties used for simple emission metrics and uncertainty beam calculation.

Variable	Definition	Unit	Value	Uncertainty and distribution type		Source
H	Time horizon	Years	1–1000	-	-	(Joos et al., 2013)
$AGWP_{CO2}$						
A_{CO2}	Radiative forcing scaling factor	W.m^{-2}.kg^{-1}	1.71 x 10^{-15}	0.21 x 10^{-15}	Normal 1.645σ	(Forster et al., 2021)
$\alpha_{0\text{-}3}$	Coefficient for fraction of atmospheric CO_2 associated with a nominal timescale	Unitless	$\alpha_0 = 1\text{-}\alpha_1\text{-}\alpha_2\text{-}\alpha_3$ $\alpha_1 = 0.2240$ $\alpha_2 = 0.2824$ $\alpha_3 = 0.2763$	-	-	(Joos et al., 2013)
$\tau_{1\text{-}3}$	Nominal timescale	Years	$\tau_1 = 394.4$ $\tau_2 = 36.54$ $\tau_3 = 4.304$			
$AGWP_{CH4}$						
A_{CH4}	Radiative forcing scaling factor with indirect effect	W.m^{-2}.kg^{-1}	2.00 x 10^{-13}	0.49 x 10^{-13}	Normal 1.645σ	(Forster et al., 2021)
τ_{CH4}	Perturbation lifetime	Years	11.8	1.8	Normal 1.645σ	(Forster et al., 2021)
τ^{OH}_{CH4}	Chemical lifetime	Years	9.7	1.1	Normal 1σ	(Szopa et al., 2021)
Y	Fractional molar yield of CO_2 from CH_4 oxidation	Unitless	0.75	[0.5 – 1]	Uniform	(Forster et al., 2021)
$AGWP_{N2O}$						
A_{N2O}	Radiative forcing scaling factor with indirect effect	W.m^{-2} .kg^{-1}	3.6 x 10^{-13}	1.4 x 10^{-13}	Normal 1.645σ	(Forster et al., 2021)
τ_{N2O}	Perturbation lifetime	Years	109	10	Normal 1.645σ	Canadell et al. (2021)
AGTP						
ECS	Equilibrium climate sensitivity	K.(W.m^{-2})$^{-1}$	0.76	0.28	Normal 1σ	(Forster et al., 2021)
c_1	ECS fractional contribution of the fast term	-	$c_1 = 0.586$	see SM.5		(Smith et al., 2021)
c_2	ECS fractional contribution of the slow term	-	$c_2 = 1\text{-}c_1$			
d_1	Fast relaxation time	Years	$d_1 = 3.4$			(Smith et al., 2021)
d_2	Slow relaxation time	Years	$d_2 = 285$			

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3 Sensitivity analysis

In LCAs, climate change CF are often used without related uncertainties, e.g. 1 $kgCH_4$ = 29.8 $kgCO_2e$. Nevertheless, common relative metrics of CH_4 and N_2O show wide uncertainty ranges: 32%-49% for GWP and 46-83% for GTP (Smith et al., 2021). Olivié and Peters (2013) highlighted that variations in IRF_{CO2} and IRF_T have a considerable impact on common emission metrics, even in linear systems, i.e. for small perturbations. IRF_{CO2}' α and τ parameters of Eq. (7) are related to phenomenological modelling, and hence have no physical meaning. They are fitting parameters of a mean that comes from a multi-model analysis. To characterise the IRF_{CO2} uncertainty, we randomly use one model's fit coefficients among the 13 ensemble members of Joos et al. (2013) (see SM.4). In this straightforward and tractable way, we ensure that the constraint $\alpha_0 = 1-\alpha_1-\alpha_2-\alpha_3$ is respected in the probabilistic analysis, but we can't give α and τ specific uncertainty values. Addition of other parameters uncertainties enable us to plot a proper uncertainty range. As done in the AR6, IRF_T' c and d parameters of Eq. (6) are derived from a constrained ensemble from FaIRv1.6.2 and MAGICC7.5.1, whereas c and d variations are computed from MAGICC7.5.1 ensemble members only (see SM.5).

Table 2 presents added uncertainties linked to radiative efficiency scaling factors, lifetime perturbations and CH_4 oxidation yield and ECS from Forster et al. (2021). AR6 mostly considers normal uncertainty distribution with [5-95]% confidence range. Monte Carlo simulations (5000 runs for AGWP; 10000 runs for AGTP) are performed to get stable uncertainty ranges. Uncertainties on CCf – γ and on $r_F(t)$ parameters – are not considered here.

