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Climate change metrics: IPCC AR6 updates, discussions and dynamic assessment applications

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Abstract. Climate change metrics result from analytical simplification of complex and diverse climate models. Assessment communities do not always take the time to understand this complexity. We investigated the last IPCC report to properly gather updated metric equations, climate parameters and associated uncertainties. In each future Assessment Reports, IPCC is encouraged to recall climate equations and parameters values in a pedagogical way. Global Warming Potential (GWP) is an easy-to-use, but simplistic and criticised metric. Alternative Global Temperature change Potential (GTP) remains as GWP: relative to carbon dioxide and used at arbitrary fixed time horizons (H). This study focuses on two dynamic metrics – cumulative radiative forcing (AGWP or ΔF) and global temperature change (AGTP or ΔT) – and applies them to the three major anthropogenic greenhouse gases (GHGs) – carbon dioxide, methane and nitrous oxide. Dynamic climate metrics better assess impacts by differentiating GHGs contribution over time. For radiative forcing metrics, indicators at common H – 20, 100, 500 years – are sufficient, with no hierarchy between these timescales. As for global temperature change metrics, they have two advantages that offset their higher uncertainties. (1) They are more policy-relevant with an easily understandable unit. (2) Peak and long-term temperature change enable to get rid of H major issue, i.e. IPCC is encouraged to adopt $AGTP_{peak}$ and $AGTP_{long\text{-}term}$ characterisation factors. We also recommend plotting complementary cumulative radiative forcing and temperature change temporal profiles of a product system up to 600 years. This enables going towards climate neutral product systems with more clarity, transparency and understanding.

1 Introduction

Human activities have now clearly put the Earth system well outside of 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 have a chance 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). There is a near-linear relationship between cumulative CO_2 emissions and global warming (IPCC, 2021b) showing that shared socio-economic pathways SSP1-1.9 and SSP1-2.6 are indeed leading to sustainability (Meinshausen et al., 2020). While it appears less and less likely, it is still physically possible to stay under the 2°C target, although choices towards strong mitigation need to be taken now.

The study of Earth's climate considers complex interactions between Atmosphere, Biosphere, Cryosphere, Hydrosphere and Lithosphere. The number of forcing mechanisms (e.g. Greenhouse Gases (GHGs), aerosols) is large, as are uncertainties. State-of-the-art Earth system models used in Model Intercomparison Projects (MIPs) attempt to describe all climate system's

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components as accurately as possible. Simplified parametric models allow for capturing dynamic climate metrics based on radiative forcing or temperature change. 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) and associated uncertainties for relative metrics such as Global Warming Potential (GWP).

GWP has been widely used since the Kyoto Protocol, thanks to its ease of calculation and simple definition, kilogram CO_2-equivalent ($kgCO_2e$) being now a common unit to assess carbon footprint of products and systems. Life Cycle Assessment (LCA)'s common indicator to assess climate change is GWP at a 100-year time horizon (GWP_{100}). Nevertheless, GWP has been largely criticised: 1) it does not explicitly represent the temperature response to a GHG emission, but compares the total energy added to the climate system by a component relative to that added by CO_2, therefore. the name 'relative cumulative forcing index' would be more appropriate (Myhre et al., 2013b; Shine et al., 2005); 2) this relative metric has a nonlinear relationship between integrated radiative forcings of CO_2 and of the studied gas (O'Neill, 2000); 3) it sums emissions independently of their timing, and thus fails to take into account temporary carbon storage (Zieger et al., 2020); 4) it does not express impacts over time, the chosen time horizon being a value judgement that has a strong effect on the metric values (Myhre et al., 2013b); 5) GWP_{100} does not lead to an accurate estimate of peak warming and net-zero timing (Fuglestvedt et al., 2018). Global Temperature change Potential (GTP) is a more policy-relevant metric developed by Shine et al. (2015) that quantifies the temperature change due to a GHG pulse emission relative to the temperature impact of a 1-$kgCO_2$ pulse, both evaluated at a particular time horizon (H). It is then still relative to CO_2 and under H value judgement.

Dynamic climate metrics might be more complex to understand but are physically more robust. Based on this observation, 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. Other impact categories than climate change are commonly not in the framework of dLCA. Due to the variety of applications and of emitted components' physical properties, there is no obvious scientific need to have one single metric, and a range of different metrics may be used in one application (Aamaas et al., 2013; Myhre et al., 2013b). But the use of several metrics for a single category adds complexity for LCA practitioners. Moreover, IPCC does not provide needed information in its reports to easily understand and use dynamic climate metrics. Lastly, pros and cons of such metrics need to be clarified for wider use.

For research purposes, we therefore found useful to carry out a review to clarify 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, 2021). We thus focus on them. Given the openness of the IPCC to revise emission metrics in future Assessment Reports (Abernethy

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and Jackson, 2022), we believe our 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;
- address up-to-date AGWP and AGTP for CO_2, CH_4 and N_2O GHGs to environmental assessment communities;
- make available an open-source dynamic climate change assessment tool;
- suggest clearer data presentation and new CF for future IPCC reports;
- discuss whether ΔF and ΔT, as well as static and dynamic approaches, are to characterise strong sustainable designs.

