D2.2 – Climate Metrics, Differences Between Simplified and Advanced Methods, and Recommendations

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Abstract

This report identifies candidate metrics and a climate methodology assessment to be used to monitor the performance of development and demonstration actions in Horizon Europe and CA projects. It builds upon Deliverable 2.1 which reviews existing climate metrics and assesses them against a specified set of requirements. This set and the test procedure were evaluated by international stakeholders in a dedicated CLAIM workshop. The recommendations from the workshop outlined in this report endorse the proposed testing of climate metrics. The stakeholders clearly prioritized the importance of "neutrality" of a climate metric. Finally, simple calculation methods for climate metrics are compared to more advanced methods to illustrate differences in their application. The presented cases indicate that the climate impact of individual fleets, such as regional aircraft or long-range single aisle aircraft, differs significantly from that of a global fleet of aircraft due to the dependence of non-CO_2 aviation effects on the location of emissions. The examples demonstrate that simple calculation methods are not able to capture these differences and are therefore not recommended for assessing technology climate mitigation options. We recommend a four-layer approach for the climate impact assessment of new technologies and propose a framework to integrate uncertainties and knowledge gap for a robust assessment.

Keywords

non-CO_2 emission, climate impacts, climate metrics

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Table of Acronyms and Abbreviations

Acronym/Abbreviation	Description / Meaning
AS4D	AirClim surrogate model for design
ATR	Average temperature response
EGWP	Efficacy-weighted global warming potential
GTP	Global temperature change potential
GWP	Global warming potential
iGTP	Integrated global temperature change potential
RF	Radiative forcing
SAF	Sustainable aviation fuels

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1. Introduction

1.1 Objective of the deliverable

One of the objectives of CLAIM is to recommend a science-based approach for a climate impact assessment methodology for aircraft technologies. This deliverable describes an intermediate step along this path.

The objective of this deliverable is

- A science-based recommendation of a climate metric for the use within a climate impact technology assessment
- To provide some insights into the usage of those climate metrics in climate impact assessment of aviation technologies by comparing simple and advanced calculation methods
- To propose a technology climate impact assessment

Within CLAIM we have chosen the following approach for both, the selection of a climate metric and the calculation procedure for a climate impact assessment of aviation technologies:

1) starting with a literature review,
2) deriving recommendations from the review,
3) providing compelling examples,
4) obtaining feedback from stakeholders in dedicated workshops,
5) summary by integrating the feedback into the recommendations.

This deliverable presents the status of the work comprising mainly the steps 1)-4) and gives a first preliminary version of step 5). The final recommendation for the whole procedure of a climate impact assessment methodology for aircraft technologies is covered by CLAIM milestone number 10 and a scientific publication that is currently in preparation[1]. The deliverable was updated after the final review meeting to include the results from milestone 10 as Section 8.

The climate assessment of aviation technologies or scenarios requires the consideration of non-CO_2 climate effects such as contrails and NO_x emissions (see Section 1.2) and hence it requires a mechanism to compare those effects and put them on the same scale, which is the primary objective of climate metrics.

This deliverable describes principles on climate metric choices and how climate metrics are used to derive equivalent CO_2 emissions (Section 2) before a description of candidate physical climate metrics selected for evaluation is given in Section 3.

[1] Grewe et al., Review on technology climate impact assessment methodologies and resulting best practice, in prep., 2025

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Section 4 describes requirements for climate metrics and testing procedure providing an objective basis for a choice of appropriate climate metrics to be used in CLAIM. Section 5 summarises the final rankings of the metric performance accordingly to the specified requirements and resulting recommendations for climate metrics.

In June 2024, a workshop was held in Hamburg, where international stakeholders from industry and academia provided feedback on the procedure outlined in Section 4. The summary of the workshop layout and the feedback is given in Section 6. This feedback is important for a broader acceptance of this CLAIM procedure for down selecting climate metrics in the technology climate impact assessment.

In order to illustrate pros and cons of simplified versus advanced calculation methods for climate metrics, Section 7 illustrates some essential differences in the methods based on examples for different aircraft and fuel combinations. These considerations will inform the recommendation of a climate impact assessment for aviation technologies, which will be detailed in MS10 and Grewe et al. (2025)[1].

1.2 Aviation climate impact

Aviation contributes to climate change via emissions of CO_2 and non-CO_2 emissions and effects. Figure 1.1 shows the process chain from aviation emissions to their climate impact. Non-CO_2 effects comprise changes in atmospheric abundances of greenhouse gases (e.g. water vapour, ozone (O_3) and methane (CH_4)), particulates (e.g. soot and sulphates) and changes in cloudiness (contrail-cirrus and changes in natural clouds). They are short-lived in comparison to CO_2 and therefore often also called short-lived climate pollutants (SLCP).

In order to reduce the climate impact of aviation, beside CO_2 emissions also those non-CO_2 effects have to be considered. The various emissions influence atmospheric composition and cloudiness, thereby having a direct impact on the climate (when emitted species are greenhouse gases) or an indirect impact (when emitted species alter greenhouse gases or cloudiness) (Figure 1.1).

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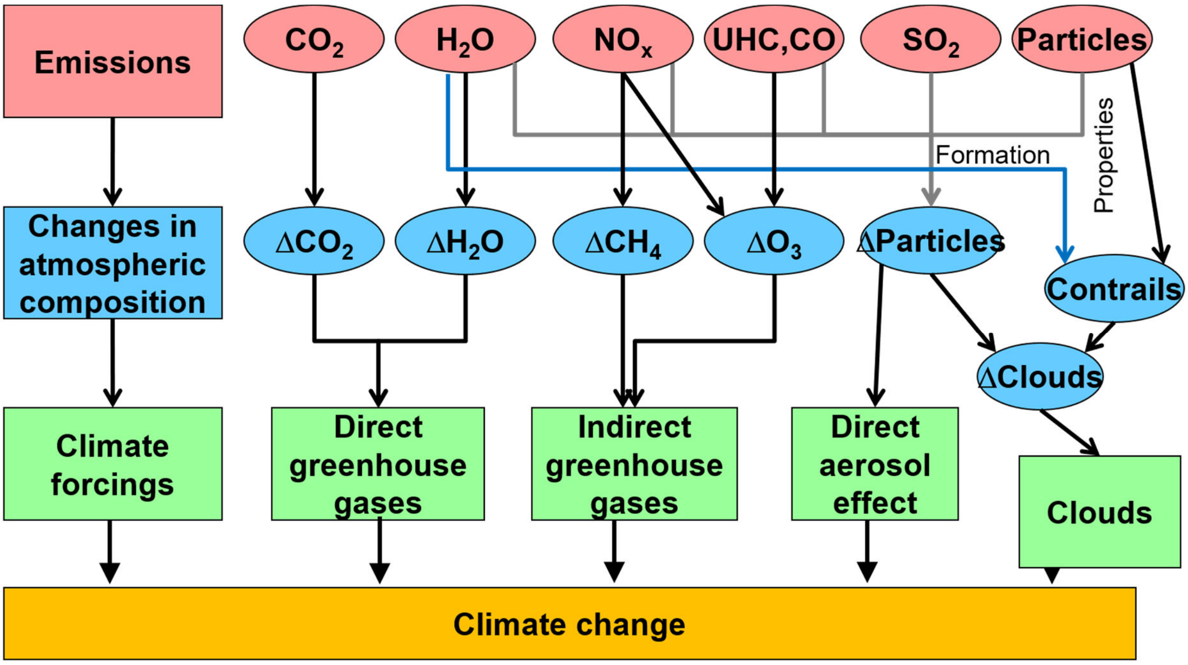

Figure 1.1 Overview on the process chain from aviation emissions to climate change

The changed composition of the atmosphere leads to the Earth's radiative equilibrium being disturbed (Figure 1.2). In order to return to a state of equilibrium, the near-surface temperature increases, causing the Earth's surface to radiate more energy back to space. The Earth reaches then a new equilibrium, but at higher surface temperatures. The extent to which the temperature near the ground increases due to the initial radiation imbalance depends on the climate sensitivity λ_x, which differs for different climate species *x*:

$$\Delta T = \lambda_x \, RF \qquad (1)$$

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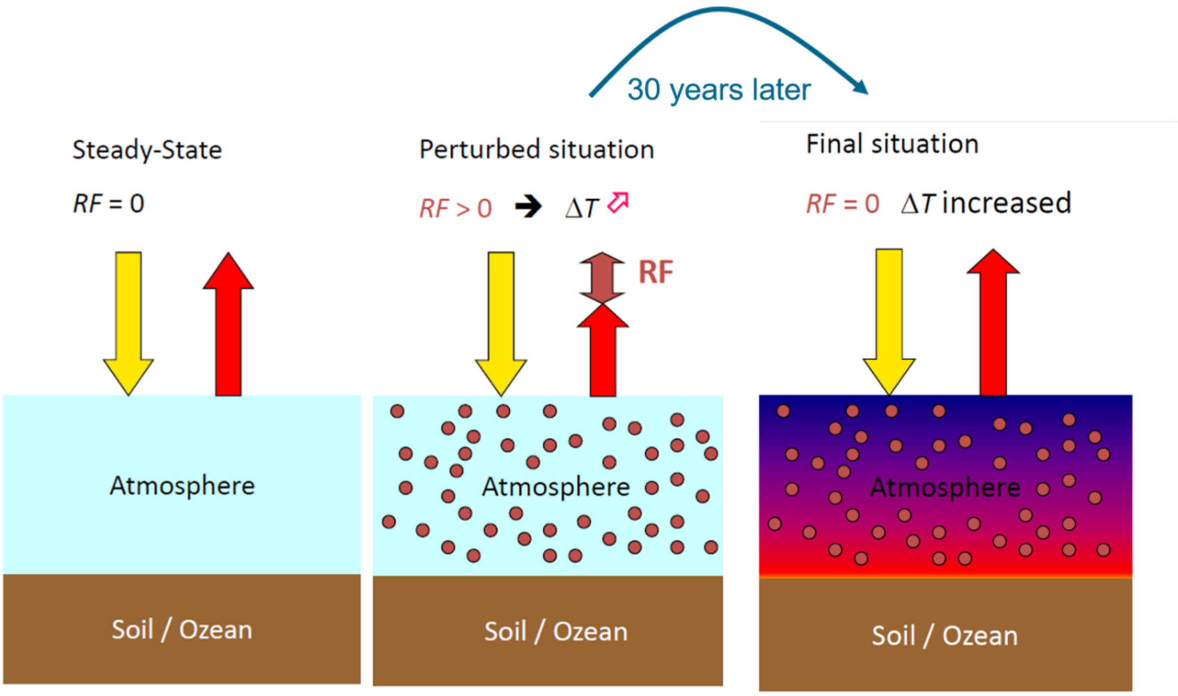

Figure 1.2 Overview on the principle relation between radiation imbalance (radiative forcing, RF>0) and future temperature change ΔT. The left figure shows a steady state in which radiation fluxes are balanced.