4 Results

We first compare in Fig. 1 the dynamic climate change impact of 1kg emission of CO_2, of CH_4 and of N_2O. Metric profiles represent responses from present day (H = 0 year) to the maximum possible long-term time horizon (H_{max} = 1000 years if multi-model mean IRF_{CO2} from (Joos et al., 2013) is used). AGWP grows up to an asymptotic value, i.e. when GHGs are no longer in the atmosphere. This asymptote comes from AGWP mathematical construct and might lead to bias in long-term interpretations. Differences in orders of magnitude between CO_2, CH_4 and N_2O's GWP_{100} are well reflected with dynamic AGWP profiles. As for AGTP, it shows a peak temperature change ($AGTP_{peak}$) shortly after emission because of the quick planetary surface response. $AGTP_{peak}$ is reached at 10, 6 and 15 years for CO_2, CH_4 and N_2O respectively, which fits and extends Ricke and Caldeira (2014)'s observation. Then, a more or less decreasing AGTP is due to deep ocean thermal inertia. Temperature change caused by a CO_2 emission decreases very slowly at long-term H, i.e. CO_2 has a significant long-term impact. Methane causes a notable short-term climate change contribution. It has also a long-term impact from its oxidation into CO_2 emissions: $AGWP_{CH4}$ keeps slightly increasing over centuries and $AGTP_{CH4}$ does not sharply decrease at long-term perspective. N_2O behaviour is in-between: GTP_{N2O} value begins to decrease with H≈30 years. AGTP temporal emission profiles reflect much more nuances than the use of static GTP values of CO_2, CH_4 and N_2O. Table 3 shows CF of both metrics with their associated uncertainties at H routinely reported by IPCC, plus at $AGTP_{peak}$.

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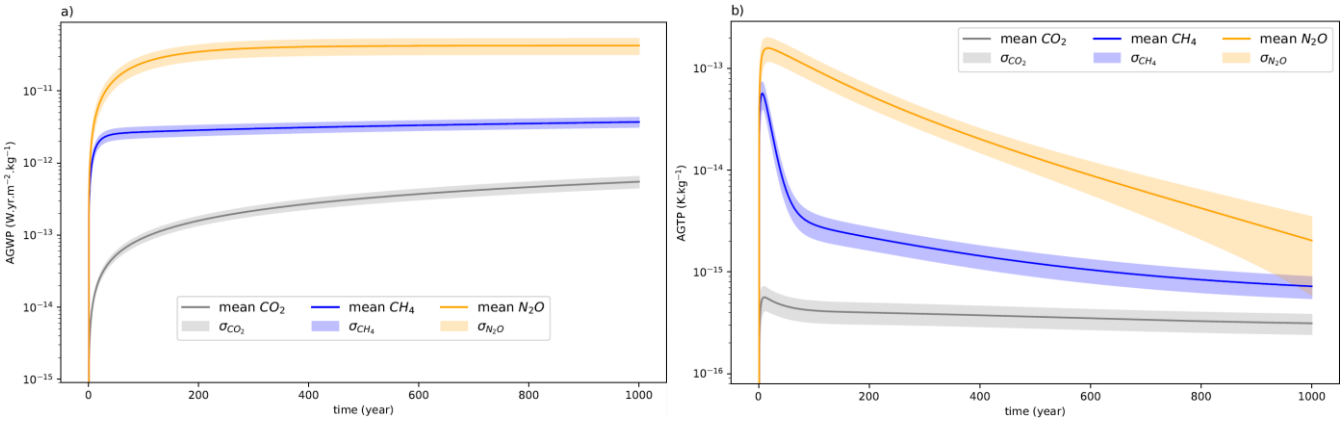

Figure 1. a) AGWP and b) AGTP profiles in logarithmic scale from present-day (H = 0 year) to very long-term perspective (H = 1000 years) after emissions of 1kg CO_2, 1kg CH_4 and 1kg N_2O. Uncertainty ranges are computed by varying all parameters listed in Table 2.

Table 3. Characterisation factors of AGWP and AGTP emissions metrics for selected species and time horizons. Uncertainties are calculated with 1 × standard deviation σ. u% represents the ratio between σ and mean value.

	W.yr.m^{-2}.kg^{-1} (x10^{-12})			*u% mean*	°C.kg^{-1} (x10^{-15})			*u% mean*
	$AGWP_{20}$	$AGWP_{100}$	$AGWP_{500}$		$AGTP_{peak}$	$AGTP_{50}$	$AGTP_{100}$	
CO_2	0.0244 ± 0.0025	0.090 ± 0.013	0.314 ± 0.053	*14%*	0.54 ± 0.16	0.43 ± 0.13	0.39 ± 0.12	*31%*
CH_4	2.01 ± 0.32	2.69 ± 0.45	3.20 ± 0.50	*16%*	55 ± 19	5.7 ± 2.3	3.02 ± 0.98	*36%*
N_2O	6.7 ± 1.6	24.6 ± 5.9	42 ± 10	*24%*	150 ± 57	125 ± 48	93 ± 35	*38%*

The key aim of metrics is the quantification of the marginal impact of pulse emissions of extra GHG units (Kirschbaum, 2014). Figure 2 compares three pulse emissions being equivalent in terms of GWP_{100}: 1) an emission of 100 kg of CO_2 ; 2) a 3.36 kg emission of CH_4 ; 3) a *mixed_GHGs* pulse reflecting 2022 global emissions proportion of major GHGs – 99% CO_2, 0,97% CH_4, 0,03% N_2O – (adapted from EDGAR (Crippa et al., 2023)). According to its definition in climate science, GWP_{100} is unitless. However, one can note that GWP_{100} is often treated as being equal to CO_2-equivalent emissions in LCA.