2 Methodology

2.1 Climate change metrics – an overview

Emission metrics aim to compare the effects of different forcing agents on the climate system (Levasseur et al., 2016). The main purpose is to provide an 'exchange rate' in multi-component policies or in areas such as Life Cycle Assessments (Aamaas et al., 2013; Myhre et al., 2013b). Equation 1 firstly gives a general formulation of an emission metric (Forster et al., 2007):

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

where $I(\Delta C_r(t))$ is the function describing the "impact" of a change in climate ΔC, at time t, with a discount function, g(t), and compared to a reference system, r, on which the perturbation i occurs. AM_i is an absolute metric. In emission metrics, g(t) need not be an exponential discounting, but is rather used to represent a fixed time-horizon using a step-function, e.g. in integrated metrics, or an instantaneous evaluation using a Dirac delta function that remove the integral of Eq. (1), e.g. in endpoint metrics (Peters et al., 2011b). To compare two emission perturbations i and j, the climate impact $AM_i(t)$ and $AM_j(t)$ can be compared. To transform the effects of different emissions to a common scale, metrics can also be given in relative terms by normalising to a reference gas – usually CO_2 (Myhre et al., 2013b): $M_i = AM_i/AM_j$.

In the present paper, absolute emission metrics are used, i.e. AGWP, AGTP, ΔF, ΔT, as well as relative ones: GWP and GTP. These are designed to facilitate rapid evaluation and comparison of the climate effects of emissions (Myhre et al., 2013b). Emission metrics are based on a linearisation of a complex system. They require input parameters based on background information (see Fig. 1) that characterise GHGs, such as radiative efficiency and perturbation lifetime. Table 1 shows how climate parameters as well as relative climate metrics have evolved over the successive IPCC reports. This supports the use of up-to-date climate metrics and climate change CF.

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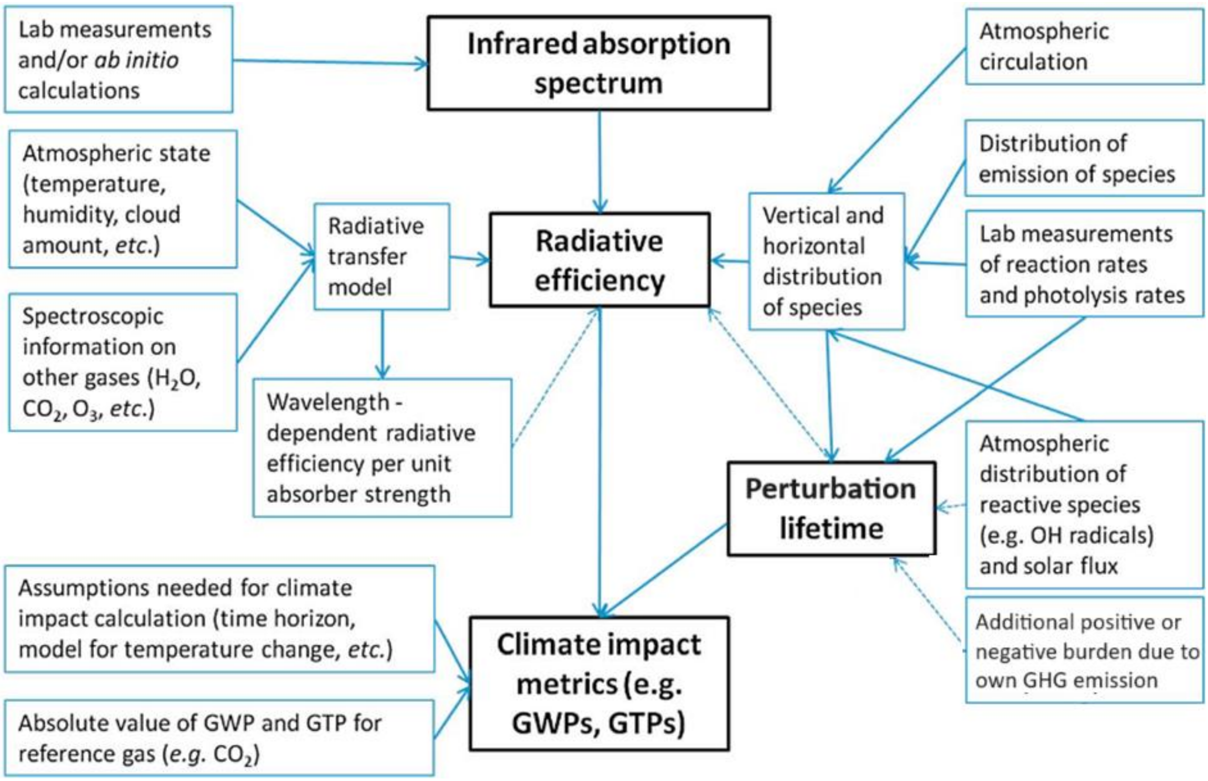

Figure 1. Main parameters and additional background information required to compute climate impact metrics – adapted from Hodneborg et al. (2013).

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., 2013b) 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	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	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 Dynamic metrics

GHGs instantaneous radiative forcing (RF) 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 RF. Following Eq. (2), it describes the

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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 RF calculations, ΔF, since product systems can be viewed as a series of pulse emissions and analysed through convolution (Eq. (3), Aamaas et al., 2013):

$$AGWP_i(H) = \int_0^H RF_i(t)\, dt = A_i \int_0^H IRF_i(t)\, dt\ , \qquad (2)$$

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

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 of in kg, and IRF_i is the impulse response function describing the atmospheric decay of a specie and whose very general formulation is described by a sum of exponential functions (Joos et al., 2013).

Radiative efficiency (RE) is the change in RF for a change in the atmospheric abundance. It is converted from per ppb to per kg 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 x 10^{18} kg) (Myhre et al., 2013a). According to simplified RF expressions of Etminan et al. (2016), RE of CO_2, CH_4, N_2O is a function of CO_2, CH_4 and N_2O background concentrations. The same applies for IRF_i.