Table 1.1 Lifetimes of the disturbance of the atmosphere by aviation emissions and effects

Species	Lifetime
CO_2	several lifetimes ranging from decades to thousands of years
O_3^s	Weeks
CH_4	Years
O_3^{pm}	Years
Contrails	hours to days
H_2O	weeks

How long an emission influences near-surface temperatures depends on two different timescales. First, the radiation imbalance of the atmosphere depends on the lifetime of the

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disturbance of the atmospheric composition (Table 1.1). Once released, CO_2 emissions can remain in the atmosphere for hundreds to thousands of years, as it is gradually absorbed by natural processes such as photosynthesis in plants and dissolution in oceans. Figure 1.3 shows the global carbon cycle. In contrast, the lifetime of contrails is only a few hours. The lifetimes of perturbations of greenhouse gases related to aviation NO_x emissions (stratospheric and primary mode ozone and methane) vary from weeks to years. The second timescale describes the physical response of a radiative imbalance to the resulting temperature changes, which relates to the inertia of the atmosphere-ocean system. This means that the resulting near-surface temperature change of a one-year pulse of short-lived species is large at the beginning and then slowly decreases, while the temperature change due to a one-year pulse of CO_2 increases for several decades, before it decreases again (Fig. 1.4).

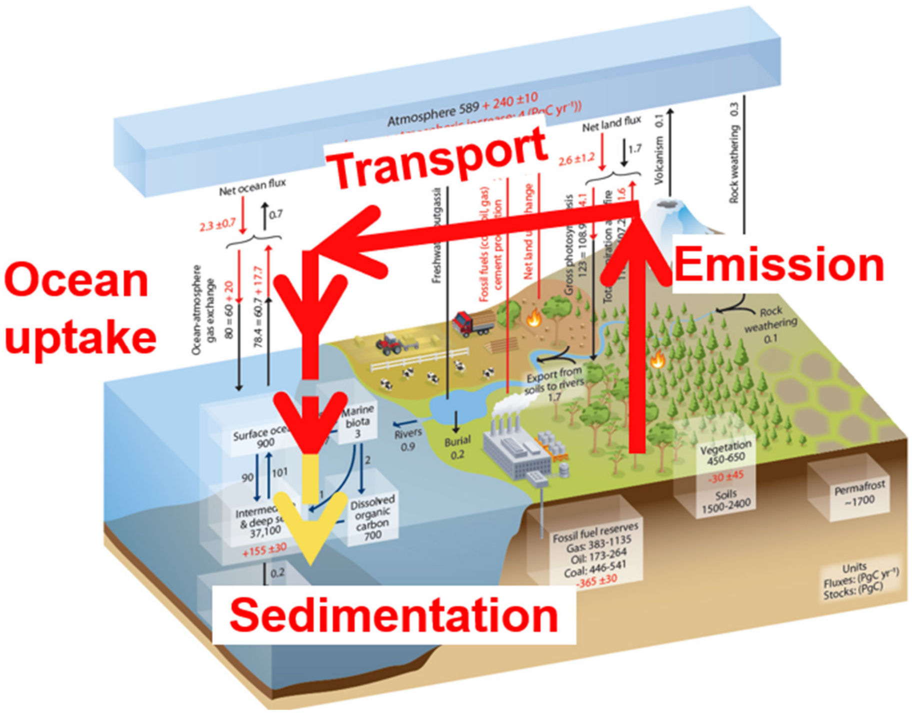

Figure 1.3 Simplified schematic of the global carbon cycle in which CO2 is emitted in and gradually removed from the atmosphere (adapted from IPCC 2013).

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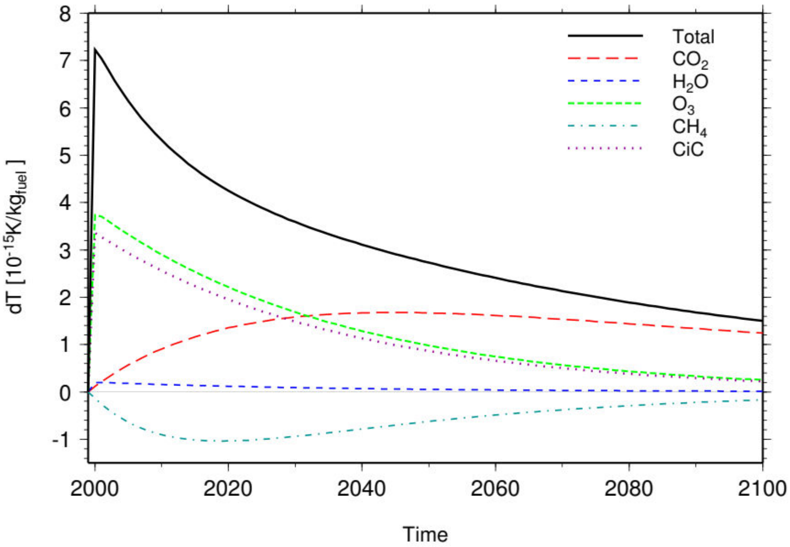

Figure 1.4 Temporal evolution of near-surface temperature changes due to one-year pulse emissions of CO_2, H_2O, O_3, CH_4, and contrails (from Dahlmann et al. 2016).

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2. Measuring climate effects by applying a physical climate metric

2.1 Overview

Different climate species impact the climate in various ways, differing in terms of their sign, lifetime, and spatial dependencies. Therefore, it is crucial to use a metric that accounts for these factors when assessing the climate impact of technologies or scenarios. A climate metric serves as a direct link or 'shortcut' between emissions and their resulting impacts. What is considered as climate impact depends on the question being asked. The further down the process chain you go from emissions to damage, the larger is its relevance, but the larger is also the associated uncertainty (Figure 2.1). Since a lot of economic assumptions (e.g. depreciation or inflation rate) are used in monetarisation (damage), damage is no longer referred to as a strict physical climate metric.

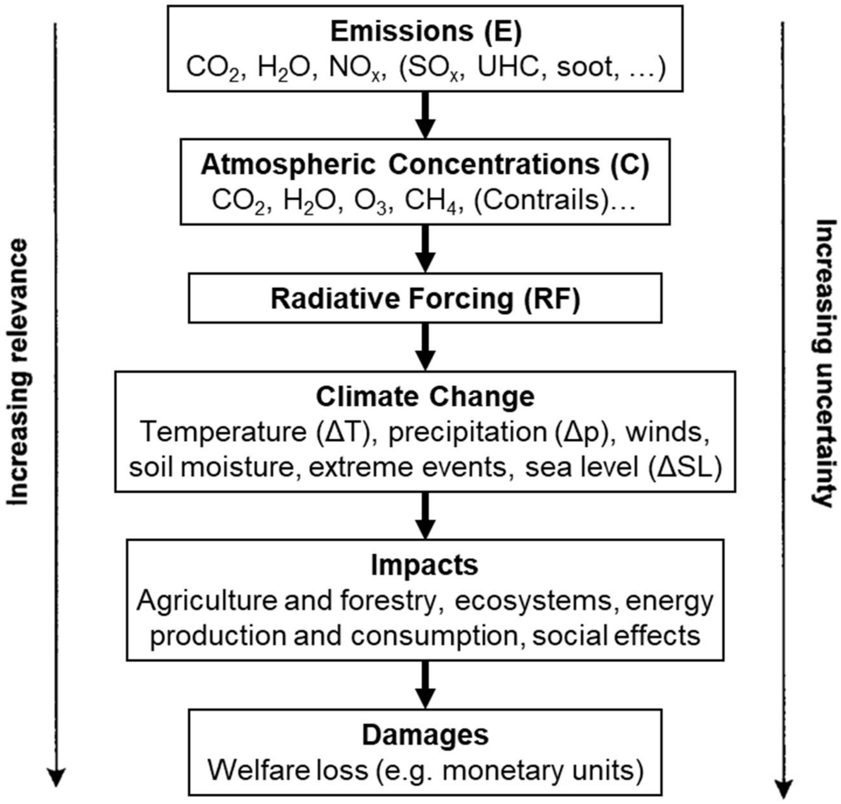

Figure 2.1 Process chain from emissions to climate change and damage (from Fuglestvedt et al. 2003).

Aviation non-CO_2 emissions are particularly complex due to their highly variable atmospheric lifetimes and efficacies, as well as their dependence on emission altitude and location, and the significant uncertainty associated with them.

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2.2 Choice of a climate metric

Selecting a climate metric to measure the impact of emissions from a new technology is very important, since this choice can affect the outcome of the assessment (Fuglestvedt et al. 2010). This process requires a well-defined question to be answered in the evaluation and entails several key decisions, including

- Determining the most suitable physical indicator for measuring the impact, such as radiative forcing or temperature change.
- Deciding whether the assessment should be conducted at a specific point in time or over a defined time span. This aids in selecting between endpoint metrics and integrated metrics, respectively.
- Deciding on the time horizon, e.g. 20, 50, 100 years.
- Deciding how emissions change over time, for example, as a pulse, sustained emission or a projected or modelled pathway of aviation emissions (emission scenario).
- Choosing between absolute metrics, which directly quantify the total impact of emissions, and relative metrics, which assess the impact of emissions in that of a reference gas (usually, CO_2).

Figure 2.2 summarises the main stages of the selection process of a climate metric. An example of temperature changes for CO_2 and O_3 over time from a sustained emission is shown in Figure 2.3. The relative importance of the impact from CO_2 and O_3 varies significantly over time, highlighting different timescales for these climate agents.

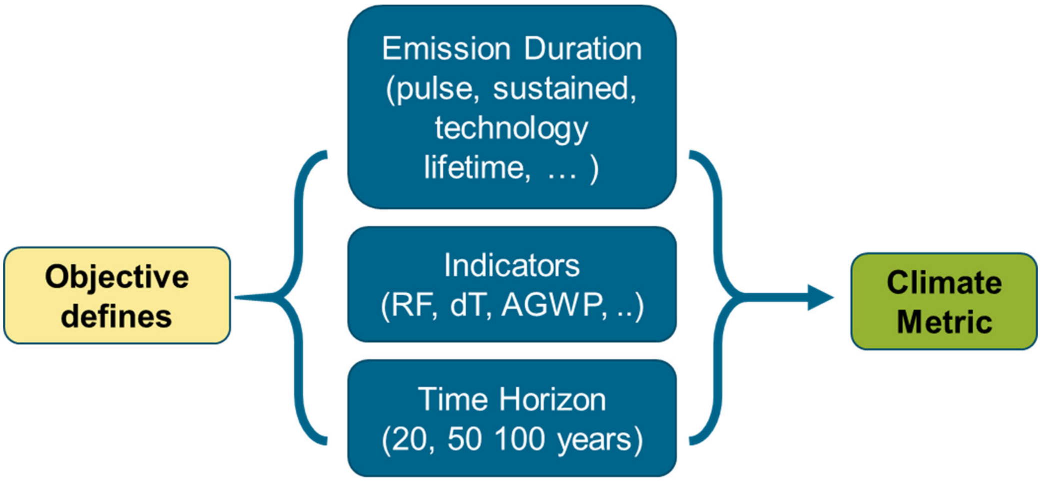

Figure 2.2 llustration of the key steps required for climate metric assessment.

