



Expanding the dynamic climate change impact model for dynamic LCA based on the climate science

Ligia Tiruta-Barna¹

Received: 15 July 2025 / Accepted: 30 December 2025 / Published online: 11 March 2026
© The Author(s) 2026

Abstract

Purpose The climate change impact in LCA typically considers only the well mixed, direct greenhouse gases (GHG). The objective of this research is to include new climate forcers and effects in dynamic LCA, according to the climate science evolution, and to make them available and operational for the LCA users. The CCI-tool was used and complemented with these new elements.

Methods First, the available data and knowledge on short-lived climate forcers (SLCFs) was compiled from IPCC reports and from recommended literature by IPCC, and translated in a model based on the concept of impulse response function (IRF) for the radiative forcing (RF). The SLCFs included are: (1) aerosols and precursors: SO₂, organic carbon, black carbon, particulate matter; (2) ozone precursors (indirect GHGs): NO_x, CO, volatile organic compounds; (3) other indirect: H₂. Differentiation was made for aviation emissions and shipping emissions. Second, the carbon cycle climate feedback was integrated in the model and allocated to each climate forcer.

Results and discussion The model was validated by calculating the GWP20, 100, and GTP20, 100 for the SLCFs and comparing with the available data in the literature. The RF and global mean temperature change (GMTC) were calculated for all SLCFs for a 1 kg pulse emission and presented for discussion. Two simple case studies were performed on: (1) aviation emissions for a one-way long-hole flight and for a 1-year daily flights; (2) wood combustion. The examples demonstrate the relevance of considering the SLCF effect especially at short term (0–20 years after emission), with higher peaks on temperature than CO₂. Uncertainties on physical parameters were used to evaluate the minimum and maximum GMTC, and confirm the behaviors observed in both case studies.

Conclusions This is the first implementation of SLCFs in a dynamic LCA tool, for climate change impact calculation. Moreover, the model was updated with the carbon-cycle climate feedback effect. The CCI-tool is well adapted to such improvements, especially for dynamic impact calculation. The results obtained on simple impulse emissions or on case studies corroborate the data and conclusions from the climate science literature.

Keywords Short-lived climate forcers · Carbon cycle climate feedback · Aviation emissions · Combustion emissions · Shipping emissions · Global mean temperature change

Notations

A Radiative efficiency (W.m⁻².kg⁻¹)
a Constants in the impulse response function of CO₂

AGWP Absolute global warming potential (W.m⁻².yr.kg⁻¹)
B Atmospheric burden (kg)
BC Black carbon
c Constants in the thermal impulse response function (K W⁻¹ m²)
CCD Cruise phase of a flight
CF Characterization factor
d Relaxation time (yr) in thermal impulse response function
ERF Effective radiative forcing (W.m⁻²)
f1, f2 Correction factors accounting in the impulse

Communicated by Enrico Benetto

✉ Ligia Tiruta-Barna
Ligia.barna@insa-toulouse.fr

¹ TBI, Université de Toulouse, CNRS, INRAE, INSA, 135 av de Rangueil, Toulouse Cedex 4 F-31077, France

	response functions of CH ₄ and N ₂ O
g	Emission flow (kg.yr ⁻¹)
GHG	Greenhouse gas
GMTC	Global mean temperature change (K) or (°C)
GMTC_CCF	Supplementary temperature increase due to the carbon cycle feedback (K) or (°C)
GMTCd	Global mean temperature change (K) or (°C) from the direct effect (infrared absorption) (K) or (°C)
GWP	Global warming potential (kg CO ₂ eq. kg ⁻¹)
GTP	Global temperature potential (kg CO ₂ eq. kg ⁻¹)
iRF	Integrated radiative forcing (W.m ⁻² .yr)
IRF	Impulse response function
IRFCCF	Impulse response function for the climate carbon cycle feedback
IRFT	Thermal impulse response function
LCA	Life cycle assessment
LCIA	Life cycle impact assessment
LTO	Landing and takeoff
NMVOC	Nonmethane volatile organic compound
OC	Organic carbon
PM	Particulate matter
RF	Radiative forcing (W.m ⁻²)
RF_CCF	The carbon-climate feedback effect on the radiative forcing
RFd	Radiative forcing from the direct effect (infrared absorption)
s	Subscript to indicate a substance
SLCF	Short-lived climate forcer
t	Time (yr)

Greek letters

ΔF	Radiative sensitivity to emission (W.m ⁻² .kg ⁻¹ .y)
δ	Dirac function
γ	Constant in the IRFCCF (kg CO ₂ yr ⁻¹ K ⁻¹)
τ	Perturbation time (yr)

1 Introduction

Nowadays, the dynamic LCA is more and more adopted by researchers and LCA practitioners especially for climate change impact assessment of systems with greenhouse gas (GHG) emissions and captures shifted in time. The need of more representative assessment of systems, for their contribution to climate change and for evaluating the mitigation actions, was recently materialized in the RE2020 standard (Ministère de la transition écologique 2021) in the field of construction. On the pathway towards climate neutrality, more representative assessments than those provided by conventional metrics such as the global warming potential

(GWP) (or the less commonly used global temperature potential, GTP) are required across all economic sectors. Dynamic (or temporal) LCA integrates both dynamic inventory and dynamic impact modeling, and conceptual analyses of the temporal dimension in LCA are available in the literature (Beloin Saint-Pierre et al. 2020; Sohn et al. 2020). Tools for dynamic climate change impact evaluation have been proposed based on two main approaches.

The first approach, proposed by Levasseur et al. (2010), and used implemented in *bx_timex* tool (Diepers et al. 2025), calculates dynamic characterization factors (CF) at the level of the radiative forcing (RF), using a one-year timestep. These CFs are then used with a temporalized inventory with a 1-year resolution. The calculation tool uses the atmospheric decay function of a given GHG as the response to the emission of 1 kg of that substance. A time horizon must be defined for the impact calculation. However, because this method relies on CFs, it limits the use of alternative, more complex, or combined mechanisms.

The second approach (Shimako et al. 2016, 2018; Tiruta-Barna 2021) directly calculates radiative forcing and global mean temperature change (GMTC) as impact indicators, without the need for characterization factors. Instead, it uses the RF and GMTC models in combination with the dynamic inventory. The formalism is based on the impulse response functions (IRF) of GHG concentration decay in the atmosphere and on the impulse response function for the planet's thermal mechanisms (IRFT). The developed tool is available as online calculator (CCI-tool; <https://www.insa-toulouse.fr/cci-tool/>).

In LCIA, the climate change impact category traditionally considers only well mixed, direct GHGs, based on established climate science. However, climate science has advanced significantly over recent decades, incorporating new knowledge (data and models) on other climate forcers and effects. Examples include carbon cycle feedback (Gasser et al. 2017), the effect of certain aerosols and the behavior of indirect GHGs such as NO_x, CO, or aviation emissions (Lee et al. 2021; Fuglestvedt et al. 2010). Although the UNEP Life Cycle Initiative has recommended including six short-lived climate forcers (SLCF) (without geographical differentiation) with their GWP20 (Levasseur et al. 2016), the ecoinvent v3.11 database currently includes only three SLCFs (CO, VOC, NO) with their GWP100 values in the IPCC-2021 LCIA method.

Moreover, GWP metrics cannot adequately accommodate, on a unique base, the very different behaviors of SLCFs and of long-lived GHGs (like CO₂ or N₂O). Distinct approaches for metrics (or CFs) calculation for SLCFs have been discussed by Aamaas et al. (2013), based on either a sustained or a pulse emission (GWP is based on a unitary pulse emission). Allen et al. (2018) pointed out that using

GWP to convert SLCFs in kg-CO₂-eq misrepresents their real impact, and proposes a modified metrics (CFs), GWP*, based on a sustained emission of SLCFs, which would more accurately evaluate the impact on radiative forcing. However, ensuring a satisfactory harmonization between SLCFs and long-lived GHGs is still matter of discussion (Cain et al. 2019). The approach proposed within the dynamic LCA is not to calculate characterization factors that are subject to bias, but to use physical parameters to calculate the climate impact directly.

The objective of this research is to integrate new climate forcers and effects into tools dedicated to dynamic LCA and to make them available and operational for LCA users. Due to its generic and flexible architecture, the CCI-tool mentioned above is the most suitable for being extended with additional mechanisms and climate forcers and was therefore used in this research.

The following improvements were implemented and discussed. A model for the radiative forcing of SLCFs, considering their direct, indirect, or combined effects on climate, was added with specific parameters for each compound. The SLCFs were differentiated by the emission compartment: combustion emissions from aviation at low and high altitudes, combustion emissions from shipping, and terrestrial emissions. These new climate forcers in CCI-tool include: gases with indirect climate effect (NO_x, CO, non-methane volatile organic carbon NMVOC), aerosols (black carbon BC, organic carbon OC, SO₂ induced, particulates containing carbon PM), stratospheric water vapor, contrails and contrail induced cirrus.

The carbon cycle climate feedback was integrated into the RF and GMTC calculation for all climate forcers. This update, based on recent models, is essential because conventional metrics global warming potential (GWP) and global temperature potential (GTP) now include the climate feedback mechanism (IPCC 2021).

After the methodology description in the next section, examples of results are presented, and their implications for climate change assessment are discussed through two case studies: an aviation scenario and a biomass combustion scenario.