Both AGWP and AGTP show that the conversion from CH_4 to CO_2-equivalent emissions underestimates short-terms impacts and overestimates long-term impacts (Allen et al., 2016). Nevertheless, the notion of CO_2-equivalent in cases of pulse emission at t_0 makes sense regarding global emissions proportion, especially for mid- and long-term H. Figure 3 shows that CH_4 contribution on temperature change caused by a 1-year emission pulse from all anthropogenic activities is almost equal to CO_2 in the short-term, with a 51:46 CO_2:CH_4 percentage contribution at H = 10 years. After some decades, temperature change is almost only driven by CO_2 and hence flattens. This is in line with Allen et al. (2022) who support separating SLCFs and LLCFs' contributions in emission targets, especially under short-term perspective. Respectively for *CO_2*, *CH_4* and *mixed_GHGs* scenarios, we compute -19%, -68% and -24% between $AGTP_{200}$ and $AGTP_{1000}$, which is little compared to the drop of -40%, -2275% and -163% between $AGTP_{peak}$ and $AGTP_{200}$. We then propose to calculate $AGTP_{long-}$

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$_{term}$ being 500 years after $AGTP_{peak}$ as a representative mean value of this observed temperature change flattening. Mean values of these two metrics are presented in Tab. 4.

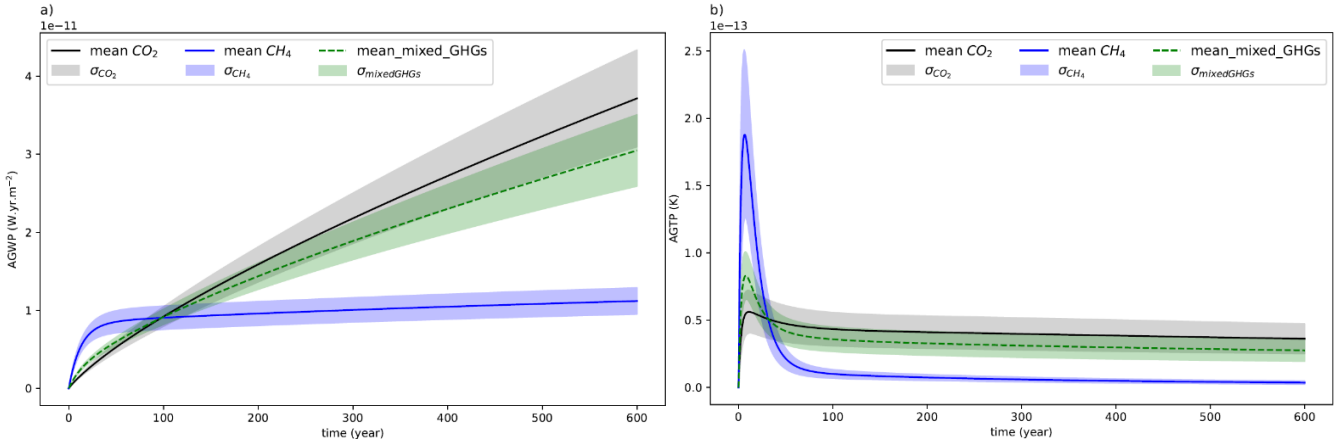

Figure 2. a) AGWP and b) AGTP profiles for three pulse emissions having the same GWP_{100} = 100 $kgCO_2e$.

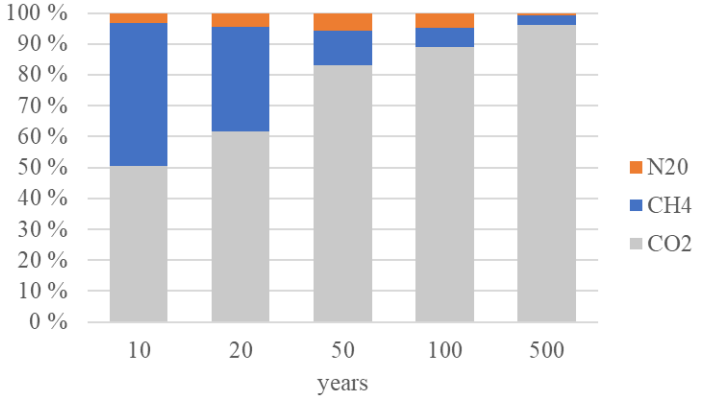

Figure 3. Evolution over time of the relative contribution of CO_2, CH_4 and N_2O to AGTP of 'mean_mixed_GHGs' reflecting 2022 global emission (mass ratio: 99% CO_2 - 0,97% CH_4 - 0,03% N_2O).