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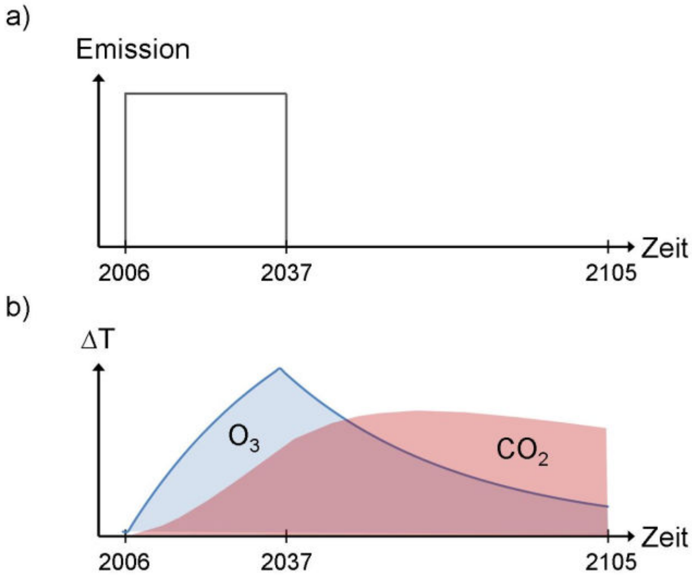

Figure 2.3 Sustained emission development of a new technology (a) and corresponding temperature changes due to O_3 and CO_2 (b) (from Dahlmann 2011).

In the following, we discuss an example from Shindell et al. (2010) that illustrates why it is important to consider the choice of climate metrics carefully. This example examines the radiative forcing associated with emissions from a newly built coal-fired power plant over time[2]. Figure 2.4 shows temporal development of radiative forcing from various emissions of a coal power plant. The coal-fired power plant initially has a cooling effect as indicated by the negative values of the total RF. It results from the cooling from the direct and indirect sulfate effects, which is initially stronger than the warming effect of CO_2 emissions. However, due to the long lifetime of CO_2, it accumulates in the atmosphere, and its warming contribution becomes more significant over time. After about 20 years, the warming effect of CO_2 predominates. If the radiative forcing were considered only during 20 years of operation, a coal-fired power plant would be incorrectly categorized as climate-friendly.

[2] For further discussions see e.g. Ocko et al. (2017).

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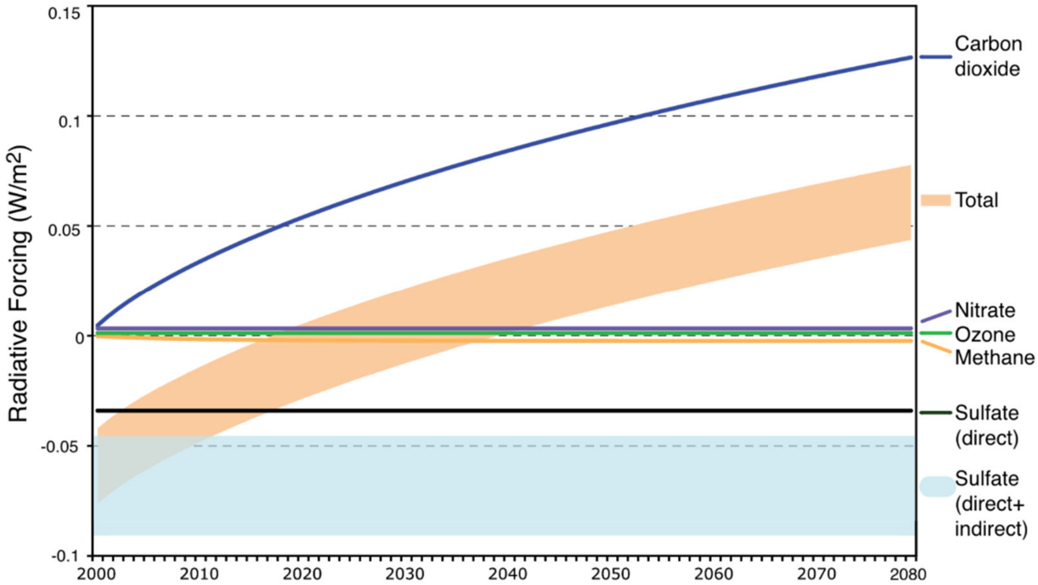

Figure 2.4 Temporal development of radiative forcing from various emissions of a coal power plant and the total radiative forcing (light orange shaded area). Figure taken from Shindell et al. (2010).

A reasonable question regarding the climate impact of a power plant could be framed as follows:

What is the future climate impact resulting from the operation of the power plant during its useful life?

From this question, an appropriate emission development, climate indicator, and time horizon can be deduced (see also Grewe and Dahlmann, 2015):

<u>Choice of emissions development</u>

Since the average useful life of a powerplant is 50 years, a sustained (constant) emission scenario for 50 years seems to be a reasonable choice, as the power plant is continuously used.

<u>Choice of time horizon</u>

The question refers to a *future climate impact* resulting from *its useful life*. Hence, this limits the value of time horizon to 50 years or even longer, considering that "*future climate impact"* refers to a time after the end of operation, e.g. to 100-year time horizon. Note that there is no a fixed value and any value between 50 and 100 years would be a reasonable choice.

<u>Choice of climate indicator:</u>

Since the question addresses future climate impact, an indicator based on near-surface temperature change would be a reasonable choice. Considering that the sign of the temperature response changes in this example, a temporal mean is a suitable solution, as it accounts for both the cooling in the first 20 to 40 years and the subsequent warming. Alternatively, a mean or integrated RF (e.g. GWP) would also serve the purpose.

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Choice summary:

> These considerations lead to the selection of climate metrics such as the average temperature response over, for example, 100 years (ATR100) or the integrated radiative forcing over 100 years (AGWP100), based on a 50-year constant emission (see Section 3 for details about these metrics).

If we now relate the example to applications in aviation, especially for Clean Aviation, we could pose a question:

What is the future climate impact resulting from a new aircraft during its useful life?

For the assessment of this technology, its impact on temperature change over its typical lifetime can be analysed over the next 100 years. For instance, a period of 32 years can be considered for the emission development, while the average temperature response (ATR) over a 100-year time horizon serves as the climate indicator.

2.3 Equivalent CO_2 emissions

In order to compare individual technology options, the values of the climate metric (*CM*) can be used or a more tangible unit that is the equivalent CO_2 emission. The conversion of any emission into CO_2 equivalents requires a climate metric (see Section 2.1). Having clarified the addressed question and deduced a reasonable climate metric that consists of an emission development, climate indicator and time horizon (see again Section 2.1), both a value for a normalized CO_2 emission of e.g. 1 ton of CO_2 ($CM_{norm}^{CO2} = \frac{CM^{CO2}}{CO2}$) and the total value can be determined that includes all CO_2 and non-CO_2 effects (CM^{tot}), which leads to a conversion factor and equivalent CO_2 emissions (*eqCO2*) of the regarded technology with the CO_2 emission (*CO2*):

$$eqCO2 = \frac{CM^{tot}}{CM_{norm}^{CO2}}$$

Note that both *CO2* and *eqCO2* are units that are already often traded.

The above conversion factor CM_{norm}^{CO2} is calculated once (independent from the aircraft emission). It only depends on the climate metric and the assumptions of the background concentration of CO_2. Therefore, this approach is equally applicable for technologies that do not emit CO_2, e.g. hydrogen powered aircraft as long as the details in the climate metric such as the temporal evolution of the emissions and time horizon is unchanged (see also recommendations on "*Challenging the technology impact*" in Section 6.2).

As an example, we consider a regional aircraft that is fuelled with kerosene and compare it with a hydrogen regional aircraft. Both with the same date of entry into service and temporal evolution of the fleet and hence emission rates. For the kerosene case, we have a CO_2 emission of 12 ktons and a value of the ATR100 of 8 and 15 mK for only CO_2 and CO_2 plus non-CO_2 effects, respectively[3]. For the hydrogen case we get a H_2 emission of 14 ktons and a value of the ATR100 of 4 mK. Hence for the kerosene aircraft we obtain:

[3] Numbers are for illustrative purpose, only

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$12\ ktons\ CO_2\ \equiv\ 15\ mK$ for CO_2 and non-CO_2 effects

$12\ ktons\ CO_2\ \equiv\ 8\ mK$ for CO_2 alone,

which gives a CO_2 equivalent emission of

$$12\ ktons\ CO_2 \frac{15\ \text{mK}}{8\ mK} = 22.5\ ktons\ eCO_2.$$

For the hydrogen aircraft, we obtain $14\ ktons\ H_2\ \equiv\ 4\ mK$,

which gives a CO_2 equivalent emission of

$$12\ ktons\ CO_2 \frac{4\ \text{mK}}{8\ mK} = 6\ ktons\ eCO_2.$$

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3. EXISTING CLIMATE METRICS

There are many different climate metrics proposed in the literature. Figure 3.1 provides a schematic overview of the most commonly climate metrics used in aviation. Among these metrics, the radiative forcing (RF), RF index (RFI), and Global Temperature-Change Potential (GTP) are endpoint metrics as they consider the impact only at a specific time horizon *H*. The Global Warming Potential (GWP) as well as its modifications and the Average Temperature response (ATR) are integrated metrics measuring the cumulative impact of emissions from emission time t_0 to t_0+*H*.

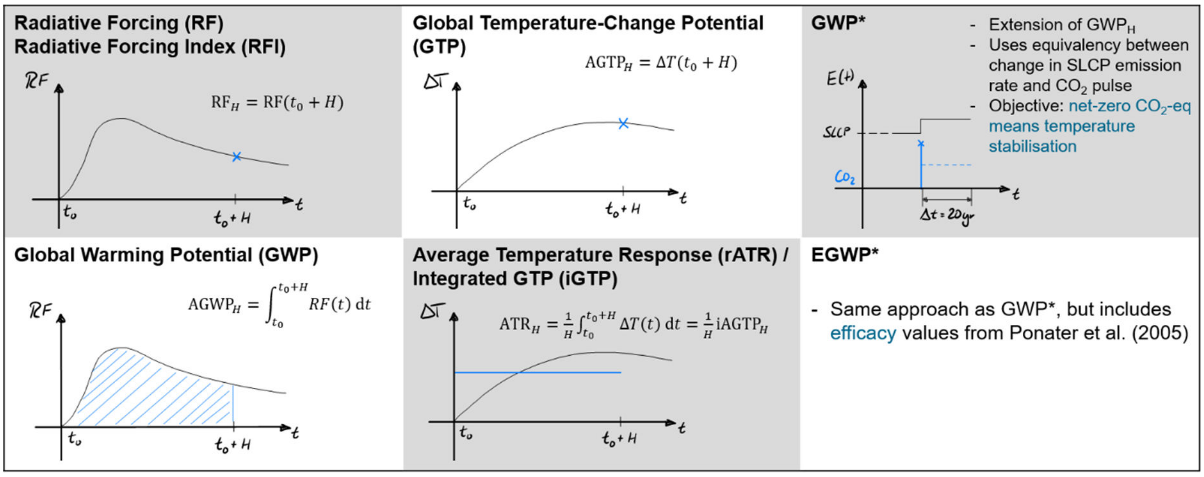

Figure 3.1: Schematic overview of the most commonly used climate metrics. Absolute climate metrics are denoted with "A" (e.g., AGWP) and relative metrics are denoted with "r" (e.g. rATR).