However, IRF_i partially offset RE changes (Aamaas et al., 2013). Also, decreasing RE_{CO2} with increasing CO_2 concentration is partially offset by an increase in climate-carbon cycle feedback (Reisinger et al., 2011) and by CO_2 sink saturation, mainly associated 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 dLCA. Constant RE and IRF_i must at least be updated with each new IPCC assessment report. As RE assumes that RF is linear with respect to the mixing ratio for small perturbations about current concentrations (Hodnebrog et al., 2013), we fixed RE and $IRF_{non\text{-}CO2}$ values with 2019-background concentrations (410 ppm CO_2, 1866 ppb CH_4 and 332 ppb N_2O) as done in the AR6. 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 (Global Monitoring Laboratory, 2024).

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, 2021).

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

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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)):

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

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

where $IRF_T(t)$ described in Eq. (6) is the temporally displaced temperature response function of the Earth system. The use of a two-layer energy balance emulator (Geoffroy et al., 2013), meaning a two-timescale impulse-response model, 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 modes : 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).

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

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 time scales 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, 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., 2016; Myhre et al., 2013b; Peters et al., 2011a), 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

To evaluate the total greenhouse effect of a given gas molecule, one needs to know its lifetime, its radiative efficiency, and its chemical interaction with other molecules. This study considers some long-lived greenhouse gases (LLGHGs), GHGs whose lifetimes are greater than the time scales for inter-hemispheric mixing (1–2 years) (Szopa, 2021). LLGHGs have relatively homogeneous spatial climate influence in the troposphere because they are well mixed.

Components of complex models such as chemical adjustments are not always incorporated in emission metrics. It is thus necessary to provide transparency on climate metrics. Chemical adjustments consider that the effect of a GHG emission is not limited to its direct radiative forcing: the perturbation of a single emitted compound can also induce subsequent chemical reactions and affect the concentrations of several climate forcers. These adjustments have to be accounted for in emissions-based ERF (Szopa, 2021).

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2.3.1 Carbon dioxide

For the majority of GHGs, the IRF following an emission at time t=0 will have the form $\exp(-t/\tau_i)$, with τ_i the e-folding time representing the atmospheric lifetime of a gas *i* after an additional gas *i* emission perturbation. Due to the variety of physical and biogeochemical processes governing the atmospheric CO_2 concentration (Levasseur et al., 2016), IRF_{CO2} cannot be represented by a simple exponential decay. Instead of a single perturbation lifetime, the perturbation's decay remaining at time t from an atmospheric CO_2 pulse 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 of land ecosystems, or changes in the surface ocean's chemistry.

IRF_{CO2} from Joos et al. (2013) includes CCf. Before AR6, this was not the case for all non-CO_2 species leading to inconsistent climate metrics. 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, 2021) :

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

with $r_F(t) = \delta(t) - \frac{\beta_1}{\kappa_1} e^{-t/\kappa_1} - \frac{\beta_2}{\kappa_2} e^{-t/\kappa_2} - \frac{\beta_3}{\kappa_3} e^{-t/\kappa_3}$ 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 (see reaction R1), 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, 2021). Methane atmospheric lifetime is shorter than its perturbation lifetime τ_{CH4} since an increase in CH_4 emissions decreases tropospheric OH, which in

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turn enhances its own lifetime and therefore the methane burden (Szopa, 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 α_0=0 (see Eq. (7)).

$$CH_4 + OH + O_2 + M \rightarrow CH_3O_2 + H_2O + M \quad \text{(R1)}$$

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, 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 well 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 literature.

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, assessment methods such as dLCA enable to account 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, 2021, Figure 6.12), inducing an adapted AGWP formulae:

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

where f_1 and f_2 are respectively the ozone and the stratospheric water vapour indirect effects, 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_{CH4}^{OH} 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 (R 2-4) are defined by O_3 and temperature stratospheric vertical profile (Prather et al., 2015).

$$N_2O + h\upsilon \rightarrow N_2 + O(^1D) \quad \text{(R2)}$$

$$N_2O + O(^1D) \rightarrow N_2 + O_2 \quad \text{(R3)}$$

$$N_2O + O(^1D) \rightarrow NO + NO \quad \text{(R4)}$$

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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 α_0=0 (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, 2021). They are relatively minor since they nearly 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. (2013a):

$$AGWP_{N2O}(H) = A'_{N2O}\left\{1 - 1.7 \times (1 + f_1 + f_2)\frac{RE_{\mathrm{CH4}}}{RE_{\mathrm{N2O}}} + RE^{O3}_{N2O}C_f\right\} \times \tau_{\mathrm{N2O}}(1 - e^{-\frac{H}{\tau_{\mathrm{N2O}}}}) + \Delta\mathrm{AGWP}_{N2O}(H)$$

$$= A_{N2O} \times \tau_{\mathrm{N2O}}(1 - e^{-\frac{H}{\tau_{\mathrm{N2O}}}}) + \Delta\mathrm{AGWP}_{N2O}(H)\,, \quad (10)$$

where A'_{N2O} and A_{N2O} are radiative efficiency scaling factors in $W.m^{-2}.kg^{-1}$ respectively without and with indirect effects, RE^{O3}_{N2O} 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)
α_{0-3}	Coefficient for fraction of atmospheric CO_2 associated with a nominal timescale	Unitless	α_0 = 1-α_1-α_2-α_3 α_1 = 0.2240 α_2 = 0.2824 α_3 = 0.2763	-	-	(Joos et al., 2013)
τ_{1-3}	Nominal timescale	Years	τ_1 = 394.4 τ_2 = 36.54 τ_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	(Forster 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)

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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	-	$c_1 = 0.586$			(Forster et al., 2021)
c_2	ECS fractional contribution of the slow term	-	$c_2 = 1\text{-}c_1$	-	-	
d_1	Fast relaxation time	Years	$d_1 = 3.4$			(Forster et al., 2021)
d_2	Slow relaxation time	Years	$d_2 = 285$			