Table 4. Mean $AGTP_{peak}$ and $AGTP_{long\text{-}term}$ associated with the three temporal emission profiles of Fig. 2.b).

x10^{-14}	$AGTP_{peak}$ (°C)	$AGTP_{long\text{-}term}$ (°C)
CO_2	5.4 ±1.6	3.6 ± 1.1
CH_4	18.6 ± 6.4	0.43 ± 0.14
mixed_GHGs	8.2 ± 1.8	2.77 ± 0.83

Lastly, we address dynamic climate metrics in multi-gas and multi-pulse cases, i.e. what is mostly encountered by assessment communities. This approach is especially interesting to assess long-lasting systems as well as bio-based products that store biogenic carbon while not degraded. To illustrate the potential benefits of using ΔF and ΔT in such cases, Fig. 4 reflects impacts of two insulating materials with a 50-year lifespan. Expensed polystyrene is fossil-based and straw bale is bio-based. At the production stage *Polystyrene* is more energy intensive while *Straw bale* sequesters much more CO_2 than it emits GHGs. At end-of-life (EoL) stage *Polystyrene* is landfilled and emits very little. *Straw bale* is composted or mulched and releases a large amount of initially captured CO_2 along with CH_4 and N_2O. Inventories can be found in SM.6.

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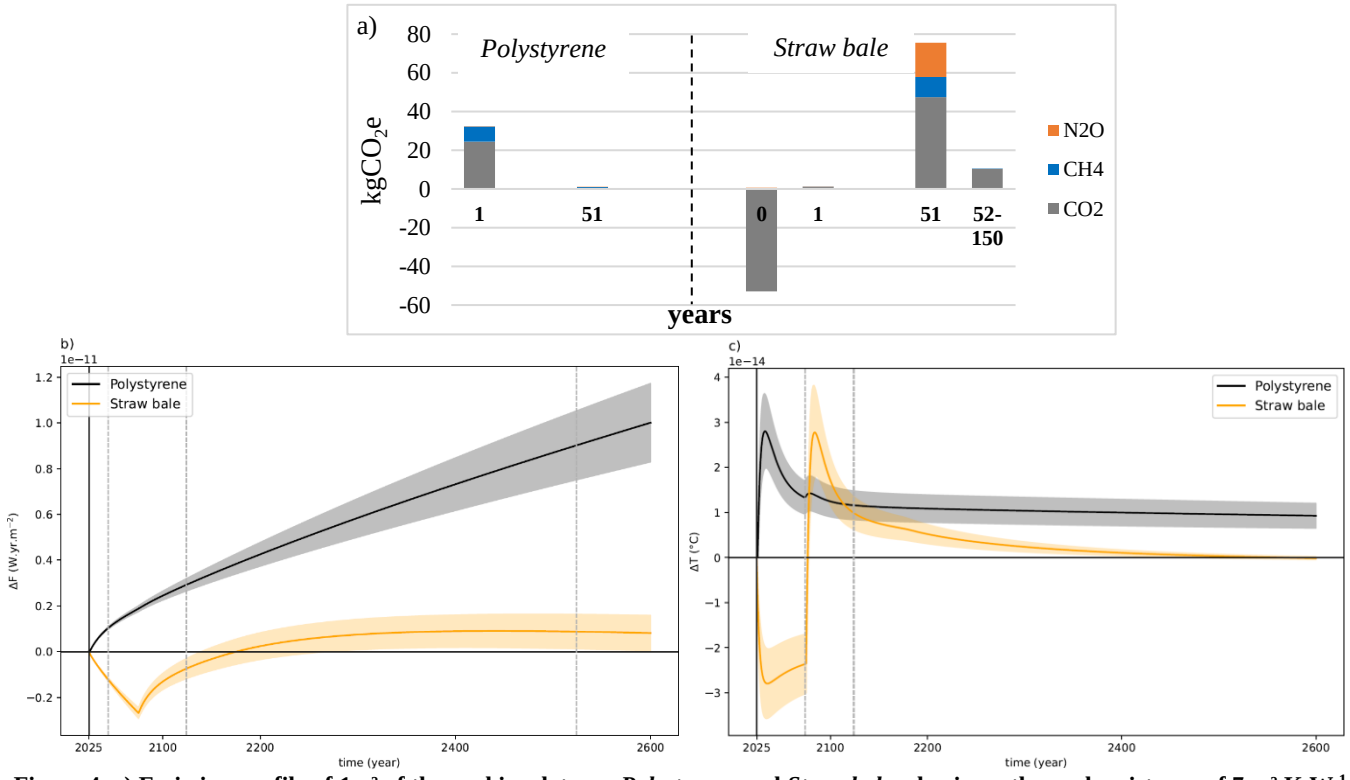

Figure 4. a) Emission profile of 1m² of thermal insulators - *Polystyrene* and *Straw bale* – having a thermal resistance of 7 m² K W^{-1} during 50 years. CO_2, CH_4 and N_2O are emitted (see inventories in SM.6). b) ΔF and c) ΔT temporal profiles of these two products over 575 years. Dotted grey lines represent recommended H by IPCC leading to ΔF_{20}, ΔF_{100}, ΔF_{500} (b) ; ΔT_{50}, ΔT_{100} (c).