2 Method

2.1 Short description of the implemented model

The model was initially (version 2016) implemented for the direct effect, well-mixed GHGs, for all GHGs present in the IPCC list and in the ecoinvent database (list updated from IPCC 2021; and ecoinvent 3.9). The model uses the IRF approach to calculate the gas decay in the atmosphere and

then the RF in function of time. The thermal response function to a pulse RF (IRFT) is used to calculate the GMTC, as preconized by the IPCC reports (e.g. IPCC 2013).

The atmospheric burden of substance *s*, *B_s*, is calculated as the convolution (symbol *) of the temporal emissions of the substance *s*, *g* (kg.yr⁻¹), and the concentration-IRF of that substance:

$$B_s(t) = g_s * IRF_s = \int_0^t g_s(t') IRF_s(t - t') dt' \quad (1)$$

The RF is calculated as the product between the radiative efficiency, *A*, and the atmospheric burden, *B*. The radiative efficiency (or specific radiative forcing) *A* (W.m⁻².kg⁻¹) can be considered constant for quasi-constant atmospheric concentrations (small emissions), so it is also time-invariant. Hereafter, the RF of direct effect GHGs is named direct radiative forcing RFd:

$$RFd_s(t) = A_s B_s(t) = A_s (g_s * IRF_s) \quad (2)$$

For well mixed GHGs, the IRF has the general form:

$$IRF(t) = e^{-t/\tau} \quad (3)$$

with *τ* the perturbation time (decay constant). For CO₂:

$$IRF_{CO_2}(t) = a_0 + a_1 e^{-t/\tau_1} + a_2 e^{-t/\tau_2} + a_3 e^{-t/\tau_3} \quad \text{and} \quad \sum_i a_i = 1 \quad (4)$$

where *a_i* are constants (dimensionless). Methane's IRF includes the effects on ozone and stratospheric water through the correction parameters *f*₁ (0.5) and *f*₂ (0.15) (IPCC 2013; chapter 8.SM.11.3.2):

$$IRF_{CH_4}(t) = (1 + f_1 + f_2) e^{-t/\tau} \quad (5)$$

Methane is oxidized to CO₂, which is included in the model. The yield of transformation is 75%, i.e. 1 kg of CH₄ generates 2.1 ± 0.7 kg CO₂; (IPCC 2021; chapter 7). Similar correction is applied for N₂O:

$$IRF_{N_2O}(t) = \left(1 - 0.36(1 + f_1 + f_2) \frac{A_{CH_4}}{A_{N_2O}}\right) e^{-t/\tau} \quad (6)$$

The global mean temperature change generated by the forcer *s* is defined as the convolution between its direct RF (noted RFd) and the IRFT (formula 8), considered independent from the GHG type. For direct GHGs, this parameter is named direct GMTC (GMTCd).

$$\text{IRFT}(t) = \sum_{j=1}^2 \frac{c_j}{d_j} e^{-t/d_j} \quad (7)$$

$$\text{GMTCd}_s(t) = \text{RFd}_s * \text{IRFT} \quad (8)$$

where c ($\text{K W}^{-1} \text{ m}^2$) and d (year) are contributions to the equilibrium climate sensitivity and relaxation times, respectively, for the fast ($j=1$) and slow ($j=2$) terms.

All the formulas above are used with their parameters/constants updated from IPCC (2021).

2.2 Model adaptation to include other climate forcers

Emissions from various combustion processes contribute to climate impacts even when their atmospheric lifetimes are short. A notable example is aviation emissions, other than CO_2 , whose effects have been estimated to be comparable to those of CO_2 from aviation (see, for example, IPCC 2021, Figure 6.12). Most of these compounds are not included in the GWP metrics used in current LCA tools (ecoinvent v3.11, for instance, includes only CO, VOC, and NO in the IPCC-2021 LCIA method), and none are currently considered in dynamic LCIA. The models and data used in this study are based on available literature consistent with the IRF approach and on the recommendations of the IPCC (2013).

2.2.1 SLCF ozone precursors

Nitrogen oxides NO_x , carbon monoxide CO, and non-methane volatile organic compounds others than methane NMVOC, contribute to ozone chemistry, ozone being a direct GHG, and interact with OH and CH_4 . For these SLCFs, emission metrics have been proposed based on a steady-state emission during one year, and not on a pulse emission as usually adopted for GHGs (Fuglestedt et al. 2010). The indirect climate contribution is due to four effects: the short-term ozone increase (sto), long-term effect of methane on ozone depletion (lto), methane decrease (m), and stratospheric water decrease if the emission is in upper troposphere/lower stratosphere (sw). Each of the components have a specific perturbation time τ .

For a pulse unitary emission, the general formula could be written:

$$\text{RF}_s(t) = A_{\text{sto}} e^{-t/\tau_1} + (A_{\text{lto}} + A_{\text{m}} + A_{\text{sw}}) e^{-t/\tau_2} \quad (9)$$

It applies for NO_x emissions from aviation (based on kg N). For tropospheric emissions (either NO_x , CO, or NMVOC):

$$\text{RF}_s(t) = A_{\text{sto}} e^{-t/\tau_1} + (A_{\text{lto}} + A_{\text{m}}) e^{-t/\tau_2} \quad (10)$$

The values of the radiative efficiency A in these equations are not provided in the literature. Instead, a parameter called “sensitivity to emission” is available (Fuglestedt et al. 2010; Lee et al. 2021), which was used in this work to calculate the A values (details in the supplementary information section S1).

The perturbation time τ_2 corresponds to the lifetime of CH_4 involved in the chemical reactions.

2.2.2 Aerosols: sulfate, sulfur dioxide SO_2 ; black carbon BC; organic carbon OC, particulate matter PM

The direct effect of aerosols is considered (radiation reflection) in one e-fold term as:

$$\text{RF}_{\text{aerosol}}(t) = A_{\text{aerosol}} e^{-t/\tau_1} \quad (11)$$

For aviation emissions, data from Lee et al. (2021) are considered. For other emission compartments, data from Fuglestedt et al. (2010) are used.

For shipping SO_2 , the indirect effect of modification of cloud properties and of the albedo from Lauer et al. (2007) is included; for 1 kg SO_2 emission:

$$\text{RF}_{\text{SO}_2/\text{sulphate}}(t) = (A_{\text{direct}} + A_{\text{indirect}}) e^{-t/\tau_1} \quad (12)$$

In case of black carbon, the parameters are expressed per kg carbon. For organic carbon OC, the parameters are also expressed per carbon mass, considering a ratio “particulate organic matter”/“organic carbon” = 1.4.

Most PMs (particulate matter) are generated by combustion processes and are composed in majority by organic compounds (e.g. Perrone et al. 2013). Data from Fuglestedt et al. (2010) for “organic carbon” were used to model the behaviour of PMs. Equation (13) applies for particulate matter like $\text{PM}_{2.5}$, PM_{10} . Since models for mineral aerosols effect are not available, only the organic part of the particulate matter is included. The composition from Perrone et al. (2013) is considered here, i.e. 17–24% (w/w) of organic carbon, with no distinctions according to the location or seasons. With the average value of 20.5%, the mass of carbon in PMs and the radiative efficiency of PMs become:

$$\text{Carbon} = 0.205 \text{ PM (kg)} \quad \text{and} \quad A_{\text{PM}} = 0.205 A_{\text{OC}} \quad (13)$$

2.2.3 Stratospheric water

In case of aviation emissions of water, the direct radiative forcing is:

$$\text{RF}_{\text{H}_2\text{O}}(t) = A_{\text{H}_2\text{O}} e^{-t/\tau_1} \quad (14)$$

2.2.4 Contrails and induced cirrus (aviation)

The model from Lee et al. (2021) is considered on the base of 1 km cruise flight:

$$RF_{\text{contrail cirrus}}(t) = A_{\text{contrail cirrus}} e^{-t/\tau_1} \quad (15)$$

with A in ($\text{W m}^{-2} \text{ km}^{-1}$)

2.2.5 Hydrogen H₂

Hydrogen has an indirect climate effect due to interaction with OH. In the perspective of the increasing use of hydrogen (e.g. Gomonov et al. 2025), it is important to evaluate its impact on climate. The radiative forcing of a 1 kg H₂ emission is taken from Hauglustaine et al. (2022):

$$RF_{H_2}(t) = A_{H_2} e^{-t/\tau_1} \quad (16)$$

2.3 Carbon cycle climate feedback

According to IPCC (2021) report, the carbon-climate feedback effect on the radiative forcing, RF_CCF, is added to the direct radiative forcing (and the other cascade indicators), for all climate forcers (except CO₂) as follows:

$$RF_s(t) = RF_{d_s}(t) + RF_CCF_s(t) \quad (17)$$

RF_CCF_s(t) represents the contribution of substance s to the additional RF of CO₂ resulting from the temperature increase induced by s. This contribution is accounted for together with the RF directly generated by s. The same applies to temperature: the additional temperature increase due to the CO₂ cycle, GMTC_CCF, is added to the direct temperature increase caused by substance s, GMTC_d, to obtain the combined temperature effect of substance s, GMTC (formula 18).

$$GMTC_s(t) = GMTC_{d_s} + GMTC_CCF_s \quad (18)$$

where:

$$GMTC_CCF_s(t) = RF_CCF_s * IRFT \quad (19)$$

$$RF_CCF_s(t) = A_{CO_2} (GMTC_{d_s} * IRFCCF * IRF_{CO_2}) \quad (20)$$

$$IRFCCF(t) = \gamma \delta(t) - \gamma \sum_{i=1}^3 \frac{\alpha_i}{\tau_i} e^{-\frac{t}{\tau_i}} \quad (21)$$

where IRFCCF is the impulse response function of the carbon cycle (CO₂ flux perturbation) following a unit

temperature pulse, in kg CO₂ yr⁻¹ K⁻¹ (Gasser et al. 2017; IPCC 2021, chapter 7.SM.5), with the constants α , τ (yr) and γ (kg CO₂ yr⁻¹ K⁻¹), and $\delta(t)$ the Dirac function.