2.3 Studied long-lived GHGs features

Commonly, emission metrics are normalised to the corresponding absolute metric of a unit mass of CO_2. If several pulses occur along the years, they are summed up into one pulse at t=0 to get absolute metrics. Normalised AGWP and AGTP leads respectively to Global Warming Potential (GWP) (Eq. (11)) and Global Temperature change Potential (GTP) (Eq. (12)):

$$GWP_i(H) = \frac{AGWP_i(H)}{AGWP_{CO2}(H)} \tag{11}$$

$$GTP_i(H) = \frac{AGTP_i(H)}{AGTP_{CO2}(H)} \tag{12}$$

GWP is the most common climate metric. However, as mentioned in Introduction, many critics have been addressed to the GWP concept. GTP, developed by (Shine et al., 2005) as an alternative in policy relevance, is the next most discussed emission metric.

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, 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. To characterise the CO_2 impulse response function uncertainty, we randomly use one model's fit coefficients among the 13 ensemble members of Joos et al. (2013) (see SM.4). In that respect, the constraint $\alpha_0=1-\alpha_1-\alpha_2-\alpha_3$ is respected in the probabilistic analysis. As AR6, we randomly draw among 600 ensemble members of MAGICC7.5.1 to represent uncertainty from IRF_T parameters (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, i.e. a uncertainty calculated with 1.645 x standard deviation σ. 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.

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4 Results

We first compare in Fig. 2 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 maximum possible long-term time horizon (H=1000 years). AGWP grows up to an asymptotic value, i.e. when GHGs are no longer in the atmosphere. Then, accumulated energy remains over centuries. Differences in orders of magnitude between CO_2, CH_4 and N_2O's GWP_{100} are well reflected with AGWP temporal emission profiles. As for AGTP, it shows a peak temperature change ($AGTP_{peak}$) short 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. Concerning CO_2 temperature change decrease at long-term H is very slight, i.e. CO_2 has a significant long-term impact. Methane causes a notable short-term climate change contribution. CH_4 oxidation implies that $AGWP_{CH4}$ keeps slowly increasing 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 static GTP_{100} 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 $AGTP_{peak}$.

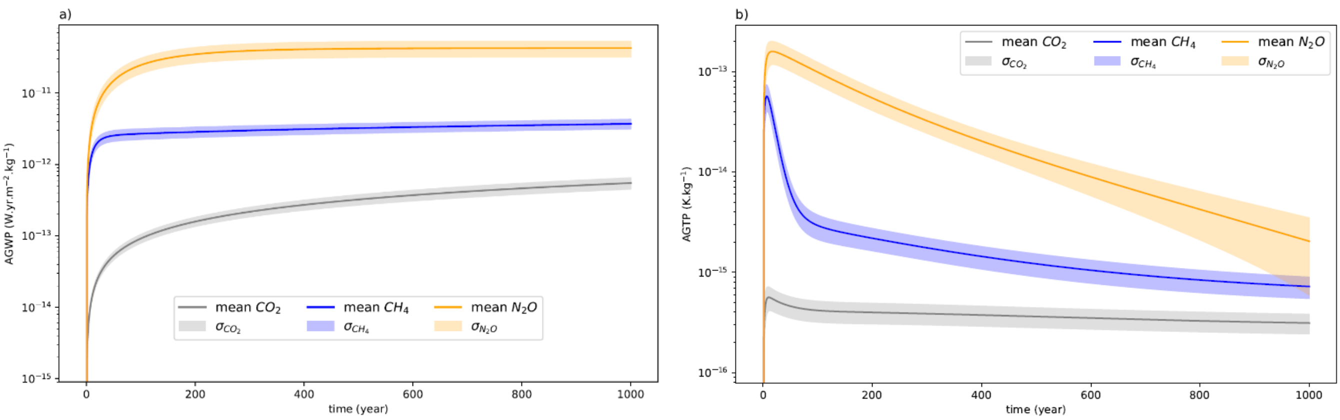

Figure 2. a) AGWP and b) AGTP profiles in logarithmic scale with associated uncertainty ranges from present-day (H = 0yr) to very long-term perspective (H = 1000yrs) after emissions of 1kg CO_2, 1kg CH_4 and 1kg N_2O. Uncertainties have been computed by varying all parameters listed in Table 2.

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 *fossil*	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%*

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The key aim of metrics is the quantification of the marginal impact of pulse emissions of extra GHG units (Kirschbaum, 2014). Hence, Fig. 3 compares three theoretical products with GWP_{100} =100 $kgCO_2e$: one emits 100% CO_2, one 100% CH_4 and a third one, *mixed_GHGs*, reflects 2022 global emission proportion of major GHGs – 99% CO_2, 0,97% CH_4, 0,03% N_2O – (adapted from EDGAR (Crippa et al., 2023)). Even if they have the same GWP_{100}, temporal emission profiles of these products display significant differences. Both AGWP and AGTP show that the conversion of CH_4 emissions into CO_2-equivalent emissions implies underestimated short-terms impacts and overestimated long-term impacts. After several decades, temperature change evolution declines very slowly due to the long response time of CO_2. 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 $AGTP_{long\text{-}term}$ being 500 years after $AGTP_{peak}$ as a representative value of this observed temperature change flatten. Mean values of these two indicators are presented in Tab. 4.