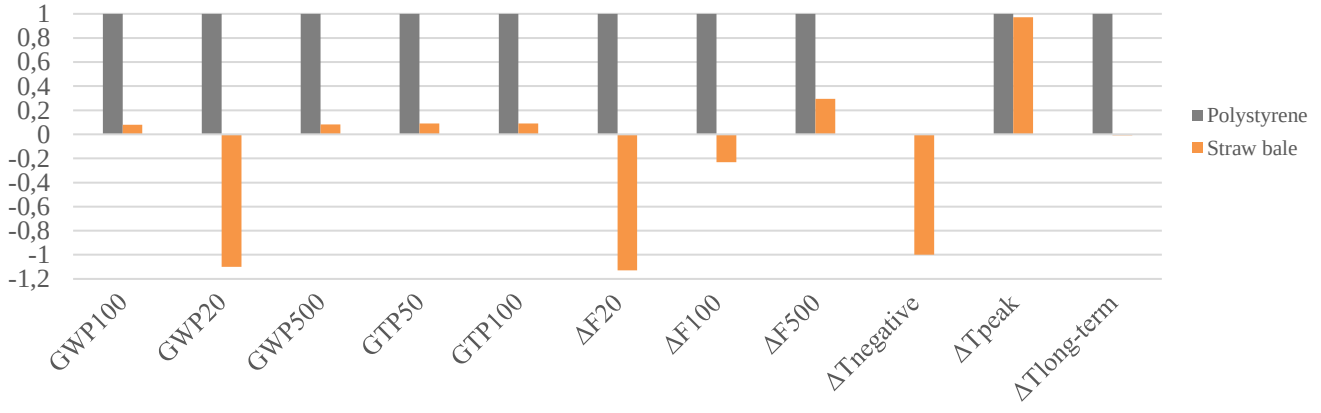

Figure 5. Relative climate change results for *Polystyrene* and *Straw bale* according to common relative metrics – GWP_{20}, GWP_{100}, GWP_{500}, GTP_{50}, GTP_{100} - and suggested metrics in this article: ΔF_{20}, ΔF_{100}, ΔF_{500}, $\Delta T_{negative}$, ΔT_{peak}, $\Delta T_{long\text{-}term}$. Absolute values are presented in SM.7.

Five main observations can be made: 1) Energy intensive materials contribute to global warming from t_0. 2) Both dynamic metrics show that temporary carbon storage of bio-based products induces a significant effect in mitigating climate change, at least up to EoL. One can observe a drop in temperature change with a negative minimum, $\Delta T_{negative}$, at H = 11 years.

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Compared to ΔT, ΔF shows longer benefits from the temporal carbon storage of bio-based materials. 3) ΔT_{peak} of *Straw bale* occurs at H = 61 years, i.e. much later than t_0 as implied by common static metrics. Peak timing as a point of reference for the long-term CF appears relevant. 4) Even if ΔT_{peak} of *Polystyrene* and *Straw bale* are similar, *Straw bale* end up with a slightly negative $\Delta T_{long\text{-}term}$, i.e is the only one fitting with climate neutrality. 5) recommended dynamic metrics by IPCC give representative values for short-, mid-, and long-term perspective with ΔF but not for ΔT:

- ΔT_{50} fails to capture the most important temperature change contributions of *Polystyrene*. Moreover, it gives a negative value for *Straw bale*, but in a 45-year-lifespan scenario, the result would be the opposite, making the EoL occurrence too sensitive to the H choice.
- unlike suggested by UNEP/SETAC recommendations, temperature change at 100 years is not representative of a long-term impact: ΔT_{100} of *Polystyrene* and *Straw bale* are almost equal whereas Fig. 4c and $\Delta T_{long\text{-}term}$ depict a big difference on a longer-term perspective. Indeed, at H = 100 years, *Straw bale* still emits GHGs.

Figure 5 clearly highlights contributions of the dCCA approach: all common relative metrics except GWP_{20} show similar relative impacts between both products. As for recommended dynamic metrics, conclusions vary according to the chosen CF, which might lead to different climate policies, especially about negative and positive impacts of bio-based systems.

5 Discussion

5.1 Towards more clarity on absolute and dynamic climate metrics

Supplementary material of AR6 WG1 chapter 7 (Smith et al., 2021) summarises main climate metric equations, but has limitations: it lacks of clearly gathered climate parameter values, associated uncertainties and contribution of indirect effects to climate equations. Preparation of the seventh Assessment Report of the IPCC (AR7) will begin soon. Each new report is an opportunity to recall climate metric common equations as well as to write down updates in specific gas species metric equations and climate parameters values in a pedagogical manner. The work done in part 2.3, notably inspired by Aamaas et al. (2013) and by what Myhre et al. (2013b) did for CH_4 and N_2O equations may be supporting materials for this purpose. This would help environmental assessment communities with less expertise and in-depth knowledge of climate models to acquire better comprehension of what underlies absolute metrics and adopt dCCA. Indeed, as mentioned above, dynamic climate metrics are scientifically more accurate and LCA practitioners should use them while assessing long-lasting products (lifespan > 5-10 years) (SCORE LCA, 2024).