2.4 Climate change impact indicators

The climate change impact indicators are the RFs (W.m^{-2}) and GMTCs (K) for the climate forcer s (Eqs. 17, 18), RF and GMTC for all forcers (Eq. 22), and integrated radiative forcing iRF ($\text{W.m}^{-2}.\text{year}$), or iGMTC (K.year), over a given time span TH (Eq. 23).

$$RF(t) = \sum_s RF_s(t) \quad \text{and} \quad GMTC(t) = \sum_s GMTC_s(t) \quad (22)$$

$$iRF(TH) = \int_{t=t_0}^{TH} RF(t) dt \quad \text{and} \quad iGMTC(TH) = \int_{t=t_0}^{TH} GMTC(t) dt \quad (23)$$

2.5 Data used with the model

In this work, the available parameters for SLCFs were selected from the most recommended literature in IPCC (2013), and from recent available literature, as shown in Table S1 in the supplementary information.

In case of ozone precursor compounds, the radiative efficiency was estimated in this work based on the parameter named radiative “sensitivity to emission”, ΔF ($\text{W.m}^{-2}.\text{kg}^{-1}.\text{y}$), used in the steady-state emission approach (Fuglestad et al. 2010; Lee et al. 2021). The radiative efficiency A ($\text{W.m}^{-2}.\text{kg}^{-1}$) can be calculated, as demonstrated in the supplementary information, by:

$$A_s = \Delta F_s / \tau \quad (24)$$

where τ is the perturbation time (years). The implemented model uses data for the effective radiative forcing, ERF, and if not available, the data on radiative forcing, along with the perturbation time of the SLCFs. Note that currently the ERF is used to define the A values (specific effective radiative forcing) of GHGs in IPCC (2021) and in CCI-tool. The updated values of ERF per unit emission from Lee et al. (2021) were used for aviation emissions. Data were completed for all the other SLCFs and for all perturbation time values from Fuglestad et al. (2010), Hauglustaine et al. (2022), Lauer et al. (2007). All radiative efficiency data are

evaluated based on the ERF while the more ancient data from Fuglestvedt et al. (2010) are based on RF.

The IPCC assessment report 5, chapter 8.7.2.4 (IPCC, 2013) reveals large differences in GWP values for SLCF compounds emitted in high altitude air, at the surface of land or at the surface of sea. These three air-compartments are included in the model with specific parameter values. All the original data from the literature and the adapted values in this work are presented in Tables 1 and 2, with the related references.

3 Results and discussion

The Results and discussion section illustrates the influence of the newly incorporated climate forcers on climate change impact outcomes in the dynamic LCA framework. Comparative analyses of RF and GMTC are provided for case studies considering both the inclusion and exclusion of SLCFs.

3.1 Validation of the model implementation

Available data from the literature were used to validate the model. Values of GWP and GTP for SLCFs are proposed by Lee et al. (2021) and Fuglestvedt et al. (2010). The Table 3 shows, as an example, the calculation results in case of aviation emissions, compared with the emission metrics taken from the first reference. In their work, Lee et al. (2021) used the IRF of CO₂ from Joos et al. (2013), with A_{CO_2} $1.68 \cdot 10^{-15}$ W m⁻² kg⁻¹ to calculate the AGWP of CO₂, and the IRFT constants from Boucher and Reddy (2008). The calculations were performed for an emission during 1 year (consistent with the approach of Fuglestvedt et al. (2010) for aviation emissions), without the carbon climate feedback.

The obtained results are in good agreement with the reported values, especially for GWP. The differences for GTP are higher due to the cumulation of small numerical errors, and especially due to the lack of precise information on τ values used in the reference study. The time step used in simulations is lower than the lowest τ , ensuring coherence from numerical point of view. Consecutive convolution calculations for GMTC cumulates small numerical errors, of the order of 0.5%. The higher difference observed for aviation NO_x for GTP₂₀ is explained by the origin of τ values used (see Table 1). Lee et al. (2021) did not mention the value of τ used in their metrics calculation, only mentioning that they “are broadly consistent with Fuglestvedt et al. (2010)”; however, an annex indicates different values (provided in Table 1). Moreover, the GTP estimates in this work are coherent with the values provided by IPCC (2013) (chapter 8SM.17). For aviation NO_x GTP₂₀, the intervals according to the cited literature are: -396 to -121; -590 to

-200. The complex chemistry of NO_x and related effects on climate are at the origin of important uncertainties, inferred in IRFs parameters.

The uncertainties associated with the IRFs are related to the uncertainties of A and τ for all climate forcers, including GHGs. In addition, the IRFT and IRF_{CO₂} functions carry uncertainties in their coefficients, which are periodically updated based on available physical data (Joos et al. 2013). Currently, there is no unified information in the literature regarding the uncertainties of A and τ values; instead, parameter values proposed by different authors can be found. Widely accepted values and uncertainties for A , as proposed by Lee et al. (2021) for aviation emissions, were adopted in this work (see Table 1). For NO_x, the uncertainty on A are about 36%, while for aviation soot aerosols it reaches 160%, or 200% for contrail induced cirrus. However, no uncertainty estimates are available for τ , nor for A in the case of other SLCF emission sources. Other literature sources provide only partial information (Table 1), such as uncertainties reported for already calculated GWP metrics, from which approximate values were inferred in this work for GMTC uncertainty. When including the maximum and minimum available values for A and τ , the calculated GMTC uncertainty for aviation NO_x is $\pm 30\%$, while for induced contrail cirrus (-67%, +185%). These uncertainties were applied to the two examples presented in Sects. 3.4 and 3.5.

3.2 SLCF behavior following a pulse emission

Figure 1 shows the RF and GMTC for a pulse emission of 1 kg (1 km for induced cirrus) of each SLCF. The calculations were performed with the data gathered in Tables 1 and 2, and including the carbon cycle climate feedback. The figures were organized by compartment of emission, i.e. air at the sea surface (shipping emissions), high troposphere-low stratosphere (aviation emissions), and air at the land surface (or others except the two former sub-compartments). For comparison, the result of a CO₂ pulse emission (1 kg) is also presented on the graphs for aviation emissions. Due to the short lifetime, the RF exhibits an initial, important peak, and falls to near zero in several days, except for NO_x, CO, NMVOC, H₂. The effect of SLCFs is rapid and of high intensity, as demonstrated by GMTC results. Even if the temperature effect duration is only of about 10 years (the specific time of thermal processes), the temperature peak is much higher than those of CO₂, result that is also reflected by the GTP values in Table 3. The effect on climate is heating for indirect SLCFs or cooling for aerosols. NO_x shows both effects, starting with a strong warming, then passing in a negative domain of ΔT and again in the positive ΔT after several decades. This behavior of NO_x was reported in the literature (Fuglestvedt et al. 2010; IPCC, 2013;

Table 1 Parameter values for SLCFs used in this work: air sub-compartment, type of forcing parameter used from the literature and the reference, perturbation time, radiative efficiency used in CCI-tool, name of the climate forcer in ecoinvent database