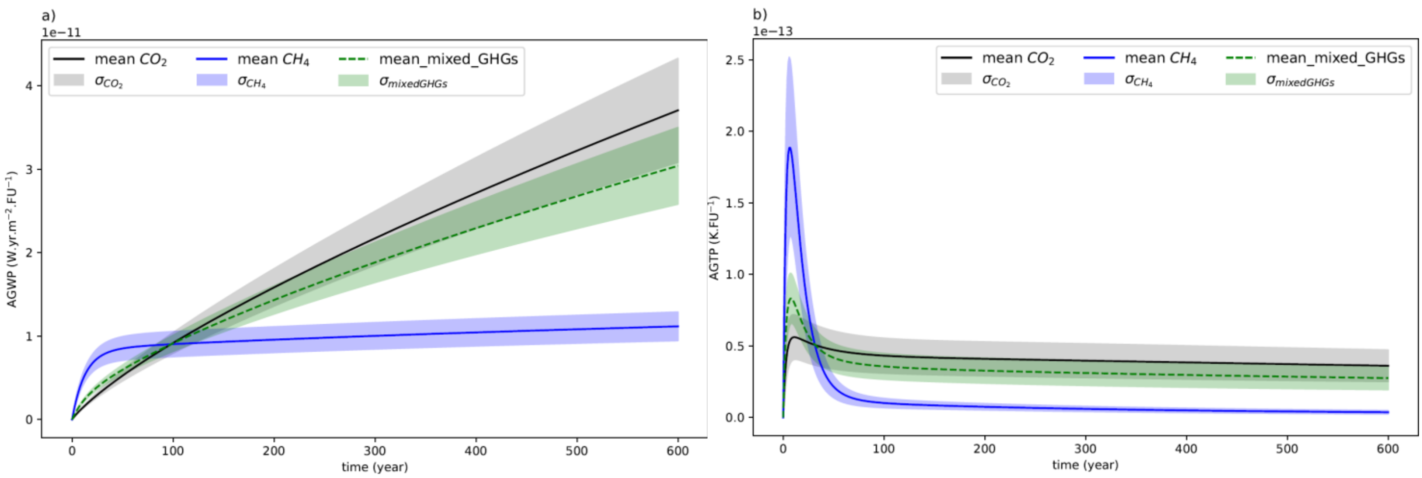

Figure 3. a) AGWP and b) AGTP profiles for 3 theoretical products having the same GWP_{100}=100$kgCO_2e$

Table 4. Mean $AGTP_{peak}$ and $AGTP_{long\text{-}term}$ associated to the three temporal emission profiles of Fig. 3.b)

x10^{-14}	$AGTP_{peak}$ (°C.FU^{-1})	$AGTP_{long\text{-}term}$ (°C. FU^{-1})
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

Figure 4 represents AGWP and AGTP profiles due to 2022 anthropogenic global GHGs emissions of CO_2, CH_4 and N_2O. Using GWP_{100}, these emissions represent a carbon footprint of 52.4 $GtCO_2e$: 73.5% due to CO_2, 21.5% due to CH_4 and 5% due to N_2O (adapted from EDGAR (Crippa et al., 2023)). Note that AGWP and AGTP metrics should not be used for such amounts of GHGs emissions since background concentrations are affected by such non-marginal levels of emission. Nevertheless, this figure is presented to show the climate impact's order of magnitude in *W.yr/m²* and *°C* due to yearly emissions. Furthermore, these metrics are effectively used in the literature to assess a sector at a country or a continental scale

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(Aamaas and Grimsby, 2024; Borella et al., 2024). Accumulated energy on the Earth system is largely driven by the large amount of CO_2 emissions. $AGTP_{peak}$ response is predominantly due to CH_4. In the long-term, CO_2 is almost the only contributor to temperature change.

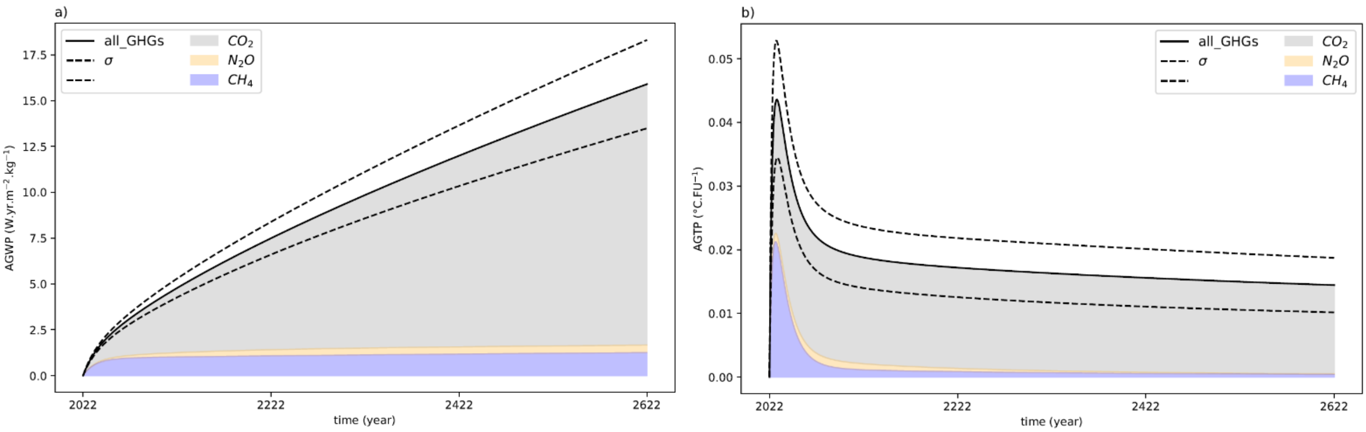

Figure 4. a) AGWP and b) AGTP profiles due to aggregated contributions from global CO_2, CH_4 and N_2O emissions for 2022

5 Discussion

5.1 Towards more clarity on dynamic climate metrics

The climate metrics overview (see part 2) was done in reaction to a lack of clear equations and gathered parameter values on climate indicators in IPCC AR6 Chapter 7, that were however provided in earlier assessment reports. Preparation of the seventh Assessment Report of the IPCC (AR7) will begin soon. As for each new report, it is an opportunity to write down updates in climate metric equations and in climate parameters values in a pedagogical manner. This would help environmental assessment communities with less expertise and in-depth knowledge of climate models. The work done here, along with Aamaas et al. (2013) and Myhre et al. (2013a), should be supporting materials for this purpose.