5.2 Dynamic climate metrics interpretation

5.2.1 Emission pulses only at t_0

AGWP and AGTP can be compared through Fig. 1 and Fig. 2. As these two climate metrics are mathematically different and display different shape types, they are complementary. Radiative forcing metrics are now considered robust and useful

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(Fuglestvedt et al., 2003). As a time-integrated metric, AGWP temporal profiles keep increasing over centuries when CO_2 is emitted. Contributions of LLCFs stock pollution as well as the effect of CO_2 temporal storage (Zieger et al., 2020) are clearly displayed. Contributions of short-lived well-mixed GHGs are displayed for short H (≤20 years). Common H values – 20, 100 and 500 years – appear well suited to get AGWP's short-, mid- and long-term CFs. In agreement with Levasseur et al. (2016a), there is no reason to prioritise a specific H. Lastly, AGWP only requires atmospheric response models, needs climate models just when CCf is included, and then embeds less uncertainty than AGTP. Drawbacks of using AGWP are rather linked to the unit – W.yr/m². First, it is not clear for policymakers. Second, calculations are not explicitly linked to ultimate climate-change impacts but to energy imbalance and may not match the expected global surface temperature (Forster et al., 2021; Kirschbaum, 2014).

AGTP is an interesting alternative metric since it directly reflects temperature change. AGTP temporal profiles of all studied gas show a peak temperature because of the rapid planetary surface response. AGTP at mid- and long-term corresponds to the thermal inertia of the deep ocean that maintains the memory of the initial pulse (Shine et al., 2005). Showing these impacts over time is much more refined than giving usual GTP values at 50- and 100-year H. Table 3 shows that the difference between $AGTP_{50}$ and $AGTP_{100}$ is low and not representative of the difference between $AGTP_{peak}$ and $AGTP_{long\text{-}term}$. Such an absolute metric is not frequently used in LCA. Yet, it offers significant advantages. 1) AGTP is in Kelvin or Celsius degree, a unit that everybody understands. 2) Endpoint metrics are most closely aligned with the Paris Agreement and the notion of time of maximum temperature rise (Collins et al., 2020). 3) AGTP is able to depict on a same graph emission profiles of both SLCF and LLCF, at least from black carbon (τ = a few days) to SF6 (τ = 1000 years), even on a 1-year time resolution (Sterner et al., 2014). 4) $AGTP_{peak}$ is a curve characteristic that varies with the type of gas and is insensitive to the inadvertent H consensus (Shine, 2009). Picking the peak temperature change is also a form of value judgment. Yet, as the global mean temperature is getting closer and closer to the 2°C peak warming target, knowing when peak temperature occurs makes this CF particularly relevant. In a systemic approach such as a sustained technological change, dynamic temperature responses would allow identifying the real optimum in terms of temperature increase and its timing. 5) Figure 2 highlights that a vast majority of human activities emit CO_2, which implies that most product systems have a characteristic almost asymptotic long-term temperature change impact.

5.2.2 Emission pulses at different timings

Temporally displaced emissions profiles raise an issue about climate change metrics: is the way CFs are designed suited for assessment purposes? Characteristic dCCA inventories with multi-time and multi-gas emission pulses, as shown in Fig. 4, impose thinking differently from using the single gas emission pulse assumed by traditional metrics.

Multi-time and -gas emissions also put emphasis on the benefits of using ΔF and ΔT for LCA practitioners. To carry out a dCCA, we first propose to get temporal profiles from 0 to 600 years. This gives a visual and detailed comparison between product systems. ΔF interpretation is similar to AGWP, i.e. assessments at 20, 100 and 500 years well accompany the temporal representation. Besides, relative ΔF of Eq. (13) computed thanks to dynamic climate change assessment tools

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(Levasseur et al., 2010; Tiruta-Barna, 2021) might be a way to obtain temporal carbon footprint profiles with a common unit. Here, *n* is the number of assessed GHGs and *i* an assessed GHG.

$$\Delta F_{relative}(H) = \frac{\sum_n \Delta F_i(H)}{AGWP_{1kg,CO2}(H)}, \quad (13)$$

In a multi-pulse framework, ΔT_{peak} metric becomes even more pertinent. Indeed, unlike with pulse emission at t_0, ΔT_{peak} might appear decades after t_0, making this non H-dependant metric highly relevant. Moreover, when CO_2 is a part of emitted GHGs, which is almost always the case when assessing products and sectors, $\Delta T_{long\text{-}term}$ is a second relevant metric. ΔT_{peak} can be interpreted as a flow climate change contribution caused by the rapid temperature response of the Earth after emissions of both SLCFs and LLCFs. It matches very well the explicit goal of the Paris Agreement to limit the instantaneous peak temperature due in part to the significance of instantaneous elevated temperature in causing heat waves and extreme events (Abernethy and Jackson, 2022). $\Delta T_{long\text{-}term}$ is representative of a stock climate change contribution of a product system. Unlike integrated RF, it displays well the 2018 IPCC Special Report on 1.5 °C statement: "Reaching and sustaining net zero global anthropogenic CO_2 emissions and declining net non-CO_2 radiative forcing would halt anthropogenic global warming on multi-decadal timescales (high confidence)."