Air sub-compartment Climate forcer	Forcing parameter	Perturbation time τ , years	Radiative efficiency A, W m^{-2} kg^{-1}	Name used in ecoinvent
Air - all Except for compounds cited in aviation and shipping	Radiative forcing $\text{W m}^{-2} \text{kg}_{\text{emission}}^{-1}$	Perturbation time, years[#]	Used in this work	
NOx :	$\text{W m}^{-2} \text{kg}_{\text{N}}^{-1} \text{y}$ Fuglestvedt et al. (2010) citing Wild et al. (2001)	Fuglestvedt et al. (2010)	$\text{W m}^{-2} \text{kg}_{\text{N}}^{-1}$	Nitrogen oxides
Short-term O ₃ increase	$4.59 \cdot 10^{-12} \pm 35\%$ Uncertainty from IPCC (2013), ch 8	0.267	$1.720 \cdot 10^{-11}$	
Long-term O ₃ decrease	$-1.79 \cdot 10^{-12} \pm 35\%$ Uncertainty from IPCC (2013), ch 8	From 10.8 to 16.1	$-1.261 \cdot 10^{-13}$	
CH ₄ induced O ₃ decrease	$-3.80 \cdot 10^{-12} \pm 35\%$ Uncertainty from IPCC (2013), ch 8	From 10.8 to 16.1	$-2.676 \cdot 10^{-13}$	
CO :	$\text{W m}^{-2} \text{kg}_{\text{CO}}^{-1} \text{y}$ Fuglestvedt et al. (2010) citing Derwent et al. (2001)	Fuglestvedt et al. (2010)	$\text{W m}^{-2} \text{kg}_{\text{CO}}^{-1}$	Carbon monoxide
Short-term O ₃ increase	$6.00 \cdot 10^{-14} \pm 26\%$ Uncertainty from IPCC (2013), ch 8	0.267	$2.247 \cdot 10^{-13}$	
Long-term O ₃ decrease	-	-	-	
CH ₄ perturbation on O ₃	$1.30 \cdot 10^{-13} \pm 26\%$ Uncertainty from IPCC (2013), ch 8	14.2	$1.057 \cdot 10^{-14}$	
NMVOC :	$\text{W m}^{-2} \text{kg}_{\text{VOC}}^{-1} \text{y}$ Fuglestvedt et al. (2010) citing Collins et al. (2002)	Fuglestvedt et al. (2010)	$\text{W m}^{-2} \text{kg}_{\text{VOC}}^{-1}$	NMVOC, non-methane volatile organic compounds, unspecified origin
Short-term O ₃ increase	$2.13 \cdot 10^{-13} \pm 40\%$ Uncertainty from IPCC (2013), ch 8	0.267	$7.978 \cdot 10^{-13}$	
Long-term O ₃ decrease	-	-	-	
CH ₄ perturbation on O ₃	$1.77 \cdot 10^{-13} \pm 40\%$ Uncertainty from IPCC (2013), ch 8	14.2	$1.451 \cdot 10^{-14}$	
Aerosols:	$\text{W m}^{-2} \text{kg}^{-1}$ Fuglestvedt et al. (2010)	Fuglestvedt et al. (2010)		
Black carbon, BC	$1.96 \cdot 10^{-9} \pm 61$ to 70% Uncertainty from IPCC (2013) ch 8.SM.8	0.020 $\pm 25\text{--}30\%$	$1.96 \cdot 10^{-9}$ $\text{W m}^{-2} \text{kg}_{\text{C}}^{-1}$	Not exis- tent as Air emission
Organic carbon, OC	$-2.90 \cdot 10^{-10} \pm 81\%$ Uncertainty from IPCC (2013), ch 8	0.021 $\pm 25\text{--}30\%$	$-2.90 \cdot 10^{-10}$ $\text{W m}^{-2} \text{kg}_{\text{C}}^{-1}$	Not exis- tent as Air emission
SO ₂	$-3.2 \cdot 10^{-10} \pm 24\%$ $\text{W m}^{-2} \text{kg}_{\text{SO}_2}^{-1} \text{y}$	0.011 $\pm 25\text{--}30\%$	$-3.2 \cdot 10^{-10}$ $\text{W m}^{-2} \text{kg}_{\text{SO}_2}^{-1} \text{y}$	Sulfur dioxide
Particulate matter, PM	-	Based on carbon content Similar to OC	Based on carbon content Similar to OC	PM (<2.5 ; $2.5\text{--}10$; $>10 \mu\text{m}$)
Hydrogen	$1.30 \cdot 10^{-4} (\text{W m}^{-2} \text{ppbv}^{-1})$ (Hauglustaine et al. 2022)	2.5 (Hauglustaine et al. 2022)	$3.66 \cdot 10^{-13}$ $(\text{W m}^{-2} \text{kg}_{\text{H}_2}^{-1})$	Hydrogen
Aviation Air/lower strato- sphere+upper troposphere	ERF sensitivity to emissions $\text{W m}^{-2} \text{kg}_{\text{emission}}^{-1} \text{y}$ Lee et al. (2021)*	Perturbation time τ, years[#] Fuglestvedt et al. (2010)	Radiative efficiency A, $\text{W m}^{-2} \text{kg}^{-1}$ Used in this work	Compartment existent but no spe- cific SLCFs
NOx:	$\text{W m}^{-2} \text{kg}_{\text{N}}^{-1} \text{y}$		$\text{W m}^{-2} \text{kg}_{\text{N}}^{-1}$	Nitrogen oxides
Short-term O ₃ increase	$3.44 \cdot 10^{-11} \pm 28.8\%$	0.267	$1.288 \cdot 10^{-10}$	
Long-term O ₃ decrease	$-9.30 \cdot 10^{-12} \pm 36.6\%$	$10.5^{\S}$	$-8.8571 \cdot 10^{-13}$	
CH ₄ induced O ₃ decrease	$-1.87 \cdot 10^{-11} \pm 36.9\%$	$10.5^{\S}$	$-1.781 \cdot 10^{-12}$	

Table 1 (continued)

Air sub-compartment Climate forcer	Forcing parameter	Perturbation time τ , years	Radiative efficiency A, $\text{W m}^{-2} \text{ kg}^{-1}$	Name used in ecoinvent
Stratospheric water vapor decrease	$-2.80 \cdot 10^{-12} \pm 35.7\%$	10.5 [§]	$-2.6667 \cdot 10^{-13}$	
Aerosols:				
SO ₂	$-1.99 \cdot 10^{-11} \pm 80.4\%$ $\text{W m}^{-2} \text{ kg}_{\text{SO}_2}^{-1} \text{ y}$	0.011 $\pm 25\text{--}30\%$	$-1.810 \cdot 10^{-9}$ $\text{W m}^{-2} \text{ kg}_{\text{SO}_2}^{-1}$	Sulfur dioxide Sulfate
Soot (or BC)**	$1.007 \cdot 10^{-10} \pm 164\%$ $\text{W m}^{-2} \text{ kg}_{\text{C}}^{-1} \text{ y}$	0.02	$5.035 \cdot 10^{-9}$ $\text{W m}^{-2} \text{ kg}_{\text{BC}}^{-1}$	Not existent
Stratospheric water vapor increase	$5.20 \cdot 10^{-15} \pm 50\%$ $\text{W m}^{-2} \text{ kg}_{\text{H}_2\text{O}}^{-1} \text{ y}$	0.08 (Lifetime at 12 km, north hemisphere)	$6.50 \cdot 10^{-14}$ $\text{W m}^{-2} \text{ kg}_{\text{H}_2\text{O}}^{-1}$	Water
Contrail cirrus***	$9.36 \cdot 10^{-13}$ uncertainty: factor 2 or 3 $\text{W m}^{-2} \text{ km}^{-1} \text{ y}$	0.00057	$1.64 \cdot 10^{-9}$ $\text{W m}^{-2} \text{ km}^{-1}$	Not existent
Emission from shipping	Radiative forcing $\text{W m}^{-2} \text{ kg}_{\text{emission}}^{-1}$ Fuglestad et al. (2010)	Perturbation time τ, years[#] Fuglestad et al. (2010)	Radiative efficiency A, $\text{W m}^{-2} \text{ kg}^{-1}$ Used in this work	Compartment not existent
Aerosols SO ₂ :	$\text{W m}^{-2} \text{ kg}_{\text{SO}_2}^{-1}$		$\text{W m}^{-2} \text{ kg}_{\text{SO}_2}^{-1}$	Sulfur dioxide Sulfate
SO ₂ direct effect	$-3.43 \cdot 10^{-10} \pm 24\%$	0011 $\pm 25\text{--}30\%$	$-3.43 \cdot 10^{-10}$	
SO ₂ direct+indirect effects	$-3.54 \cdot 10^{-9}$ (citing Lauer et al. 2007; inventory A)	0.011 $\pm 25\text{--}30\%$	$-3.54 \cdot 10^{-9}$	
NOx :	$\text{W m}^{-2} \text{ kg}_{\text{N}}^{-1} \text{ y}$ citing Fuglestad et al. (2010)		$\text{W m}^{-2} \text{ kg}_{\text{N}}^{-1}$	Nitrogen oxides
Short-term O ₃ increase	$7.19 \cdot 10^{-12}$	0.267	$2.692 \cdot 10^{-11}$	
Long-term O ₃ decrease	$-1.88 \cdot 10^{-12}$	10.2; 12.2 [§]	$-1.843 \cdot 10^{-13}$	
CH ₄ induced O ₃ decrease	$-7.56 \cdot 10^{-12}$	10.2; 12.2 [§]	$-7.412 \cdot 10^{-13}$	

[#]Most relevant value (most occurrence or average)

*IPCC (2021) chapter 6. indicates Lee et al. 2021 as the best estimate of ERF for aviation

**Soot=BC and OC (Lee et al. 2021)

***Contrail cirrus: the value in Lee et al. (2021) is in $\text{mW/m}^2/\text{km}$. This unit seems not correct, it should be $\text{mW/m}^2/(\text{km/yr})$. Demonstration from the GWP100, GWP50, GWP20 values, using CO₂ AGTP ($8.89526 \cdot 10^{-14}$; $5.1477 \cdot 10^{-14}$; $2.42365 \cdot 10^{-14}$). From the GWPs given by Lee et al. (2021), the iRFs (A/ τ values) are in average $9.50096 \cdot 10^{-13}$. At 20 year there is no more RF (contrails disappear), so $\text{iRF}_{20} = \text{iRF}_{50} = \text{iRF}_{100}$. The specific ERF is thus $9.50096 \cdot 10^{-13}/\tau$ (0.00057 year). The uncertainty on the value was taken from Forster et al. (2007) as being a factor of 2 or 3

[§] from Lee et al. (2021)

WG1-chapter 8) and is due to the lifetimes of ozone and methane involved in the NOx reactions. Remarkably, the black carbon has a strong warming effect, 5000 times those of CO₂ at the peak. The graphs also demonstrate the importance of the region in which SLCFs are emitted, for example NOx from aviation warms three times more than NOx from land emissions as shown in Fig. 2.