This overview also aims to help LCA practitioners acquire better comprehension of dynamic climate change assessment. Indeed, as mentioned above, dynamic climate metrics are scientifically more accurate and should be used when long-lasting products (>5-10 years) are assessed (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. 2-4. 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 (Fuglestvedt et al., 2003). As a time-integrated metric, AGWP temporal profiles keep increasing over centuries when CO_2 is emitted. It displays well LLGHGs stock pollution, as well as CO_2 storage (Zieger et al., 2020), but not that well flow pollution of shorter-

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lived well-mixed GHGs. Even if more exhaustive, AGWP gives similar impact ranges than common GWP values. Hence, same H as conventionally used for GWP – 20, 100 and 500 years – seems sufficient to get AGWP's CF. In agreement with Levasseur et al. (2016), 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 embed less uncertainty than AGTP. Drawbacks of using AGWP are rather linked to the unit – W.yr/m². First, it is not clear for policy makers. 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. Showing the impact evolution over time is much more refined than giving usual GTP values at 50- and 100-year H: AGTP temporal profiles of all studied gas show a peak temperature because of the rapid planetary surface response. This peak is particularly significant when methane is emitted. AGTP at mid- and long-term corresponds to the thermal inertia of the deep ocean that maintains memory of the initial pulse (Shine et al., 2005). It is somewhat surprising that such a metric has not been more attractive in the open literature before. 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) $AGTP_{peak}$ allows getting rid of the time horizon issue. H choice being a significant value judgement, this might even offset bigger uncertainty of temperature change metrics. 4) Figure 4 highlights that a vast majority of human activities emit CO_2, which imply that most product systems have a characteristic almost asymptotic long-term temperature change impact. These are key features to design a transparent dynamic metric that may be more widely accepted. AR6 expresses AGTP and GTP's CF at 50- and 100-year H. Table 3 shows that the difference between $AGTP_{50}$ and $AGTP_{100}$ is low compared to the difference with $AGTP_{peak}$ and $AGTP_{100}$. We encourage AR7 to replace $AGTP_{50}$ and GTP_{50} values by $AGTP_{peak}$ and GTP_{peak} values, to keep 100-year H values and to propose a long-term H, e.g. 500 years after $AGTP_{peak}$ occurs, for assessment purposes.

5.2.1 Emission pulses at different timings

Temporally displaced emissions profiles imply the use of ΔF and ΔT. To carry out a climate footprint assessment with these dynamic metrics, we first propose to get temporal profiles from 0 to 600 years. This gives a first visual and clear comparison between product systems.

ΔF interpretation is similar to AGWP one, i.e. assessments at H=20, H=100 and H=500 years are sufficient to accompany the dynamic profile. Relative ΔF of Eq. (13) computed thanks to dynamic climate change assessment tools (Levasseur et al., 2010; Tiruta-Barna, 2021) might be a way to obtain temporal carbon footprint profile with a common unit:

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

where n is the number of assessed GHGs and *i* an assessed GHG.

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In a multi-pulse framework, ΔT_{peak} metric becomes even more pertinent. Indeed, temperature change peak might appear decades after the production stage, making this non H-dependant CF 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 CF. Both are important:

- ΔT_{peak} can be interpreted as flow pollutants, whose rate of change may cause extreme climate events (Abernethy and Jackson, 2022) and may contribute to instabilities in the climate system, especially when the +2°C carbon budget is about to be reached.
- $\Delta T_{long\text{-}term}$ represents global temperature change long-term effect, i.e. stock pollutants, 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)."

Integrated temperature change metrics (iAGTP, iΔT, iGTP), that reflect for instance sea-level rise or even economic damage (Hsiang et al., 2017), were not considered here since they have similar behaviours as integrated radiative forcing metrics (AGWP, RF, GWP), at least for LLGHGs (Collins et al., 2020; Levasseur et al., 2016). Also, we estimate that the unit – °C.yr – is less clear for climate non-experts.

5.3 Uncertainty issues

While static and relative climate change metrics' (GWP, GTP) CF are most of the time used as values without uncertainty, AR6 recalls that uncertainties are significant (Smith, 2021). Hence, this paper addresses a particular issue on absolute metric uncertainties in order to make proper comparisons between product systems.

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 estimate IRF_{CO2} uncertainty, almost all fitting curves derived from Joos et al. (2013) are used (see SM.4). In this straightforward and tractable way, we ensure that correlation between α and τ is kept 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.

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 preindustrial 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.

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Concerning GHGs, CO_2 data are less uncertain than N_2O and CH_4 ones due low CO_2 radiative forcing scaling factor uncertainty that offset its more uncertain IRF. N_2O has the highest radiative forcing scaling factor uncertainty. Future work could also add uncertainties on CCf parameters. To conclude, we highly recommend to add associated uncertainties while using relative or dynamic climate metrics.