These are key features to design transparent absolute and dynamic temperature change CFs. AR6 expresses AGTP and GTP's CF at 50- and 100-year H. For assessment purposes, IPCC is invited to replace $AGTP_{50}$ and GTP_{50} values by $AGTP_{peak}$ and GTP_{peak} values in the coming AR7. IPCC could also adopt a long-term temperature change perspective, e.g. 500 years after $AGTP_{peak}$ occurs, in addition to the common 100-year H. Lastly, LCA practitioners are encouraged to go beyond CF by implementing a graphical representation that depicts yearly climate impacts on a basis over centuries. This would enable them to lessen value judgements in assessements.

5.3 Uncertainty issues

CO_2 data are less uncertain than N_2O and CH_4 ones due to low CO_2 radiative forcing scaling factor uncertainty that offset its more uncertain IRF. N_2O has the highest radiative forcing scaling factor uncertainty. About temperature change metrics, the equilibrium climate sensitivity is known as one of the most uncertain features of the climate system and causes much of the uncertainty in projections of future global warming (Forster et al., 2021; Shine et al., 2005). Indeed, AR6 concludes that there is a 90% or more chance (very likely) that the ECS is between 2°C and 5°C (Forster et al., 2021). Hence, AGTP's relative uncertainties are about two times higher than AGWP ones (see Table 3). Nevertheless, ECS uncertainty is not a barrier to develop metrics based on temperature change (Shine et al., 2005). Furthermore, as ECS directly represents long-term global warming from doubling CO_2 from pre-industrial level, it also contributes to AGTP and ΔT policy relevance. Indeed, this uncertain response time of the climate system is a real feature which is not captured by radiative forcing metrics.

As future warming scenarios are not considered, i.e. GHG concentrations are static, uncertainties are even bigger as computed here. How far the potential advantage of $AGTP_{long\text{-}term}$ to achieve long-term climate targets compared to the

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disadvantage of being subject to considerably larger uncertainties (Reisinger et al., 2010) is still open to conjecture. In short, computing uncertainties as proposed here while using relative or dynamic climate metrics is a minimal recommendation.

6 Conclusion

While we are becoming more and more aware of the Earth's climate system's complex functioning, it is critical to keep clear and understandable climate metrics for the LCA community. It might indeed be difficult to make connections between the complexity of climate models and successive recommendations as and when IPCC reports are presented. As preparation for the next IPCC assessment will begin soon, this paper highlights the importance to clearly recall dynamic equations that underlie climate metrics and to properly gather updated climate parameter values with associated uncertainties. The overview of up-to-date climate data has been presented here with this pedagogical purpose in order to help environmental assessment communities adopt consistent dynamic climate metrics.

Absolute and dynamic metrics enable us to properly represent specific behaviours of different climate forcers over time. There is a growing interest in using them to take the analysis one step further than with CO_2-relative and static metrics (GWP, GTP). But while climate metrics are designed with single gas pulses emitted at time zero, LCA modelling of products and systems generally leads to multi-pulse with multi-gas emission profiles. Hence, usually recommended and used CFs might not be suitable for dCCA. To investigate that, we have compared main dynamic metrics: AGWP and AGTP for one-pulse emissions, and their multi-pulse emissions equivalent, ΔF and ΔT. Cumulative radiative forcing and temperature change metrics appear to be complementary. Radiative forcing metrics are quite simple to compute and give less uncertain results. With impacts that keep growing with time, they display in a more pronounced manner the impact of very long-lasting CO_2 and temporary carbon storage. Global temperature change endpoint metrics are more complex and uncertain, but meet both scientific completeness and pragmatic policy choice. First, they represent climate impacts in the common Celsius degree unit, explicitly matching the target of keeping global warming below 2°C above the preindustrial level. Second, graphical representation captures well the nature of both LLCFs and SLCFs, i.e integrates both short-term perspective with target overshoot concerns and temperature change that will remain for centuries. Lastly, CFs proposed here (ΔT_{peak}, $\Delta T_{negative}$, $\Delta T_{long\text{-}term}$) are an attempt to get rid of the time horizon issue that has plagued the LCA community for so long.

Assessments using CO_2-equivalent climate impacts give sufficiently reliable results to go towards mitigation. Nevertheless, to achieve ambitious objectives such as carbon neutrality, this work showed that climate policy should gain in consistency by adopting temporal metric profiles and selecting some specific values in addition or in substitution to relative metrics. Hence, environmental assessors should display dynamic assessment results from 0 to 600 years and to adopt ΔF_{20}, ΔF_{100}, ΔF_{500}, $\Delta T_{negative}$, ΔT_{peak}, $\Delta T_{long\text{-}term}$ with their associated uncertainties as new climate change CF. IPCC could support this by adopting $AGTP_{peak}$ and $AGTP_{long\text{-}term}$.