Additionally, climate metrics can be absolute, also referred as dynamic, or relative. Some common uses of absolute climate metrics are climate policy evaluation, sectoral emission analysis, regulatory compliance, impact assessment of mitigation scenarios[4]. Relative metrics evaluate the impact of emissions to that of a reference gas, usually CO_2. They are used for calculations of CO_2 equivalent emissions that have wide applications such as in multi-gas emission trading schemes, for informing policy decisions and monitoring performance of the aviation industry towards climate goals.

In the following, we discuss these climate metrics in more detail.

3.1 Radiative Forcing

Radiative Forcing (RF) is a very important concept for climate metric design. It describes an annual mean change in the atmospheric radiation budget that eventually will lead to an equilibrium temperature change (ΔT). Figure 3.2 illustrates how the RF definition has evolved over time to best fit the linear relation between RF and the resulting equilibrium temperature change (see Sect. 1.2). Nowadays, rapid atmospheric adjustments, such as stratospheric

[4] The absolute metrics (AGWP and AGTP) may be more suitable in policy-making than relative metrics for impact assessment of various emissions over time (Ziegler et al. 2025).

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temperatures and cloud changes are considered in the calculation of the RF leading to the adjusted RF (stratospheric temperatures) and effective radiative forcing (ERF, stratospheric temperatures and other processes like cloud changes). Those adjustments are occurring over timescales of hours to a few months and exclude changes driven by changes in ocean temperatures. Feedbacks that arise from changes of surface, especially ocean temperatures have the potential to largely change the atmospheric properties such as stability, clouds etc. This slow feedback is considered in terms of efficacy.

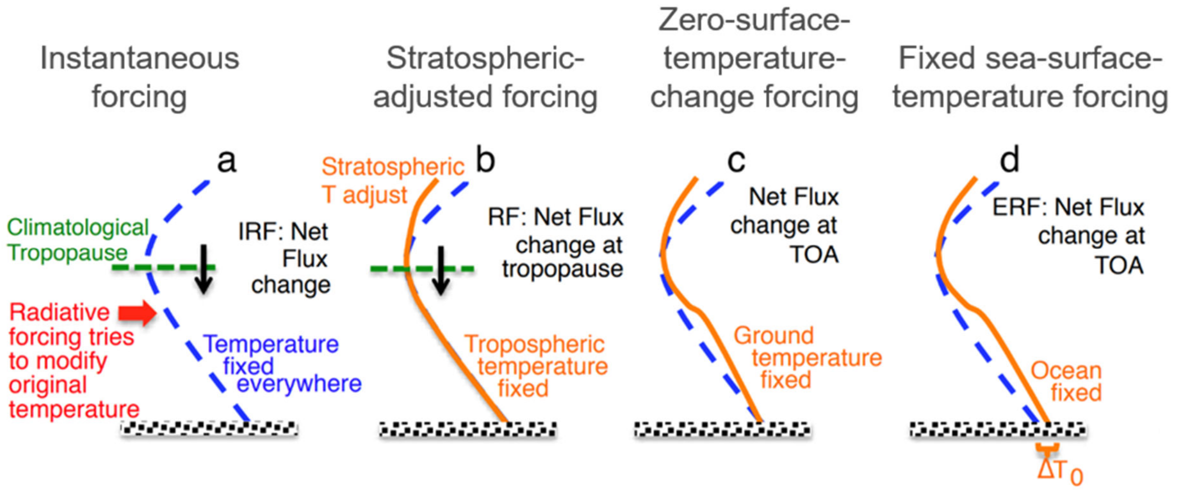

Figure 3.2 Schematic illustration of various concepts of radiative forcing: instantaneous, adjusted, and effective radiative forcing. Adopted from IPCC (2013).

3.2 Global Warming Potential (GWP)

The Global Warming Potential is traditionally defined as the temporal integration of RF caused by a unit pulse of an emission species relatively to that of CO_2. It is the most commonly used climate metric in climate policies and assessment reports (e.g, Rodhe 1990, Fuglestvedt et al. 2003, Shine et al. 2007, IPCC 2007, IPCC 2013). It is most commonly used with 20-, 50-, and 100-year time horizons. The Global Warming Potential (GWP) metric has gained significant acceptance among policymakers due to its perceived transparency and ease of application, which stem from its straightforward calculations and widely available data.

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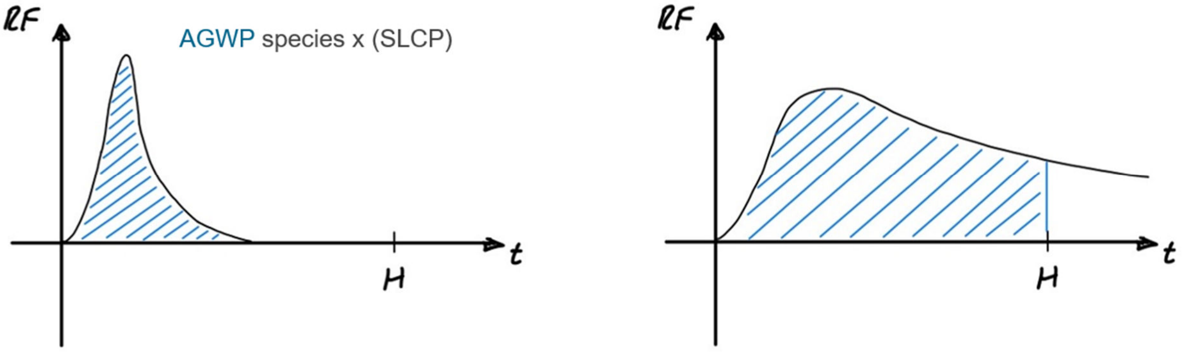

Figure 3.3: Schematic illustration of the AGWP concept for a pulse emission that represents the temporal integral (blue shaded) and the role or the time Horizon H. Left: The integration of the RF from a pulse emission of short-lived climate forcers is covering the whole perturbation. Right: A pulse of CO_2 emissions has an impact on CO2 concentration and thereby associated RF that continues after the time horizon H.

3.3 Efficacy-weighted Global Warming Potential

The Efficacy-weighted Global Warming Potential (EGWP) is the derivative of the GWP metric which proposed by Megill et al (2024) with the goal of aligning the outcome of impact assessment closer to the temperature-based climate metrics. This approach introduces the efficacy of non-CO_2 emissions in the GWP methodology as follows

$$\mathrm{AEGWP}_{i,H} = r_i \int_{t_0}^{t_0+H} RF_i(t)\,\mathrm{d}t$$

where r_i is the efficacy of aviation component *i* defined as the ratio of the climate response (in terms of temperature change) to this component compared to the climate response to an equivalent increase in CO_2, hence including adjustments and slow feedbacks of the climate system. Table 3.1 shows the values for sensitivity parameters and corresponding efficacies determined from ECHAM4 equilibrium climate change simulations derived by Ponater et al (2006).

Table 3.1 Climate sensitivity parameters (λ, in K/(W m^{-2})) and efficacies (r) for aviation components

	CO_2	O_3	CH_4	H_2O	Contrails
λ	0.73	1.00	0.86	0.83	0.43
r	1.00	1.37	1.18	1.14	0.59

3.4 Global Temperature Change Potential

The Global Temperature Change Potential (GTP) is a metric used to quantify the change in the average near-surface temperature at a time horizon (Shine et al. 2005, Fuglestvedt et al. 2010). It is by definition an endpoint metric. It includes more physical processes compared to

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the GWP, therefore it is more appropriate for temperature-based climate goals such as those outlined in the Paris Agreement.

However, the GTP metric has raised several critical concerns. One major issue is its strong dependence on the chosen time horizon. Economists have criticized it for only accounting for the well-being of individuals alive at the endpoint, neglecting the long-term climate impacts that may extend beyond the temperature goal. This limitation is not unique to the GTP metric, as it is a common challenge faced by other climate metrics as well, and remains an unresolved issue.

3.5 Average Temperature Response

The Average Temperature Response (ATR) metric was designed by Dallara et al. (2011) specifically for comparing the climate impacts of different aircraft designs and technologies rather than for policy decision-making. This metric quantifies the global mean temperature change caused by the operation of an aircraft. It has been initially defined as (Dallara et al., 2011):

$$\mathrm{ATR}_H = \frac{1}{H}\int_0^{\infty} \Delta T_{sust,H(t)} w(t)\,\mathrm{d}t,$$

where $\Delta T_{sust,H(t)}$ refers to the time-varying global mean temperature change caused by *H* years of sustained operation of a particular aircraft and $w(t)$ refers to the weighting function designed to account for depreciation effects. Initially, sustained (constant) emissions over the lifetime of a single aircraft (30 years) were considered.

Recently, it has been commonly defined simply as an average temperature over a time horizon *H* (Grewe et al. 2014, Dahlmann et al. 2016, Megill 2022, and Proesmans and Vos 2022)

$$\mathrm{ATR}_H = \frac{1}{H}\int_{t_0}^{t_0+H} \Delta T(t)\,\mathrm{d}t.$$

3.6 GWP* and extended GWP*

The GWP* is another modification of the conventional GWP introduced by Allen et al (2018) and aimed to account for the important effect that short-lived pollutants such as CH_4 may have on the temperature change in the near future. It is a "flow-based" method designed to equate the climate impact of SLCPs and long-lived climate pollutants (LLCPs) using "warming-equivalent" emissions. The key distinction between LLCPs and SLCPs is that the radiative forcing for the former scales with the GWP owing to the CO_2 accumulation. In contrast, the RF from SLCPs scales with the flow (emission rate) times their atmospheric lifetimes (Allen et al

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2018). While conventional equivalent CO_2 is calculated as $\mathrm{GWP}_H \times E_{\mathrm{SLCP}}$, equivalent emission under GWP* is defined by the change in the SLCP emission rate $\frac{\Delta E_{\mathrm{SLCP}}}{\Delta t}$

$$E_{\mathrm{CO_2-e^*}} = \mathrm{GWP}_H \times \frac{\Delta E_{\mathrm{SLCP}}}{\Delta t} \times H,$$

where GWP_H is a the standard GWP value for the SLCP for the time horizon H. Figure 3.4

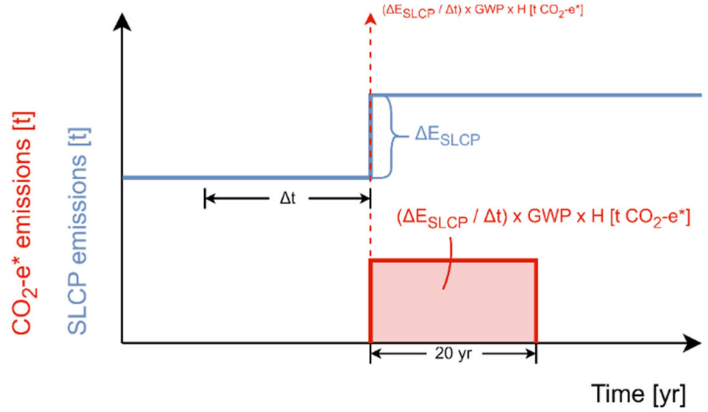

Figure 3.4 Illustration of the GWP* concept. The blue line shows a step increase in the SLCP emissions and the red line represents the respective eqCO2-e* equivalent emission defined using the climate metric GWP* with Δt=20 years.