3.3 A case study on aviation emissions

In a first exercise, a flight of 12,000 km with a commercial aircraft was considered. For the dynamic LCA application, only the trip stage was considered (no aircraft construction, infrastructures, or fuel production), with the kerosene consumption for the selected aircraft model estimated with an available calculator (Burzlaff 2017). The landing

and takeoff (LTO) and cruise (CCD) phases were differentiated in time. The total consumption in LTO of 7977 kg was divided into two parts: taxi-takeoff-climb_out (shortly “takeoff”) then approach-landing-taxi (named “landing”), with roughly equivalent consumption (based on Chati and Balakrishnan 2014). The CCD step (climb-cruise-descent) consumes 67,864 kg of kerosene. The emission factors of kerosene combustion are taken from Su-ungkavatin et al. (2023), based on ten sources (compilation of IPCC and other literature sources). The inventory is listed in Table 4. The timeline is decomposed in takeoff at $t=0$ during 0.5 h, CCD phase during 11 h, and landing during 0.5 h. This temporality could be considered as a pulse emission; however, the calculation was performed with an adapted time step of 0.5 h and with the real schedule of the emissions, in order to demonstrate the CCI-tool’s capabilities. Differentiation was

Table 2 Data used in the impulse response functions (concentration decay) IRF of CO₂, CH₄, N₂O, in the temperature impulse response function IRFT, and in carbon climate feedback impulse response function IRFCCF (from IPCC 2021)

$IRFT(t) = \sum_{j=1}^2 \frac{c_j}{d_j} e^{-t/d_j}$	$c1 = 0.44 \text{ K W}^{-1} \text{ m}^2$ $c2 = 0.32 \text{ K W}^{-1} \text{ m}^2$ $d1 = 3.4 \text{ year}; d2 = 285 \text{ yr}$
$IRFCCF(t) = \gamma \delta(t) - \gamma \sum_{i=1}^3 \frac{\alpha_i}{\tau_i} e^{-t/\tau_i}$	$\alpha1 = 0.6368; \alpha2 = 0.3322$ $\alpha3 = 0.0310$ $\tau1 = 2.376 \text{ yr}; \tau2 = 30.14 \text{ yr}$ $\tau3 = 490.1 \text{ yr}$ $\gamma = 11.06 \cdot 10^{12} \text{ kg CO}_2 \text{ yr}^{-1} \text{ K}^{-1}$ $\delta(t)$: Dirac function
CO ₂ $IRF(t) = a_0 + a_1 e^{-t/\tau_1} + a_2 e^{-t/\tau_2} + a_3 e^{-t/\tau_3}$	$a0 = 0.2173; a1 = 0.224$ $a2 = 0.2824; a3 = 0.2763$ $\tau1 = 394.4 \text{ year}; \tau2 = 36.54 \text{ yr}$ $\tau3 = 4.304 \text{ yr}$ $A = 0.0000133 \text{ W m}^{-2} \text{ ppb}^{-1}$
CH ₄ $IRF(t) = (1 + f1 + f2) e^{-t/\tau}$	$f1 = 0.5; f2 = 0.15$ $\tau = 11.8 \text{ yr}$ $A = 0.000345 \text{ W m}^{-2} \text{ ppb}^{-1}$
N ₂ O $IRF(t) = (1 - 0.36(1 + f1 + f2) \frac{A_{CH_4}}{A_{N_2O}}) e^{-t/\tau}$	$f1 = 0.5; f2 = 0.15$ $\tau = 109 \text{ yr}$ $A = 0.0028 \text{ W m}^{-2} \text{ ppb}^{-1}$ including the correction factor

Table 3 Results for GWP and GTP obtained with CCI-tool and reported in Lee et al. (2021) (noted ref in the table), for examples of aviation emissions

	GWP20			GWP50			GWP100		
	this work	ref	difference	this work	ref	difference	this work	ref	difference
NOx	598	619	-3%	193	205	-6%	109	114	-4%
Black carbon	4268	4288	-0.5%	2007	2018	-0.5%	1161	1166	-0.4%
Contrail cirrus (km basis)	39	39	0%	18	18	0%	11	11	0%
Stratospheric water	0.22	0.22	0%	0.10	0.10	0%	0.06	0.06	0%
SO ₂	-833	-832	0.1%	-387	-392	-1.3%	-224	-226	-0.9%
	GTP20			GTP50			GTP100		
	this work	ref	difference	this work	ref	difference	this work	ref	difference
NOx	-312	-222	40%	-66	-69	-4%	13	13	0%
Black carbon	1296	1245	4%	195	195	0%	161	159	1.3%
Contrail cirrus (km basis)	12	11	9%	1.9	1.8	5.5%	1.6	1.5	6.7%
Stratospheric water	0.06	0.07	-14%	0.01	0.01	0%	0.008	0.008	0%
SO ₂	-247	-241	2.4%	-38.8	-38	2%	-32	-31	3%

made between the emission altitude (LTO considered as on land emissions and CCD as low stratosphere emissions) of the different species with the specific parameters listed in Table 1.

The simulation results for the GMTC indicator are shown in Fig. 3 (top), with the contribution of CO₂ emissions for comparison. CO₂ contribution to the temperature peak is low compared with SLCFs' contribution. In contrast, its effect persists, while the contribution of SLCFs becomes negligible roughly 50 years after the cessation of emissions. The GMTC results, detailed per compound, are presented in Fig. 3 (bottom). Among the analyzed forcers, CCD NOx and contrail-induced cirrus show the largest temperature peaks—approximately 30 times higher than that of CCD CO₂, which itself is about 25 times greater than the peak values of the other emissions. Particularly important is the

negative peak of SO₂ but not sufficient to compensate the other positive peaks.

The obtained results are compared with the conventional metrics GWP and GTP provided in Table 4. The GWP and GTP values for all SLCFs were taken from the IPCC reports (IPCC 2013; WG1 chapter 8). The values vary according to different authors and are not yet stabilized. The choice was to select the global values (no continental regionalization), differentiated only by the emission sub-compartment (Table 1), as used in CCI-tool. For the dynamic approach, the temperature and time at the temperature peak were mentioned.

The conventional impact of CO₂ is always the mass of CO₂, irrespective of the metrics, i.e. 238,939 kg CO₂ eq. The ratio “total impact/CO₂ impact” indicates that the impact of all other climate forcers is similar to that of CO₂ at 100 years, 2 times higher at 20 years according to GWP20 and

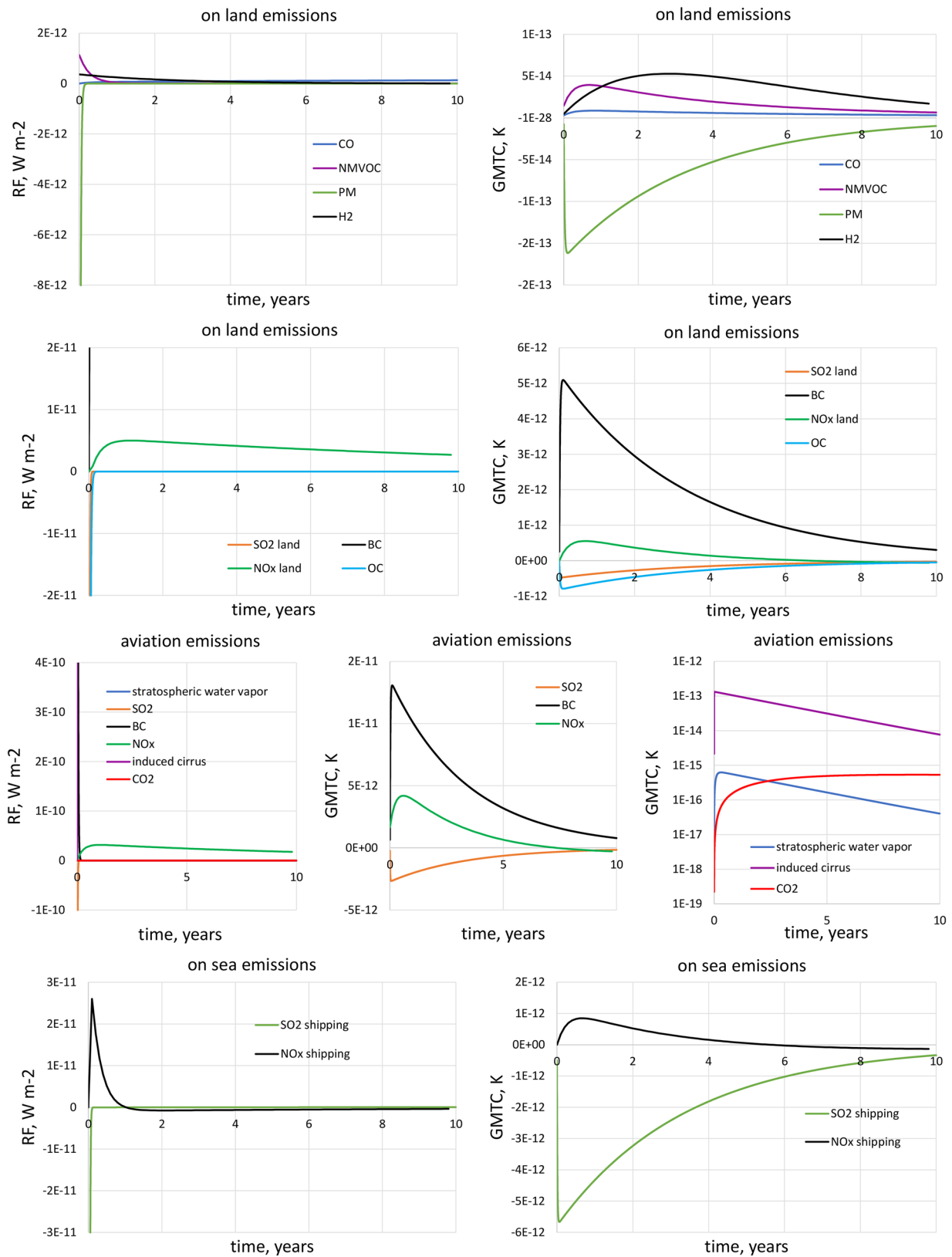
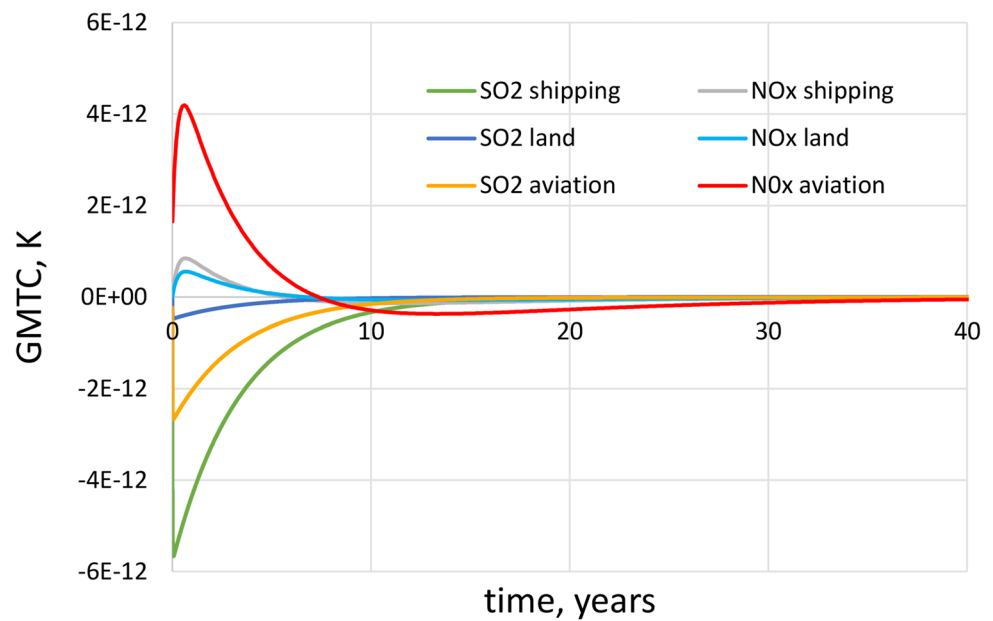