5.4 Mitigation of all GHGs

Dynamic climate metrics also enable the depiction of GHG specific features. CO_2-equivalent emission inventories are ambiguous in terms of implications for global temperature (Allen et al., 2022): it leads to underestimate short-term climate impacts, especially at peak temperature change and overestimate long-term climate impact for both radiative forcing and temperature change metrics (see Fig. 3). Thus, in addition to CO_2e targets on aggregated GHG emissions, governments and corporations should also separately report long-lived and short-lived GHG contributions (Allen et al., 2022; Collins et al., 2020). As a matter of fact, we have seen that multi-gas emission profiles from dynamic climate metrics would provide more "information necessary for clarity, transparency and understanding" in nationally determined contributions (NDCs). However, raising the question of which GHG should be mitigated first is not relevant any more. For instance, CH_4 emissions mitigation is crucial to reduce severe short-term climate change, i.e. flow pollution, as well as long-lasting climate change, i.e. stock pollution due to CO_2 production from methane oxidation. As +1.5°C is about to be reached, and +2°C may well be reached around the middle of the century (IPCC, 2021b, using reference scenarios SSP2-4.5 or SSP3-7.0), with worrying tipping cascade that might lead the Earth system towards a hothouse state (Steffen et al., 2018), both near- and long-term warming need to be strongly reduced. In other words, limiting human-induced global warming requires at least net zero CO_2 emissions, along with stringent reductions in other GHGs (IPCC, 2021a), i.e. human activities urgently need to reduce operations and to value frugality (Parrique, 2019).

5.5 Addressing dynamic climate metrics to long-life products

As annual global emissions significantly decrease the remaining carbon budget to stay below +2°C, bio-based products that store carbon show increasing interests. To initiate interpretations on the potential benefits of such products using ΔF and ΔT, Fig. 5 reflects impacts of four theoretical materials with a 50-year lifespan. Even if their climate impact profiles are different, two of them have the same GWP_{100} or GTP_{100}: *fossil-based* is more energy intensive but capture CO_2 at end-of-life (EoL) and *bio-based* releases 100% of captured biogenic carbon at EoL. *fossil-based_reused* and *bio-based_reused* are respectively the same as *fossil-based* and *biobased* but with an EoL scenario where one third is reused, i.e. 33.3% less CO_2 emission at EoL.

Three main observations can be made: 1) same CO_2 emissions over the life cycle leads to equal ΔT and more or less equal ΔF on a long-term perspective. 2) Both metrics show that temporary carbon storage of bio-based products has a significant cooling effect, at least up to EoL. Indeed, both bio-based materials show a drop in temperature change with a negative minimum, $\Delta T_{negative}$, and ΔT_{peak} occurs at H=61 years. Compared to ΔT, ΔF shows longer cooling effect and benefits from the use of bio-based materials. 3) More energy intensive materials that capture carbon during usage or disposal stages directly

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contribute to global warming. 4) Major improvement appears only when CO_2 emissions over the whole life cycle decrease, for instance by reducing grey energy or EoL biogenic CO_2 emissions of bio-based products. In other words, sustainable carbon storage is only possible in a bio-based, low-tech and circular economy. Table 5 reflects principal dynamic metrics we proposed to adopt with this article: ΔF20, ΔF100, ΔF500, $\Delta T_{negative}$, ΔT_{peak}, $\Delta T_{long\text{-}term}$.