In application for contrails and NO_x-induced effects (O_3, Primary Mode O_3, and long-term CH_4) from aviation, it is meaningful to define the CO_2 equivalence based on radiative forcing rather than emission rate. Using GWP* metric, the warming equivalent $E_{\mathrm{CO_2-we^*}}$ (also denoted as CO_2-we*) is defined as

$$E_{\mathrm{CO_2-we^*}} = \mathrm{GWP}_H \times \frac{\Delta RF_{\mathrm{SLCP}}}{\Delta t} \times \frac{\mathrm{H}}{\mathrm{AGWP}_{H(\mathrm{CO_2})}},$$

where $\mathrm{AGWP}_{H(\mathrm{CO_2})}$ is the absolute GWP of a CO_2 pulse at the horizon *H*.

The "extended" GWP* is an evolution of the original GWP* metric designed to better represent the warming impact SLCPs over time (Cain et al. 2019, Smith et al. 2021). The extended GWP method combines both the rate of change in SLCP emissions (or forcing, for effects like contrails or NOx in aviation) and the existing stock of those emissions/forcings. The warming-equivalent emission using this method is calculated as

$$E_{\mathrm{CO_2-we}} = g \times \left[(1-s) \times \frac{\Delta RF_{\mathrm{SLCP}}}{\Delta t} \times \frac{H}{AGWP_{H(CO_2)}} + s \times \frac{\overline{RF}_{SLCP}}{AGWP_{H(CO_2)}}\right],$$

where s is the fraction of the stock term, g is a function of s introduced to improve consistency with the linear models used for climate metric calculations, $\overline{RF}_{SLCP}$ is the running average of RF.

Figure 3.5 compares the modelled temperature change from methane emissions CO_2 and the respective equivalents derived with the conventional GWP_{100}, warming equivalents (GWP*

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flow) and improved warming equivalents (GWP* flow and stock). The extended GWP* represents the temperature change best compared to GWP_{100} and GWP*.

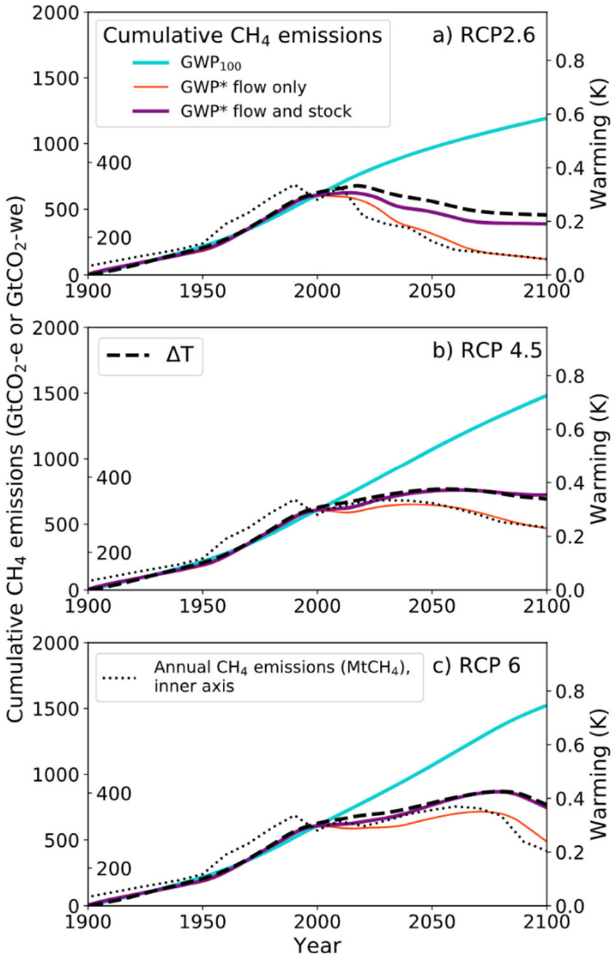

Figure 3.5 Cumulative methane emissions (dotted line) and the respective temperature change (dashed line) is given for three future scenarios (a-c). The coloured lines represent the estimated temperature change based on climate metrics, showing that the extended GWP* (thick magenta) represents the temperature change best compared to GWP100 (cyan) and GWP* (orange) (from Cain et al. 2019).

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4. REQUIREMENTS OF A CLIMATE METRIC

In preceding sections, we discussed various climate metrics and the importance of carefully considering the choice of a climate metric. We already have addressed in Sec. 3 that not all climate metrics are equally well suited to answer a research question or a political objective. In addition, we believe that even more requirements can be formulated and the climate metrics can be tested against those. This allows for the reduction of applicable climate metrics to a select a few that are suitable for the objective discussed here, which pertains to the climate impact assessment of aviation technologies. We propose to follow the work by Megill et al. (2024), who applied exactly this approach. The requirements outline therein are largely based on literature, with the exception of one requirement (neutrality, see Sec. 4.1 for more details) that includes the requirement of consistency between the results of a climate metric and a more detailed scenario analysis. The important achievement in the work by Megill et al is the stringent testing method (Sec. 4.1). Another requirement is the temporal stability (Sec. 4.2), meaning that a change of the time horizon of a few years should not lead to principle changes. A metric for assessing the climate impact of aviation emissions should be able not only to quantify atmospheric response to emissions, but also to effectively communicate its implications to stakeholders, i.e. being easy to understand (Sec. 4.4.) and to ensure consistency with existing policies (Sec. 4.3). Hence the recently formulated set of requirements by Megill et al., (2024) for evaluation of climate metrics for aviation sector:

- Neutrally represent the chosen climate indicator including the consistency with scenario assessments
- Be temporally stable
- Be compatible with existing climate policy
- Be transparent and simple to understand and implement

In the following, we will discuss each requirement in detail and results of evaluation of metrics against these criteria.

4.1 Climate metric neutrality

The first requirement is the neutral evaluation of the climate metric. It means that the difference in the climate impact between two aircraft concepts assessed with climate metrics should have the same sign as the difference assessed with an emission scenario calculation. In other words, it should not be biased towards a specific technology, hence being neutral in this way. This means that the value of a climate metric should have the same sign as the peak temperature change, for example. We select the peak temperature as an indicator to align with the Paris agreement's goal of limiting global surface temperature rise to 1.5 or 2°C. Note that Megill et al. also tested the mean temperature change instead of the peak value, which resulted in the same findings. Since the agreement does not specify a target year, our focus is on preventing temperature from exceeding a specific threshold, making the peak temperature change the best choice. Alternatively, one could use average temperature over the next x years, if we assume that the 1.5 or 2°C target will be exceeded within the same x

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years. In contrast, temperature at a time horizon is not suitable for our purpose, as it only represents conditions for endpoint metrics (e.g., GTP) and not, for example, for the GWP100 which describes total impact over a period.

The major advancement in the work by Megill et al. is the stringent testing of the climate metrics especially against this requirement. To assess climate metric neutrality, a Monte Carlo simulation was carried out in which the following parameters were randomly varied within the specified limits to mimic different technologies: fuel consumption, NO_x emission, flight altitude, contrail distance, fuel type, year of fleet introduction and background concentration. The ranges of the parameter changes are given in Table 4.1 and Table 4.1.

Table 4.1 Ranges of fleet design parameters in Monte-Carlo simulations

Parameter	Range	Reference	Minimum	Maximum
Fuel burn (40% of category) [Tg]	70 - 100%	100%	70%	100%
NO_x emission [Tg]	70 - 100%	100%	70%	100%
Cruise pressure [hPa]	80 - 120%	100%	120%	80%
Contrail distance modifier [km]	40 - 100%	100%	40%	100%
Fuel used [-]	Jet-A1, SAF, H_2	Jet-A1	H_2(FC)	Jet-A1
Year of fleet introduction [yr]	2030 - 2050	2030	2030	2030
Background emissions [-]	SSP1 - SSP5	SSP2-4.5	SSP2-4.5	SSP2-4.5

Table 4.2 Assumed changes in in-flight emissions and effects for three fuel types

Fuel	CO_2	NO_x	H_2O	Contrails	Total
SAF	-65-80%[1]	-0%	-0%	-10-40%	-30-60%
Hydrogen combustion	-100%	-50-80%	+150%	-30-50%	-50-75%
Hydrogen fuel cell	-100%	-100%	+150%	-60-80%	-75-90%

Figure 4.2 shows temperature response for emissions from the designed fleet. The peak temperature change (*ΔT*) and the climate metric values (*CM*) are then compared for arbitrary pairs (fleet 1 and fleet 2). If both *CM* and *ΔT* differences have the same sign, a neutral evaluation is assumed. The condition for neutral evaluation is then

$$(CM_2 - CM_1) \times (\Delta T_2 - \Delta T_1) > 0$$

If the differences have different signs (upper left and lower right red boxes in Figure 4.2), the result is an incorrect fleet pairing.

In order to compare neutrality of the metrics, the total number of incorrect fleet pairs was then calculated for each metric for different values of the time horizon (Figure 4.3).

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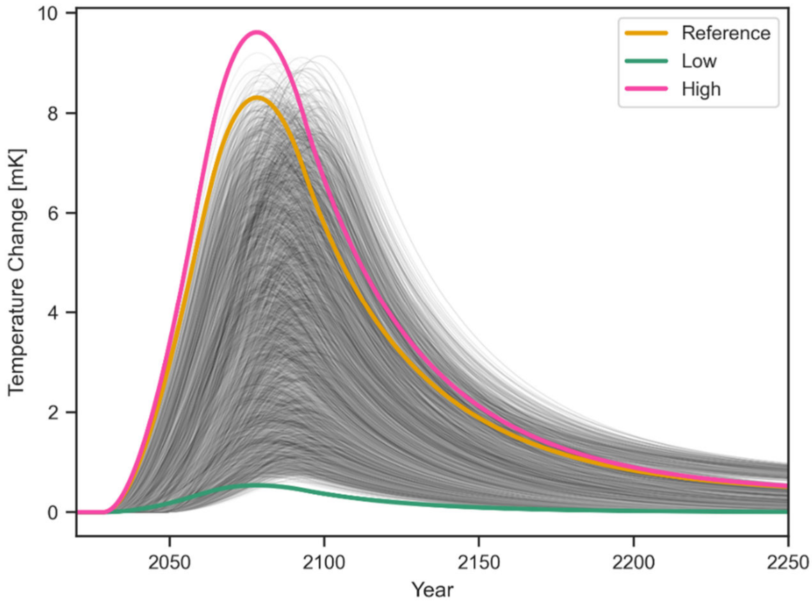

Figure 4.1 Temperature change for various fleet pairs in the fleet-pairing analysis (from Megill et al., 2024).