Fig. 1 Instantaneous RF and GMTC profiles following a pulse emission of 1 kg of each SLCF (for contrail induced cirrus, the pulse is 1 km)

Fig. 2 Comparative GMTC of NO_x and SO₂ from shipping, aviation and on-land emissions**Table 4** Emissions for a one-way trip - inventory and climate change impact results

Inventory	LTO (total)	CCD
Compound	kg/one way trip	kg/one way trip
Carbon dioxide, fossil	25,167	213,772
Dinitrogen monoxide	0.80	6.8
Methane, fossil	3.8	-
Carbon monoxide, fossil	118	-
Sulfur dioxide	9.6	1.2
Black carbon	0.24	0.03
Nitrogen oxides	113	950
NMVOC	83	-
stratospheric water	-	1200
aviation induced cirrus, km	-	11,500 (in km)
Results for conventional metrics		
Total impact, kg CO ₂ eq		Ratio Total impact/CO ₂ impact
GWP20	547,277	GWP20 2.29
GWP100	244,870	GWP100 1.02
GTP20	46,287	GTP20 0.19
GTP100	247,870	GTP100 1.04
Dynamic impact results		
Total		CO ₂ only
GMTC max	4.4 10 ⁻⁹ K	GMTC max 1.3 10 ⁻¹⁰
	year 1	year 9
GMTC min	-2 10 ⁻¹⁰ K	
	year 14	
GMTC 100	9.4 10 ⁻¹¹	GMTC 100 9.4 10 ⁻¹¹

5 times lower according to GTP20. In contrast, the dynamic approach results clearly show the temporality and magnitude of the impact, for example the ratio of temperatures “total/CO₂” at the peaks is 33, which demonstrates a much greater discrepancy between the effect of CO₂ and that of SLCFs. The temperature peak surpassed the expected effect

evaluated by GWP or GTP, justifying a temporal analysis of such scenarios.

The uncertainty available values (Table 1) were used here to calculate the GMTC interval of values. In Fig. 3, the maximum (max) and minimum (min) limits were obtained by simulating the GMTC with the extreme values of A for each climate forcer. Figure 3 shows these intervals in case of total impact (-37%, +72%), stratospheric NO_x (-30%, +30%) and induced contrail cirrus (-66%, +185%), the most important contributors to the short-term aviation impact. For comparison, the uncertainty of A_{CO₂} is of only 10%, and given the relatively low GMTC value, the min and max limits are not visible. Even in the case of min limits, the GMTC peak generated by NO_x and induced contrail cirrus, and consequently the total temperature peak, is much higher than that of CO₂, and demonstrates the strong warming effect of these forcers.

3.4 A case study on wood combustion

In this case study, direct emissions from wood combustion for heat production were analyzed. Emission data were obtained from experiments conducted on various heating devices by Bhattu et al. (2019). Specifically, data were extracted from the supplementary Excel file of the cited publication, corresponding to device no. 6 operating with wet wood under a reload-flaming combustion regime. The study reported several pollutant emissions, including CO, NO_x, CH₄, black carbon, organic carbon, NMVOC, which are both harmful to human health and relevant to climate impacts. The GMTC net value and its breakdown by SLCF, was calculated together with conventional climate metrics

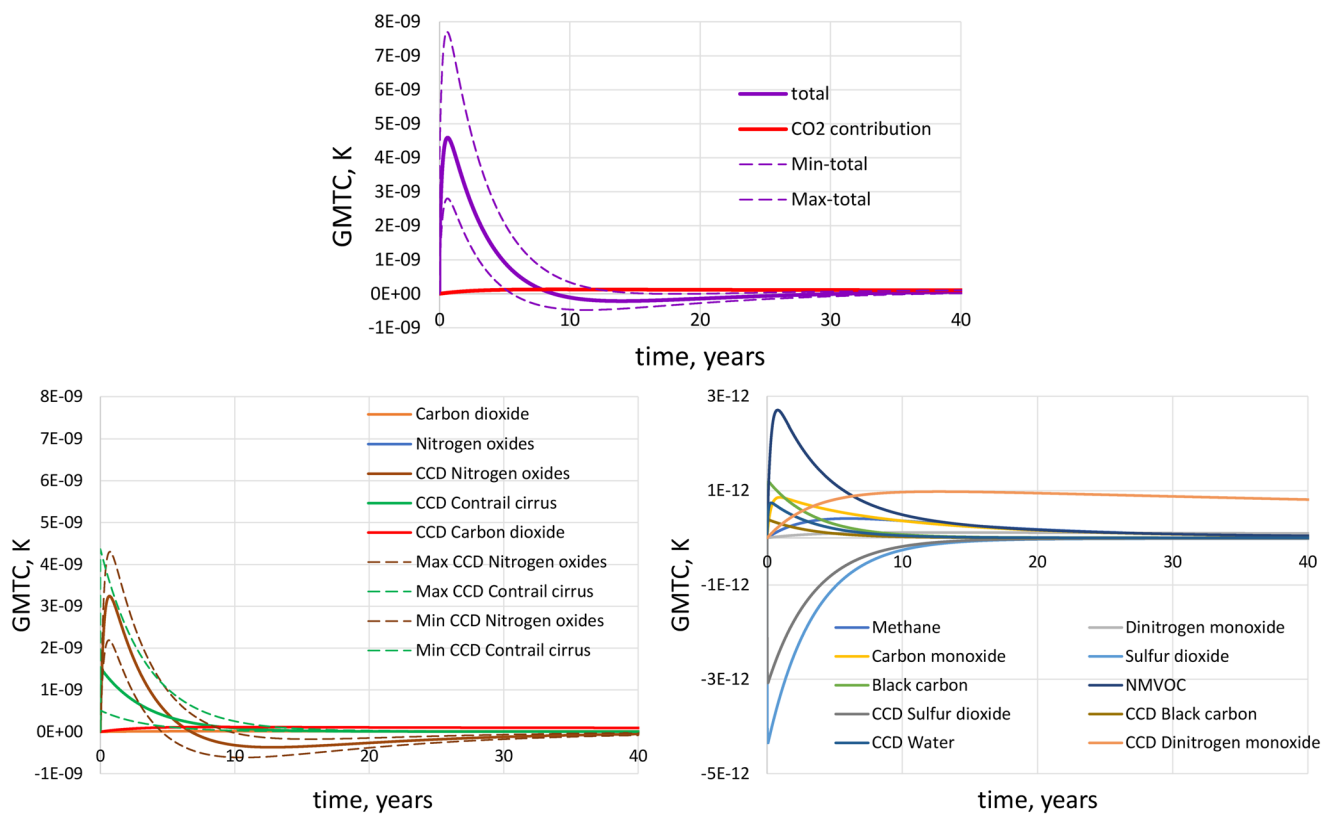


Fig. 3 Impact on temperature of a one-way flight. Top: the effect of all emissions together (blue) and the CO₂ contribution only (red). Bottom: contribution of the different climate forcers. The legend indicates

the emissions in the CCD phase, the others correspond to LTO phase. Dashed line: minimum and maximum

Table 5 Inventory in kg/kg dry wood for wood combustion. Conventional metrics and dynamic indicator results

Compound	kg/kg wood	Compound	kg/kg wood
Carbon dioxide	1.66	Organic carbon	0.000042
Methane	0.00025	Black carbon	0.00024
Carbon monoxide	0.0138	NMVOC	0.00048
Nitrogen oxides	0.00103		
Results for conventional metrics			
GWP20	2.35	GTP20	1.81
GWP100	1.84	GTP100	1.68
Dynamic impact results			
GMTC max	1.8 10 ⁻¹⁵ (at year 1.2)	GMTC 100	6.5 10 ⁻¹⁶

for the combustion of 1 kg of wood (dry mass), assuming emissions evenly distributed over one year. The corresponding inventory data and calculation results are presented in Table 5 and Fig. 4, respectively.