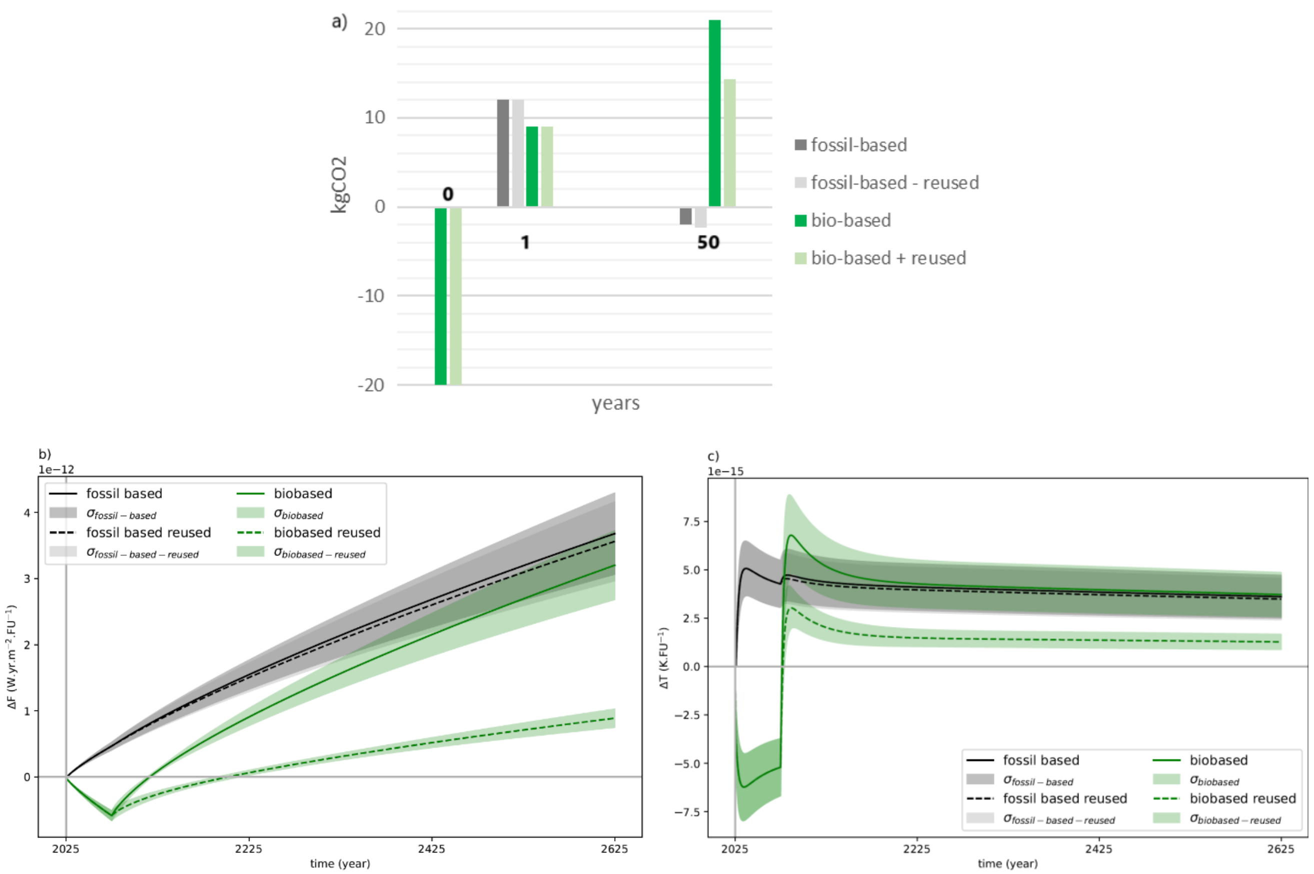

Figure 5. a) Emission profile of four theoretical products: production stage at years 0 and 1 ; EoL stage at year 50. *Fossil-based* and *Biobased* have the same GWP_{100}=10kgCO_2. If *reused*, EoL emissions are reduced by one third. No CH_4 and N_2O are emitted. b) ΔF and c) ΔT temporal profiles of these four products.

Table 5. Mean ΔF and ΔT indicators encouraged to be used for assessments, with their associated uncertainties, applied on the four materials of Fig. 5. ΔF is in 10^{-12} W.m^{-2} and ΔT in 10^{-15} °C.

	ΔF_{20}	ΔF_{100}	ΔF_{500}	$\Delta T_{negative}$	ΔT_{peak}	$\Delta T_{long\text{-}term}$
Fossil-based	0.210 ± 0.021	0.85 ± 0.12	3.11 ± 0.53	–	4.9 ± 1.4	3.6 ± 1.2
Fossil-based – reused	0.210 ± 0.021	0.83 ± 0.12	3.01 ± 0.51	–	4.9 ± 1.4	3.5 ± 1.1
Biobased	-0.277 ± 0.029	0.096 ± 0.028	2.63 ± 0.43	-6.0 ± 1.8	6.8 ± 2.1	3.7 ± 1.2
Biobased – reused	-0.277 ± 0.029	-0.249 ± 0.051	0.69 ± 0.11	-6.0 ± 1.8	3.2 ± 1.2	1.26 ± 0.40

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6 Conclusion

While we are getting more and more aware of the Earth's climate system's complex functioning, it is critical to keep clear and understandable climate metrics. 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.

Furthermore, there is a growing interest in the use of dynamic climate metrics to take the analysis one step further than with CO_2-relative and static metrics (GWP, GTP). This overview is also meant to help environmental assessment communities adopt consistent dynamic climate metrics. These metrics enable to properly represent climate impact over time and, with multi-GHG inventories, to include specific behaviours of different climate forcers. We have compared the two 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 more certain 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 metrics are more complex and uncertain, but give much more policy-relevant results. They represent an actual climate impact in the common Celsius degree unit, which is a clear advantage. They also display a characteristic peak temperature change. Lastly, product systems that store biogenic carbon can show a negative temperature change peak. ΔT_{peak}, $\Delta T_{negative}$ and $\Delta T_{long\text{-}term}$ are the first attempts to get rid of the time horizon's issue that has plagued the LCA community for so long. In other words, dynamic temperature change metrics captures both CO_2 nature as a stock pollutant and CH_4 nature as a flow pollutant without the need of any specific time horizon. These make AGTP and ΔT very interesting metrics to push forward, notably for LCA practitioners to lower not avoidable subjective judgments during metric choice.

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 emission profiles and selected dynamic metric values in addition or in substitution to relative metrics. Hence, environmental assessors are encouraged to 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 CF. IPCC should support this by adopting at least $AGTP_{peak}$.

Lastly, as global warming is a significant threat for the present and future of all living species, strong mitigation is needed, for both short-lived and long-lived GHGs, to avert this threat as much as possible. At the global scale, this means reducing the amount of materials and energy by developing a frugal and circular economy. At the product system scale, going towards carbon neutral products seems to be a combination of bio-based, low energy intensive, reuse, recycled and long-lasting materials. This proposal should be deepened sector by sector.

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Appendix A: Endpoint climate metrics & endpoint LCA modellings – semantic clarification

As presented in 0, metrics in climate science are either integrated or endpoint metrics corresponding to two different mathematical constructs. Integrated metrics measure cumulative GHGs impact from emission time to H whereas endpoint metrics measure impacts at a particular H after the emission. Furthermore, in Life Cycle Impact Assessment (LCIA) there are midpoint and endpoint modellings (Bare et al., 2000) leading to midpoint and endpoint indicators. Characterisation factors (CF) at the midpoint level are located somewhere along the cause-impact pathway, generally where the environmental mechanism is identical for each environmental flow allocated to that impact category. CF at endpoint level increases both uncertainty and policy relevance by reflecting damage between three areas: human health, ecosystem quality and resource scarcity (Huijbregts et al., 2017).

In LCA, climate change is a midpoint indicator, mainly assessed by GWP_{100}. Use in LCA of endpoint metrics such as AGTP or GTP is still based on midpoint CF. Then, one has to have well understood differences between climate metric and LCA indicator categories especially when 'endpoint' is specified.

Code availability

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

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	Sixth assessment report
AR7	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
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
LLGHGs	Long-lived greenhouse gases
MIP	Model intercomparison project
N_2O	Nitrous oxide
NDCs	Nationally Determined Contributions
OH	Hydroxyl radical
RE	Radiative efficiency
RF	Instantaneous radiative forcing
σ	Normal standard deviation

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