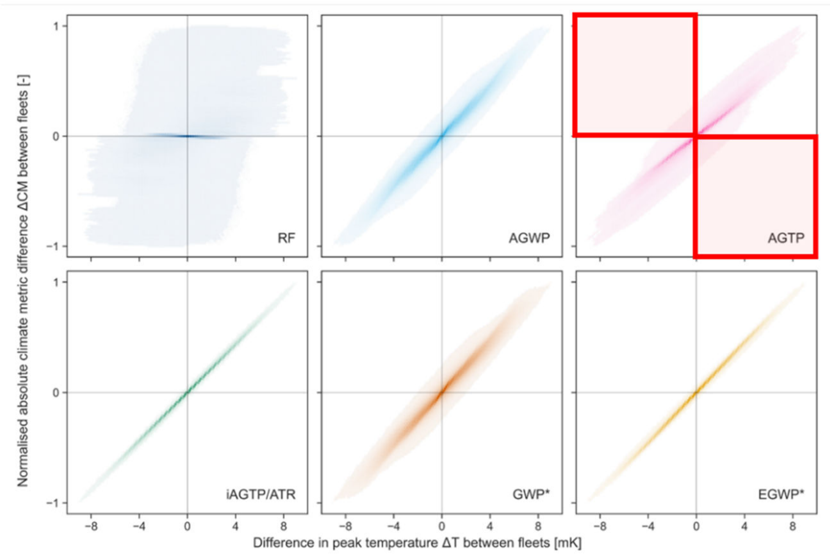

Figure 4.2 Normalised absolute metric difference for the arbitrary fleet pairs vs. the difference in the peak temperature change for selected climate metrics. Red squared in the plot for the AGTP mark the areas in the fleet pair is identified as incorrect. The same criterium is applied for all considered metrics. (adapted from Megill et al., 2024).

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The fleet pairing analysis of metric neutrality leads to the following conclusions regarding the considered metrics

- **RF**: strongly dependent on the temporal emission development, is ill-suited at higher time horizons; this metric could even incentivise higher NO_x emissions since warming from short-term O_3 increase has dissipated
- **AGTP**: similar to another end-point, RF, highly dependent on time horizon H; fully dependent on the shape of the fleet temperature profile
- **AGWP** and **GWP***: largely independent of *H*, particularly for *H* > 60 yr, but have a higher error frequency than temperature-based metrics
- **ATR**, similarly to **iAGTP** and **AEGWP** metrics: less dependent on time horizon than the AGTP, but still has a clear minimum in the error frequency
- **EGWP***: **ideal behaviour** for a climate metric in this context, because the EGWP* method used in this study is a direct proxy for the peak temperature. This metrics has the best performance wrt. neutrality requirement.

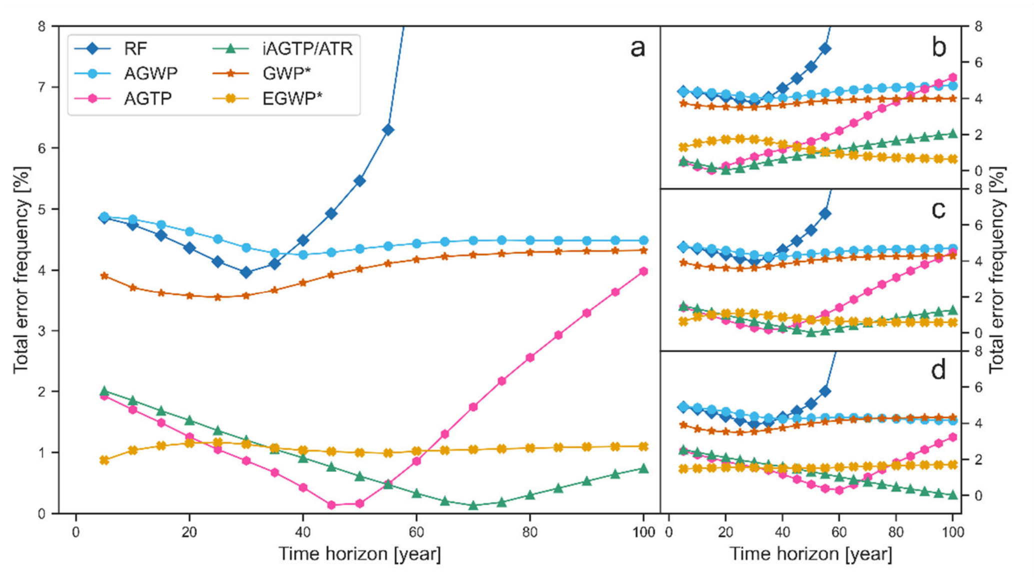

Figure 4.3 Frequency of incorrect fleet pairs as a function of time horizon for the peak temperature (a) and 20-, 50- and 100-year average temperature (b-d) climate objectives (from Megill et al., 2024).

4.2 Temporal stability

Another requirement for a climate metric is stability over time, which refers to its ability to represent climate impacts accurately and consistently over different time periods. A different name of this requirement, referred to as “Insensitive to small changes in the time horizon”, is discussed in Sect. 6.2. This evaluation considers performance of climate metrics in accounting CO_2-eq emissions across the entire aviation industry at the policy level.

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Here, we analyse how the CO_2 equivalent emissions calculated for two different scenarios (CORSIA and FlightPath (FP2050)) change over time. Figure 4.4 shows temporal evolution of fuel use in these scenarios. The resulting temporal trajectories of CO_2-eq are presented in Figure 4.5. The RFI, GWP, EGWP, GTP and ATR climate metrics show relatively similar trends, while GWP* and EGWP* show significantly decreasing CO_2 equivalents for CORSIA from 2035 and even clearly negative values for FP2050. This would suggest that aviation is contributing to cooling here, although only emissions are falling.

A notable feature of Figure 4.5 is that GWP and ATR produce similar results for the total CO_2-eq. This may reduce the political capital required for moving from using GWP to ATR. This is also found by Niklaß et al. (2019). The very close similarity is likely model-dependent due to the relative importance of different emission species impacts (primarily NO_x and contrails) to the total.

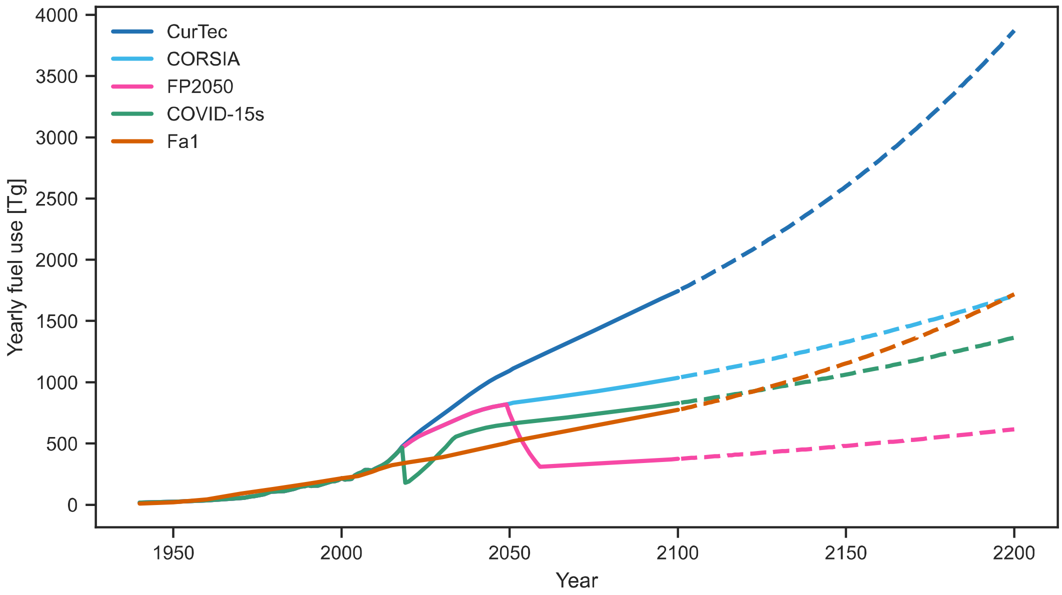

Figure 4.4 Fuel scenarios adapted from Grewe et al. (2021).

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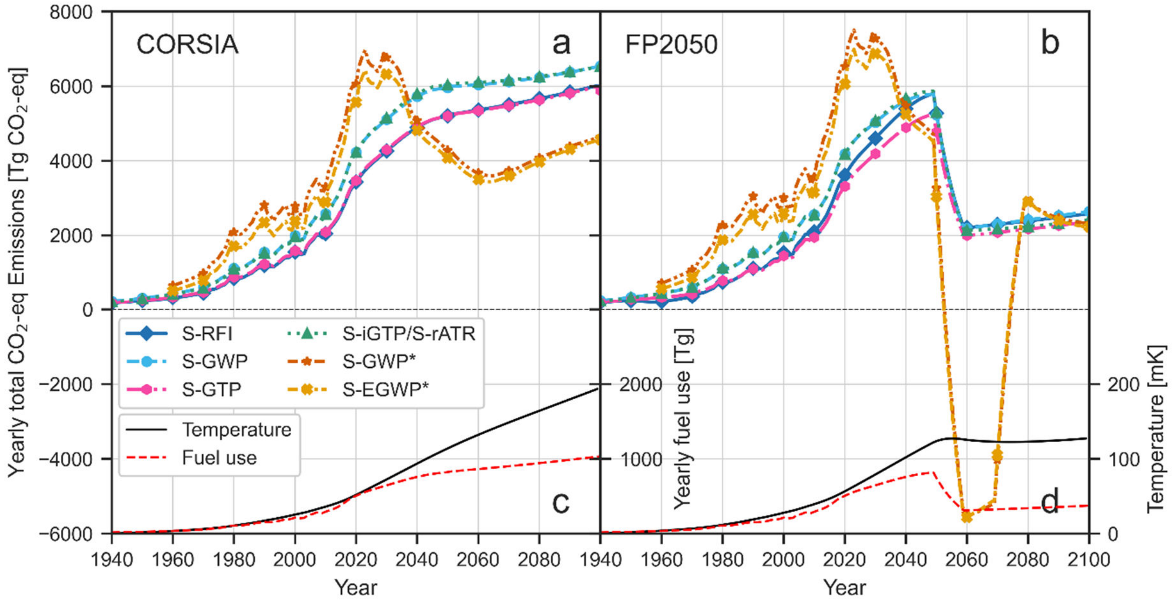

Figure 4.5 Temporal development of CO2-eq emissions for different climate metrics calculated with AirClim 2.0 for CORSIA and FP2050 emission scenarios. Temperature and fuel use are shown in the bottom panels.

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4.3 Compatibility with climate policy

It is important that climate metrics are compatible with existing climate policy frameworks, which have been established primarily on the GWP metric. We consider metrics compatible with climate policy if they can provide the same functionality as the GWP. In the context of aviation, this stipulates that a metric should be able (1) to calculate the temporal trajectories of CO_2-eq emissions; and (2) to calculate single values for fleets and individual flights to provide the possibility to introduce aviation non-CO_2 emissions into the ETS. All conventional climate metrics – RF, GWP, GTP, iGTP and ATR – can provide this functionality and hence can be used in existing climate policy. It is however not the case for GWP* and EGWP* metrics.