Note that the characterization factor for biogenic CO₂ is zero in conventional LCA, when both absorption and emission are included within the system boundaries. Here CO₂ is accounted for because only the emission (combustion) is considered. The characterization factors for SLCFs were taken from IPCC (2013) (chapter 8.SM.16) and listed in the supplementary information (section S1). The dynamic

indicator includes the effect of biogenic CO₂ on climate because the dynamic approach doesn't differentiate between biogenic and non-biogenic, the only important parameter is the time of CO₂ capture or emission. Both static and dynamic calculations include the carbon-cycle climate feedback.

Figure 4 shows a temperature peak after the emission stop (year 1), due to SLCFs and, particularly, due to black carbon and nitrogen oxides. The SLCFs' effect becomes negligible with respect to those of CO₂ after around 15 years. The conventional GTP20 accounts for the short-term effects, however, GTP20 and GTP100 values are not so different. As Fig. 4 shows, the short-term effect occurs well before 20 years (at 1.2 year) with a high intensity. The ratio between the temperature at the peak and at 100 years is 2.8, much higher than 1.08 in case of GTP20/GTP100, demonstrating that GTP underestimates the relative importance of these SLCFs. Even if GWP is based on the integrated RF and not on temperature, GWP100 and GWP20 are recommended for climate change impact when SLCFs are present. However, the ratio GWP20/GWP100 is 1.3 (versus 2.8 in dynamic approach) which underestimates the SLCFs effect. Although discrepancies between dynamic and static approaches were expected, this example illustrates them concretely.

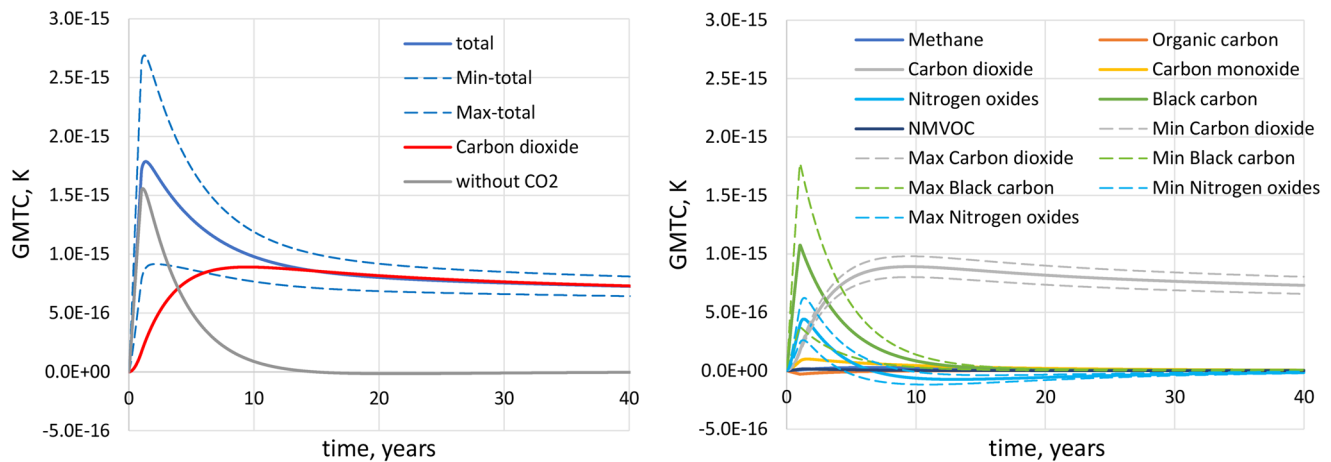


Fig. 4 GMTC results for the combustion of 1 kg wood during 1 year. At left: total impact (blue line) compared with the contribution of CO₂ (red line), and total impact except CO₂ (grey line). At right: contribution of all considered climate forcers. Dashed line: minimum and maximum

Another example, on coal combustion, is presented in the supplementary information (section S2). For this example, direct emissions (CO₂ fossil, CO fossil, CH₄ fossil, NMVOC, N₂O, NO_x, SO₂, and particulate matter PM) were considered from ecoinvent 3.11. The occurrence of a negative temperature peak after the pulse emission is due to the aerosol emissions, which corroborates the conclusions of Shindell and Faluvegi (2010) on the net effect of coal fired power plants.

The uncertainty analysis was performed in case of wood and coal combustion (Fig. 4, Figure S1). The min and max limits for GMTC were represented for the main contributors: CO₂, black carbon, SO₂ and NO_x. The general behavior of the GMTC in function of time is not changed for the min and max limits, only the amplitudes of the temperature peak is increased or decreased. However, in all examples, the uncertainty doesn't diminish the high contribution of the SLCFs to the net GMTC result.

3.5 Model and tool capabilities and limitations

Regarding the scientific understanding of SLCF behavior, it is now well established that the latitude of emissions is an additional factor influencing their climate effects. Regionalized parameters or models could be implemented once sufficiently robust data—particularly for the radiative efficiency (A) and perturbation lifetime (τ) parameters—become available for well-defined regions, in a manner compatible with the regionalization approach in LCA. Moreover, current LCA tools (e.g. ecoinvent 3.11) do not differentiate the elementary flows (i.e., biosphere matrix) by region or latitude. Therefore, additional methodological development is required to enable regionalization at the impact assessment level. This implies considering the elementary flows not only by environmental compartment (e.g. air, freshwater,

etc.) but also by latitude, country, altitude, and propose adapted characterization factors. Such detailed modeling of CFs is proposed, for example, by Usetox standalone method (toxicity/ecotoxicity impacts).

The carbon cycle climate feedback was added in the model as explained in Sect. 2.3, which represent an update of the model. The effect on the GMTC results is an increase by several percentages (2 to 8 globally), as presented in IPCC (2013) (chapter 8.SM).

CCI-tool demonstrated its flexibility in adding new climate forcers. The numerical solutions of the theoretical models are obtained with inventory time series. The timestep could be any value desired by the user. In its current version, the timestep is constant for the whole considered timespan for impact calculation (desired by the user). A sensitivity analysis was performed on timestep value and is presented in the supplementary information section S3. This demonstrates that, for accurate results, a timestep smaller than τ value of the evaluated climate forcer is needed. The timestep for the simulations is chosen by the user. Often the inventories are defined with an annual timestep. A one-year timestep can be used for all GHGs because their perturbation times is higher, but induces errors on SLCFs evaluation.

Moreover, the tool is fully compatible (via input-output formatted files) with the DyPLCA tool for dynamic inventory calculation (Pigné et al. 2019) and can be plugged-in with other dynamic LCA software. This flexibility in the simulation parameters and addition of different climate features discriminates CCI-tool from the other available tools based on dynamic characterization factors (e.g. Levasseur et al. 2010) for climate change impact.

4 Conclusions

In an effort to improve LCA methodologies and tools using current scientific knowledge, new elements were incorporated into the methodology for calculating dynamic climate change impacts in dynamic LCA. Owing to its flexible architecture, which allows continuous updates and improvements, the CCI-tool was used in this work.

To date, SLCFs are not considered in climate change impact calculations in dynamic LCA tools, despite their acknowledged importance in climate science. This applies, for example, to emissions from aviation, shipping, on-land combustion processes, and the hydrogen industry.

These climate forcers were included in CCI-tool: (1) aerosols and precursors: SO₂, organic carbon, black carbon, particulate matter; (2) ozone precursors (indirect GHGs): NO_x, CO, volatile organic compounds; (3) other indirect: H₂. The model was validated based on several available values of conventional metrics GWP20, GWP100, GTP20, GTP100. The calculated values (for a 1 kg pulse emission, or for a 1 year – 1 kg step emission, depending on the available GWP, GTP data) agree well with literature values. Furthermore, the behavior of calculated RF and GMTC following a pulse emission is consistent with descriptions reported in climate science literature.

While conventional metrics reported by the IPCC include the carbon cycle climate feedback for GHGs, this effect has not been considered in existing dynamic LCA tools. In this work, the carbon cycle climate feedback mechanism was integrated into the CCI-tool for all climate forcers.

Uncertainties reported in climate science literature are generally higher for SLCFs than for long-lived GHGs, particularly for A, which can range from 20% to over 100% (e.g., contrail-induced cirrus), compared to A_{CO₂} which has an uncertainty of about 10%. Simulations conducted in this work show that, even accounting for these high uncertainties, the climate impact of SLCFs can be comparable to or exceed that of CO₂ emitted from combustion processes. This is true for species such as NO_x, SO₂, and contrail-induced cirrus.

The two case studies presented—an aviation scenario and wood combustion—illustrate these findings. In the aviation scenario, the GMTC peak of SLCFs is much higher than that of CO₂, with peak amplitude ratios far exceeding GWP ratios. This impact occurs several decades after emissions cease, whereas 100 years after emission, the impact is dominated by long-lived GHGs, such as CO₂. Considering SLCFs is therefore particularly important when evaluating short- and medium-term pathways toward achieving climate neutrality around 2050.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s11367-026-02583-7>.

26-02583-7.