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Appendix A: Glossary

Characterisation factor (CF): produced by modelling consequences of withdrawals and discharges on ecosystems, human health or on resources, a characterisation factor provides the contribution of an elementary flow to an impact category. For climate metrics, a CF converts the impact of 1 kg of a GHG emission or uptake into a defined unit and time horizon.

Chemical adjustments: the perturbation of a single emitted compound is not limited to its direct radiative forcing, but can induce subsequent chemical reactions and affect the abundances of other climate forcers. As an example, CH_4 emissions cause tropospheric ozone production as well as stratospheric water vapour increase.

Dynamic climate metrics: absolute metrics used in a temporal dynamic approach that considers storages and emissions timing. First attempts on dynamic climate change assessment calculated the benefits implied by a delayed emission, but still with a fixed time horizon (Fearnside et al., 2000). Levasseur and her co-workers (2010) extended the approach by calculating absolute and relative radiative forcing metrics on a yearly basis over several hundreds of years.

Effective radiative forcing (ERF): ERF is employed as the central definition of radiative forcing in AR6. It quantifies change in net downward radiative flux at the top-of-atmosphere following adjustments in both tropospheric and stratospheric temperatures, water vapour, clouds, and some surface properties (Forster et al., 2021). Hence, AR6 includes tropospheric rapid adjustments (+5% for CO_2, –14% for CH_4 and +7 % for N_2O) to the stratospheric-temperature-adjusted radiative forcing equations of Meinshausen et al. (2020) to get ERF and RE values (Smith et al., 2021).

Impulse response function (IRF): describes the atmospheric decay of an emitted species. Its general formulation follows one or several exponential decay functions (Joos et al., 2013), $e^{\frac{-t}{\tau_i}}$, where τ_i is the e-folding time representing the perturbation lifetime of a gas *i*

Radiative efficiency (RE): equals the ERF for a change in the atmospheric abundance. It is converted from $W.m^{-2}.ppb^{-1}$ to $W.m^{-2}.kg^{-1}$by multiplying with $(M_A/M_i)*(10^9/m_{atm})$, where M_A and M_i are the molecular weight of dry air (28.97 $g.mol^{-1}$) and the studied gas *i* respectively, and m_{atm} is the mean dry mass of the atmosphere (5.1352×10^{18} kg) (Myhre et al., 2013b).

Short-lived climate forcer (SLCF): SLCFs include aerosols and chemically reactive gases, both affecting climate (Szopa et al., 2021). Depending on the species, their perturbation lifetimes, τ, range from a few hours to more than a decade. If τ<1-2 years, SLCFs are also called near-term climate forcers (NTCFs) i.e. are spatially highly heterogeneous. Otherwise they might also be called short-lived well-mixed GHGs.

Code availability

The dynamic climate change assessment tool is accessible here : https://gitcdr.univ-ubs.fr/DynCC/Metrics_assesment_tool

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Author contribution

Vladimir Zieger : Writing – original draft preparation, Conceptualization, Methodology, Visualization. **Thibaut Lecompte:** Writing – review & editing, Conceptualization, Methodology, Supervision, Funding acquisition. **Simon Guihéneuf:** Writing – review & editing, Conceptualization, Supervision. **Yann Guevel :** Software. **Manuel Bazzana:** Writing – review & editing, Supervision. **Thomas Gasser:** Writing – review & editing, Resources, Validation. **Yue He :** Software.

Competing interests

The authors declare that they have no conflict of interest.

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Nomenclature

AGTP	Absolute global temperature change potential
AGWP	Absolute global warming potential
AR6 / AR7	Sixth / Seventh assessment report
CCf	Climate-carbon feedback
CF	Characterisation factor
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
ΔAGTP	Climate-carbon feedback contribution to AGTP
ΔAGWP	Climate-carbon feedback contribution to AGWP
ΔF	Cumulative radiative forcing in a multi-pulse framework
ΔT	Global mean temperature change in a multi-pulse framework
dLCA	Dynamic life cycle analysis
EoL	End-of-life
ERF	Effective radiative forcing

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GHG	Greenhouse gas
GTP	Global temperature change potential
GWP	Global warming potential
H	Horizon time
IPCC	International panel on climate change
IRF_i	Impulse response function describing the atmospheric decay of a gas i
IRF_T	temporally displaced temperature response function of the Earth system
LCA	Life cycle analysis
LCIA	Life cycle Impact Assessment
LLCF	Long-lived climate forcer
MIP	Model intercomparison project
N_2O	Nitrous oxide
OH	Hydroxyl radical
RE	Radiative efficiency
RF	Instantaneous radiative forcing
SLCF	Short-lived climate forcer
σ	Normal standard deviation

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