The GWP* method is designed to provide a continuous assessment that reflects ongoing changes in emissions and their immediate impacts. These metrics effectively have a second time horizon (e.g. 20 years), which represents the period during which changes in the flow are considered. The GWP* is itself essentially a micro climate model rather than a ready-to-use policy metric (cf. Meinshausen et al., 2022). Figure 4.6 illustrates flow-based nature of the GWP* closely following changes in the emission rate. A study conducted by Schleussner et al. (2019) find that applying GWP* directly to interpret the goals of the Paris Agreement can lead to profound inconsistencies in its mitigation architecture.

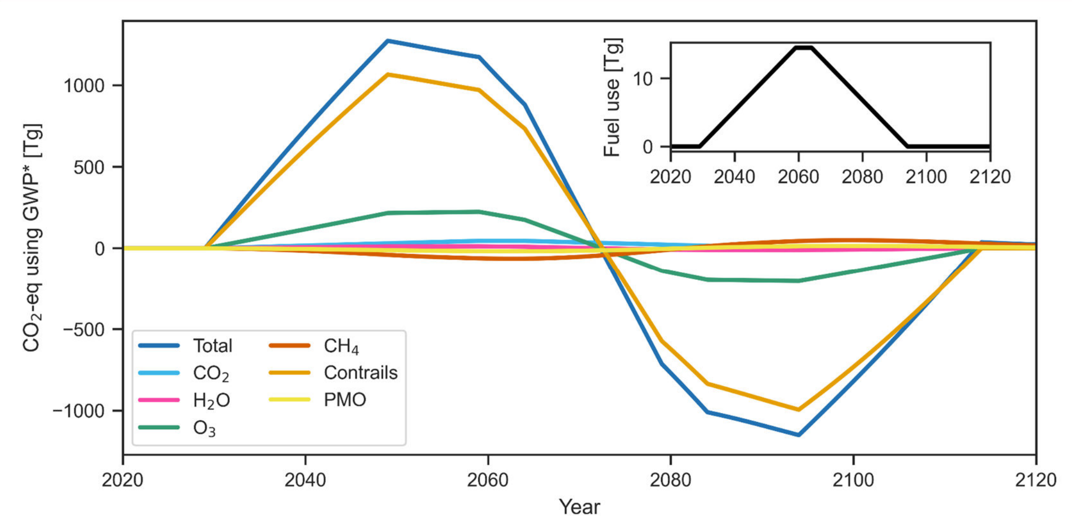

Figure 4.6 Illustration of flow-based nature of GWP*. The inset shows temporal profile for the fuel use and color lines show respective CO_2-equivalent emissions for each species and total derived using GWP^*_{100} metric (from Megill et al. 2024). Results are shown for an example fleet. Negative CO_2 equivalent s correspond to the decreasing emission rates of the fleet.

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4.4 Climate metric transparency

For climate metrics to be accepted and effectively used by non-specialists and in policy application, they should be as easy to understand and to implement as possible. Endpoint metrics like RF and GTP are the easiest to understand as they indicate the climate effect at one single given point in time (see introduction in Sect. 3). The RF is considered more transparent and somehow less model-dependent than temperature-based metrics. It is also more straightforward than calculating the climate response. The GTP, while further down the cause-effect chain than RF (Figure 2.1), is more complex to implement because it requires additional parameters like climate sensitivity. The major criticism of these metrics is their strong dependence of time horizon (Sec. 4.2).

Integrated metrics are more complex to understand, in particular, to ascertain the roles of individual emissions in the impact. Their calculation requires to average or integrate over a dedicated time horizon. Among integrated metrics, the GWP represents cumulative RF and is therefore most straightforward to understand. The simplicity in understanding together with an easy calculation method and availability of data needed for its calculation are the causes of continuous use of the GWP in policies and assessments, despite a lot of criticism.

The concept of ATR metric as an average global temperature response is relatively simple to understand for non-specialists, whereas the iGTP defined similarly to the ATR has units of $\mathrm{K} \times year$, which are less intuitive to understand. Similar to the GTP, these temperature-based metrics include uncertainties associated with climate modelling.

The GWP* and EGWP* are the least transparent and simple climate metrics. Their use requires in-depth understanding of the equivalency between changes in SLCP emission rates and a CO_2 pulse. It can be difficult to understand the response even to simple emission profiles. As for implementation, it is more complex than other metrics, because they require a value of the AGWP for CO_2 pulse that has to be calculated for each scenario. Moreover, the method requires a temporal emission profile twenty years preceeding the considered time span for integrated or horizon time for endpoint metrics. It is therefore considered less suitable as a climate metric for policy applications.

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5. Summary, conclusion and recommendations for the climate metrics overview

Here we draw a first conclusion of the climate metrics overview and give recommendations that were in the successive step evaluated by external stakeholders in the CLAIM workshop (Section 6).

Since all climate metrics simplify complex atmospheric processes and involve value judgments regarding time horizons and metric form (e.g., end-point or integrated), they inherently contain trade-offs and can thus favour certain aircraft designs over others. Consequently, the choice of climate metric is always the result of a trade-off. An overview of the performance of the considered physical climate metrics with respect to the identified requirements is presented in Table 5.1. It shows the ratings of how well each metric satisfies respective criteria, from +++ ("very high") to "---" (very low). The ranking scale is arbitrary chosen for illustrative purpose.

Performance of metrics wrt. the neutrality criterium is based on the fleet-pair analysis (see analysis of Figure 4.3 in Sect. 4.1). Metrics with high neutrality should have low values of the total error frequency that are also largely independent of time horizon and thus emission scenario. Such metrics represent well the chosen indicator, which is the peak (average) temperature in the considered case. The EGWP metric shows the best results wrt. this condition and therefore is assigned "very high" neutrality score. The end-point metrics RF and GTP are strongly dependent on time horizon, so they are placed on the opposite end. The ATR and iAGTP show lower values of the total errors compared to GWP and GWP* indicating higher neutrality than these metrics.

As for the requirement of temporal stability, all considered metrics, except flow-based metrics (GWP* and EGWP*), indicate similarly good results for the considered full aviation scenarios. The GTP and RFI metrics are ranked less stable than iGTP, ATR and GWP because of an additional test that compares responses to a pulse versus a constant emission. The GTP and RF struggle to provide qualitatively similar responses for certain time horizons (Dahlmann 2011).

The compatibility with existing climate policy is evaluated in terms of proving the same functionality as the generally used GWP metric (Sect. 4.3). We assign "0" to metrics that are compatible. The RF is assigned "-" as it is less suitable for temperature-rise limiting goals outlined in Paris agreement than temperature-based metrics or EGWP. The analysis of temporal trajectories of CO_2-eq emissions indicates that starred metrics do not provide the same functionality as the GWP. Moreover, using the GWP* to interpret the goals of the Paris Agreement can lead to profound inconsistencies in its mitigation architecture. They are hence ranked very low wrt. the compatibility requirement.

Finally, the fourth requirement is judged based on how easy a metric is to understand and implement. It is the most qualitative in the proposed set. The highest rank "++" that corresponds to "easy" in this case belongs to endpoints, which are simply indicators of radiative forcing and temperature at horizon time. The starred metrics are ranked "very low" wrt the transparency requirement for several reasons. In comparison to other metrics, they require more effort from a non-expert to understand as well as to implement. This includes understanding of equivalences between a CO_2 pulse and change in ongoing emission rates and additional data that depend on emission scenario.

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Overall, this table indicates that both the ATR and EGWP metrics have the highest ratings compared to the rest of metrics and thus represent options that meet all four requirements at least an "acceptable" level. Therefore, we evaluate ATR and EGWP as overall good compromises. Based on this analysis, we recommend the use of ATR and EGWP metrics, depending on the specific needs of policymakers.

Whilst the ATR as a temperature-based climate metric has the potential to include more climatic processes and be more relevant for temperature-based targets than the GWP, the larger number of assumptions and uncertainties must also be considered. The EGWP may, therefore, be a useful compromise for policymakers, as it can more accurately represent climate impact of aviation whilst still using the GWP methodology (Megill et al., 2024). The time horizon should be greater than 70 years for aviation policy and aircraft design. Determining the appropriate time horizon remains a challenge. However, since sensitivity decreases with larger time horizons – we generally recommend using time horizons of over 70 years. To be consistent with existing policy, a 100-year horizon is appropriate. If a low time horizon is chosen, policymakers have to be aware of the potential consequences, provide sufficient justification for the choice and potentially also produce values for different time horizons. The total CO2-eq emissions calculated by the ATR100 and EGWP100 for current aircraft are similar and would enable a timely introduction of the ATR in aviation policy. This would allow a more accurate assessment of novel aviation fuels and aircraft designs in the future.

Table 5.1 Evaluations of climate metrics against the requirements. Evaluation of how well a metric satisfies the respective criterium ranges from +++ ("very high") to "---" (very low).

Climate Metric	Neutrality	Stability	Compatibility	Transparency
RF	---	-	-	+
GWP (reference)	0	0	0	0
EGWP	++	0	0	0
GTP	-	-	0	+
iGTP	++	0	-	-
ATR	++	0	0	-
GWP*	0	---	---	---
EGWP*	+++	---	---	---

Recommendation:

As stated above, there is no general best climate metric, nevertheless the trade-off analysis enables a choice of a metric to be recommended for the use in Clean Aviation impact

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assessments. Note that this choice is preliminary and might me adapted over time, e.g. after considering the feedback from the climate metric workshop participants.

Referring to Section 2.2 the underlying question is

What is the future climate impact resulting of a new aircraft during its useful life?

and a climate metric that acceptably fulfils the set requirements is a life-cycle emission scenario combined with ATR100 or as stated above the EGWP may be a useful compromise for policymakers.

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6. Feedback from the Climate Metrics & Impact Assessment Workshop

On 17 and 18 June 2024, a workshop on climate metrics was held by the CLAIM project in Hamburg, which involved scientific community and stakeholders. It allowed an in-depth exchange on requirements, elements and methodologies for providing a technology assessment of CO_2 and non-CO_2 effects. In general, a climate impact assessment of technologies has two major areas to be considered, the choice of the climate metric and the method of assessing technologies with respect to its climate impact. CLAIM is addressing both, provides solutions and yields feedback from external stakeholders in dedicated workshops. Here, we give a brief overview on the CLAIM workshop on climate metrics, which is the 2nd CLAIM workshop and summarise the outcome. The basis of the workshop was the paper by Megill et al. (2024) that established a framework for assessing climate metrics against requirements.

6.1 Workshop description

Workshop objective

The 2-day workshop was dedicated to obtain feedback on

1. the list of (weighted) requirements that a climate metric should consider
2. the procedure on how climate metrics can be tested against those requirements
3. the research gaps that are associated with the choice and usage of climate metrics
4. the implications of a climate metric choice on the technology assessment

Workshop outline

In order to address those four objectives, introductory talks were given on the first day to

1. recap the definition of climate metrics (see Section 3) and the work by Megill et al., especially the identification of requirements for climate metrics and the test environment
2. represent work from outside CLAIM (IPSL Paris/University Reading) on the impact of climate metrics
3. the usage of climate metrics in technology assessment from outside CLAIM (TU-Delft).