Acknowledgements This work was supported by the European Union under the grant number 101135371 – project LCA4BIO.

Funding Open access funding provided by INSA Toulouse.

Data availability The CCI-tool is freely available at <https://www.insa-toulouse.fr/cci-tool/>.

Declarations

Conflict of interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Aamaas B, Peters GP, Fuglestedt JS (2013) Simple emission metrics for climate impacts. *Earth Syst Dynam* 4:145–170. <https://doi.org/10.5194/esd-4-145-2013>
- Allen MR, Shine KP, Fuglestedt JS, Millar RJ, Cain M, Frame DJ, Macey AH (2018) A solution to the misrepresentations of CO₂-equivalent emissions of shortlived climate pollutants under ambitious mitigation. *npj Clim Atmos Sci* 1:16
- Beloin-Saint-Pierre D, Albers A, Hélias A, Tiruta-Barna L, Fantke P, Levasseur A, Benetto E, Benoist A, Collet P (2020) Temporal Considerations in Life Cycle Assessment: A Review. *Sci Total Environ* 743(2020):140700. <https://doi.org/10.1016/j.scitotenv.2020.140700>
- Bhattu D, Zotter P, Zhou J, Stefanelli G, Klein F, Bertrand A, Temime-Roussel B, Marchand N, Slowik JG, Baltensperger U, Prévôt ASH, Nussbaumer T, El Haddad I, Dommen J (2019) Effect of stove technology and combustion conditions on gas and particulate emissions from residential biomass combustion. *Environ Sci Technol* 53(4) <https://doi.org/10.1021/acs.est.8b05020>
- Boucher O, Reddy MS (2008) Climate trade-off between black carbon and carbon dioxide emissions. *Energy Policy* 36:193–200. <https://doi.org/10.1016/j.enpol.2007.08.039>
- Burzlauff M (2017) Aircraft fuel consumption – estimation and visualization. Project. Hamburg, Germany: Hochschule für Angewandte Wissenschaften Hamburg. Report. <https://doi.org/10.7910/DVN/2HMEHB>
- Cain M, Lynch J, Allen MR, Fuglestedt JS, Frame DJ, Macey AH (2019) Improved calculation of warming-equivalent emissions for short-lived climate pollutants. *npj Clim Atmos Sci* 2:29. <https://doi.org/10.1038/s41612-019-0086-4>
- Chatl YS, Hamsa Balakrishnan H (2014 May 26–30) Analysis of aircraft fuel burn and emissions in the landing and take off cycle using operational data. In: 6th International Conference on

- Research in Air Transportation (ICRAT 2014), Istanbul, Turkey. https://www.mit.edu/~hamsa/pubs/ICRAT_2014_YSC_HB_final.pdf. Accessed 20 Oct 2025
- Collins WJ, Derwent RG, Johnson CE, Stevenson DS (2002) The oxidation of organic compounds in the troposphere and their global warming potentials. *Clim Change* 52:453–479. <https://doi.org/10.1023/A:1014221225434>
- Derwent RG, Collins WJ, Johnson CE, Stevenson DS (2001) Transient behaviour of tropospheric ozone precursors in a global 3-D CTM and their indirect greenhouse effects. *Clim Change* 49:463–487. <https://doi.org/10.1023/A:1010648913655>
- Diepers T, Müller A, Jakobs A (2025) Time-explicit LCA with bw_timex. <https://docs.brightway.dev/projects/bw-timex/en/latest/index.html>. Accessed 14 Oct 2025
- Forster P, Ramaswamy V, Artaxo P, Bernsten T, Betts R, Fahey DW, Haywood J, Lean J, Lowe DC, Myhre G, Nganga J, Prinn R, Raga G, Schulz M, Van Dorland R (2007) Changes in atmospheric constituents and in radiative forcing. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds) *climate change 2007: The physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge university press, cambridge, UK and new york, NY, USA
- Fuglestedt JS, Shine KP, Bernsten T, Cook J, Lee DS, Stenke A, Skeie RB, Velders GJM, Waitz IA (2010) Transport impacts on atmosphere and climate: Metrics. *Atmos Environ* 44:4648–4677
- Gasser T, Glen P, Peters JS, Fuglestedt WJ, Collins DT, Shindell (2017) Philippe Ciais, Accounting for the climate-carbon feedback in emission metrics. *Earth Syst Dynam* 8:235–253. <https://doi.org/10.5194/esd-8-235-2017>
- Gomonov K, Permana CT, Tri Handoko C (2025) The growing demand for hydrogen: current trends, sectoral analysis, and future projections. *Unconv Resour* 6:100176. <https://doi.org/10.1016/j.uncres.2025.100176>
- Hauglustaine D, Paulot F, Collins W, Derwent R, Sand M, Boucher O (2022) Climate benefit of a future hydrogen economy. *Commun Earth Environ* 3:295. <https://doi.org/10.1038/s43247-022-00626-z>
- IPCC (2013) *Climate change: The physical science basis: Working Group I contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge. <https://doi.org/10.1017/CBO9781107415324>
- IPCC (2021) *The Earth's energy budget, climate feedbacks, and climate sensitivity*. In *Climate change 2021: the physical science basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge. <https://doi.org/10.1017/9781009157896.009>
- Joos F, Roth R, Fuglestedt JS, Peters GP, Enting IG, von Bloh W, Brovkin V, Burke EJ, Eby M, Edwards NR, Friedrich T, Frolicher TL, Halloran PR, Holden PB, Jones C, Kleinen T, Mackenzie FT, Matsumoto K, Meinshausen M, Plattner G-K, Reisinger A, Segschneider J, Shaffer G, Steinacher M, Strassmann K, Tanaka K, Timmermann A, Weaver AJ (2013) Carbon dioxide and climate impulse response functions for the computation of greenhouse gas metrics: a multi-model analysis. *Atmos Chem Phys* 13:2793–2825. <https://doi.org/10.5194/acp-13-2793-2013>
- Lauer A, Eyring V, Hendricks J, Jockel P, Lohmann U (2007) Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget. *Atmos Chem Phys* 7:5061–5079. <https://doi.org/10.5194/acp-7-5061-2007>
- Lee DS, Fahey DW, Skowron A, Allen MR, Burkhardt U, Chen Q, Doherty SJ, Freeman S, Forster PM, Fuglestedt J, Gettelman A, De Leon RR, Lim LL, Lund MT, Millar RJ, Owen B, Penner JE, Pitari G, Prather MJ, Sausen R, Wilcox LJ (2021) The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmos Environ* 244:117834
- Levasseur A, Lesage P, Margni M, Deschenes L, Samson R (2010) Considering Time in LCA: Dynamic LCA and Its Application to Global Warming Impact Assessments. *Environ Sci Technol* 44:3169–3174
- Levasseur A, de Schryver A, Hauschild M, Kabe Y, Sahnoune A, Tanaka K, Cherubini F (2016) Greenhouse gas emissions and climate change impacts. In: Frischknecht R, Joliet O (eds) *Global Guidance for Life Cycle Impact Assessment Indicators - Volume 1*. United Nations Environment Programme, pp 60–79
- Ministère de la Transition écologique (2021) *Réglementation environnementale 2020 (RE2020)*. <https://www.ecologie.gouv.fr/re2020>
- Perrone MG, Gualtieri M, Consonni V, Ferrero L, Sangiorgi G, Longhin E, Ballabio D, Bolzacchini E, Camatini M (2013) Particle size, chemical composition, seasons of the year and urban, rural or remote site origins as determinants of biological effects of particulate matter on pulmonary cells. *Environ Pollut* 176:215–227
- Pigné Y, Navarrete Gutiérrez T, Gibon T, Schaubroeck T, Popovici E, Shimako AH, Benetto E, Tiruta-Barna L (2019) A tool to operationalize dynamic LCA, including time-differentiation on the complete background database. *Int JLCA* 25(2019):267–279
- Shimako AH, Tiruta-Barna L, Pigné Y, Benetto E, Navarrete Gutiérrez T, Guiraud P, Ahmadi A (2016) Environmental assessment of bio-energy production from microalgae based systems. *J Clean Prod* 139(2016):51–60
- Shimako AH, Tiruta-Barna L, Bisinella de Faria AB, Ahmadi A, Spérando M (2018) Sensitivity analysis of temporal parameters in a dynamic LCA framework. *Sci Total Environ* 624:1250–1262
- Shindell D, Faluvegi G (2010) The net climate impact of coal-fired power plant emissions. *Atmos Chem Phys* 10:3247–3260. <https://doi.org/10.5194/acp-10-3247-2010>
- Sohn J, Kalbar P, Goldstein B, Birkved M (2020 May) Defining temporally dynamic life cycle assessment: a review. *Integr Environ Assess Manag* 16(3):314–323. <https://doi.org/10.1002/ieam.4235>
- Su-ungkavatin P, Tiruta-Barna L, Hamelin L (2023) Framework for life cycle assessment of sustainable aviation (SA) systems. *Sci Total Environ* 885:163881. <https://doi.org/10.1016/j.scitotenv.2023.163881>
- Tiruta-Barna L (2021) A climate-goals-based, multicriteria method for system evaluation in Life Cycle Assessment. *Int JLCA* 26:1913–1931. <https://doi.org/10.1007/s11367-021-01991-1>
- Wild O, Prather MJ, Akimoto H (2001) Indirect long-term global radiative cooling from NO_x emissions. *Geophys Res Lett* 28:1719–1722. <https://doi.org/10.1029/2000GL012573>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.