On the second day, feedback was requested in the format of world cafés with a guidance on main questions (see appendix) and supported by a CLAIM participant as a facilitator. Latter summarised the feedback and presented it in a plenary session. This outcome will be presented in Section 6.2.

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Workshop participation

A balanced participation of individuals from industry, academia (EU and US), CAJU, the CLAIM cooperation board and CLAIM participants was targeted and achieved. The participation was by invitation, only, and reconciled with CAJU. Although the workshop was planned in-person, due to time restriction of the participants, the event was eventually held hybrid, with one group of the world café in a purely on-online forum. 32 persons from 14 institutions/institutes attended the workshop.

Workshop feedback

At the end of the workshop a brief feedback on the workshop organisation was inquired. The participants gave a very positive feedback, stating that enough time for discussions were planned and discussion were well guided, though very intense and the separation of the two days with talks on the first day and discussions on the second could have been better mixed to make the event varied. This recommendation will be a guidance for the next workshop on technology climate impact assessment.

6.2 Feedback and recommendations

The feedback and recommendation from the summary of the world café sessions is structured according to the 4 objectives outline in Section 6.1.

Challenging the requirements

- The first requirement in Megill et al. was named “Neutrality” introduced in Section 4.1. This requirement was rated very helpful and most important among all requirements. However, it was recommended to rename it to be easier to understand. “Not prescriptive” or “Representative of temperature change (or scenario)“ was suggested.
- "Be temporally stable” is rated as the second most important aspect. It was recommended to rename this requirement to, for example, “insensitive to small changes in the time horizon”, since all climate metrics depend on the chosen time horizon, which might cause confusion.
- The requirement “Simple to understand (and implement)” was identified as being insufficiently defined since the targeted audience is unclear. In the discussion it became clear that the educated user is meant.
- The participants identified aspects for requirements that are not covered, such as
    a. being in line with the Paris agreement
    b. focus on a longer time horizon (e.g. 100 years)
    c. robustness
    d. possibility to represent or implement new findings
    e. compatibility with all technologies, fuels and species
- Recommendation beyond the assessment of requirements
    a. The non-CO_2 effects are largely non-linear. It is recommended to be at least aware of assuming linearity in responses in assessment methodologies

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b. Efficacy that describes the slow atmospheric feedback that includes e.g. ocean feedbacks should be addressed in the discussion. Whether including or non-including them in climate metrics should be discussed.
c. Every climate metric has some limits in its applicability that should be discussed in more detail.
d. Be clear about objective weighting of factors in metric selection versus subjective value judgments

Challenging the climate metrics assessment

- Generally, the assessment procedure was approved and there was no need for major improvements identified.
- The used error frequency might be revised into a weighted error frequency that considers how wrong a pairing is, rather than a simple count.
- The question came up whether neutrality can be verified and validated?
- It was recommended to include an understanding of the physics behind. Using climate metrics simply as black-boxes might be dangerous.

Identification of research gaps

- Using the uncertainty language of IPCC is recommended. This includes a two-dimensional matrix on a) the physical understanding and b) the number of data available. For example, the impact of the metric choices is well understood, but only limited work is available on assessing the risks (Megill et al., Borella et al.).
- Climate metrics include many assumptions, a thorough understand of their impact is needed
- When should a climate metric be chosen during an evaluation process?
- Efficacies and their effects on uncertainty ranges are only addressed in a limited way in technology assessments
- Technology assessments need to integrate robustness metrics
- Education is required to understand the calculation methods: Guidance for limits and use and Fact sheets.
- Currently no standardization is available, a standard on quality criteria, verification, transparency should be developed
- Benchmarking of a direct comparison with the same aircraft would be useful (fossil vs. SAF vs. H2)
- Are there cases were climate metrics are not the right tool anymore and climate models should be used or time series be analyzed?
- Can a suitability indicator similar to the “nutri-score” be developed?
- If risk associate to the uncertainties in the calculation of the climate metrics is too high, what are the consequences? Should one stay with CO_2 optimizations? What would be the acceptable limit of uncertainty or associated risk?

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Challenging the technology impact

- All CO_2 and non-CO_2 emissions and impacts should be regarded, including NO_X, nvPM, H_2O, SO_X, contrails, UHC, CO, and lubrification oil.
- All climate effects that can be modelled today should be included in the selected climate metric.
- The climate impact allocation of the different species (net soot, net sulphur, net NO_X) needs to be updated
- More clarity on aerosol-cloud interactions / aerosol-radiation interactions required before they can be included.
- The climate metric could be evaluated in a multi-factor multi-dimensional trade-off that also considers several technology metrics like weight reduction, fuel burn reduction, noise. For manufacturers, a risk analysis (e.g. maintenance, climate impact, …) could be included. For (engine) manufacturers this multi-dimensional weighting is intellectual property of the company.
- Climate impact assessment might be part of an overall life cycle analysis.
- Certification standards (and safety) are a must.
- How can technologies with different entry-into-service (EIS) be compared? (e.g. should a technology A with EIS 2025 be compared with the same metric, incl. time horizon like a technology B with EIS 2050?) This question can be interpreted in different ways: If it is about the fleet forecast, the time horizon and the metric should be fixed. If it is a question of product comparison, assumptions need to be taken and possibly exclude the change of background conditions. If it is a question of reaching a climate target, background conditions should be taken into account. Concepts like moving time horizons need more research, but a minimum time horizon of 20 years is advised.
- The technology assessment has an underlying estimate of a route network and emission inventory which was regarded as appropriate. However, feedbacks on the route network through disruptive technologies may exist, though challenging to forecast.
- For hydrogen it is recommended to evaluate the full life-cycle (well-to-wake) and concentrate on equivalent CO_2, even though CO_2 is not emitted, as it better fits into current considerations. (Note that for a given climate metric, the equivalent CO_2 emission can be calculated for H_2).
- Climate metrics should also be able to consistently estimate climate impacts of sub-fleet replacements.
- Overall, it is recommended to base the climate impact assessment of technologies on a scenario (4D emissions) and fleet assessment using a climatological-based framework rather than weather-related estimates.

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6.3 Feedback summary and response

In general, the constructive exchange between scientific community and industrial stakeholders with the feedback achieved has been extremely helpful. In the following a condensed summary with nine take-away messages followed with a response for the two areas “Choice of Climate Metrics” and “Climate Metrics as Part of a Climate Impact Technology Assessment” is presented.

Choice of Climate Metrics

1) Approach of testing climate metrics against requirements as well as the requirements themselves are basically valid, though might need a better explanation.

   Response: The general support of the methodology and the requirements are an important step towards a commonly accepted CLAIM approach for a climate impact technology assessment. A renaming of the requirement

   - “Neutrality” into “Representative of scenario temperature change “
   - “Temporal Stability” into “Insensitive to small changes in the time horizon”

   are considered.

2) Requirements might also be aligned with the Paris Agreement and concentrate on longer time horizons, especially for technology assessments.
   Response: The recommendation on a longer time horizon suggests the use of 100 years. The Paris Agreement does not have a specific target for the aviation sector. Therefore, this recommendation is difficult to directly implement into a climate metric. However, a temperature-based metric is closest to this recommendation and hence ATR100 might be prioritised over GWP100.

3) Efficacy that describes the slow atmospheric feedback that includes e.g. ocean feedbacks should be addressed in the discussion. Whether including or non-including them in climate metrics should be discussed.

   Response: The recommendation that the climate metric should be “Representative of scenario temperature change“ (Requirement 2) suggests the use of efficacies in climate metrics for technology assessments. Hence, together with a) and b) the conclusion is to concentrate on ATR100 and EGWP100.

Climate Metrics as Part of a Climate Impact Technology Assessment

4) Together with climate metrics, robustness, uncertainty language, inclusion of new findings, their limitations and possibilities to understand the outcome of climate metrics might be included (not to be treated as box model) into the climate impact technology assessment.

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Response: This recommendation is extremely important, fully supported and largely in-line with earlier publications (Grewe et al., 2016). The second workshop on technology assessments should carefully take this recommendation into consideration.

5) Clarification of an acceptable limit of uncertainty or associated risk

   Response: This recommendation is equally important, though currently there is no scientific consensus. This recommendation should be taken further to the 3rd workshop to better clarify the associated needs and possibilities.

6) Develop a sustainability score similar to the "Nutri score" and address the whole lifecycle

   Response: This is an interesting suggestion and goes far beyond the scope of CLAIM. It includes a variety of open questions. A new technology that addresses a small part of the fleet only, would have a large relative score, but a small absolute. In contrast a new technology that has a very low reduction in eqCO2 for a single aircraft, but is used for the whole fleet has a low relative score but a large absolute. The question which of both options should be prioritised might be more complex and a single score could be too simple.

7) Comparison of technologies with different EIS

   Response: This is an important issue. If a climate metric is defined for a 100-year time horizon from 2025 to 2124, a technology that is implemented in 2030 compared to one in 2050 has a larger potential to affect climate impact reduction simply because of the implementation time relative to the time horizon chosen. This refers more to the definition of the technology assessment strategy and will be an important input for the 3rd workshop.

8) Develop a standard on quality criteria, verification, transparency
   Response: This recommendation is a clear implication from 4) to 7). The way the technology assessment is set up is not unique and a clear standardisation could be a very helpful next step after the topics 4) to 7) are more elaborated. In any case, also here this topic should be further addressed in the 3rd workshop.

9) Education is required to understand the calculation methods
   Response: Agreed.

To conclude, concerning the choice of a climate metric, the workshop delivered a proposal that was generally supported. The design of the technology climate impact assessment, where the choice of the climate metric is one part out of many, has various open aspects that have to be assessed in more detail in the third workshop.

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7. Differences between advanced and simplified methods for calculating climate metric

7.1 Introduction

This section applies advanced and simplified methods for calculating climate metrics for three show cases and demonstrates the differences resulting from these two distinct assessments of the climate impact of aviation emission. Note the focus of this chapter is not on the difference in individual climate metrics, but on the method of calculation of climate metrics. Simple calculation methods rely on an approach in which the atmosphere and its response is represented by a box, i.e. a 0-D response, whereas for advanced calculation methods a 3D atmospheric response, i.e. dependence on the 3D nature of the emissions, is considered.

We selected the work by Lee et al. (2021) as an example of simple calculation methods, which are well established and widely used. We therefore refer to a simple calculation of the GWP100. Note that the simple calculation method is very useful for a wide range of applications and the authors did not explicitly suggest to use the simple calculation method for a climate impact assessment of technologies. Hence, the question arises as to whether simple calculation methods can also be used in this context. We illustrate that the simple calculation method does not adequately represent impacts such as those caused by changes in cruise altitude, i.e. the location of emissions. It is important to note that the method was not designed to account for such factors and these results are thereby not surprising. Nevertheless, it is important to understand what impact this can have. Therefore, we believe it is sufficient to present a relevant example rather than performing an extensive analysis as was done for the selection of climate metrics in Sec. 3.

Therefore, we showcase simple and advanced calculation methods for the GWP100 metric, illustrating the limitations of the simple calculation method in the framework of a climate impact assessment of aviation technologies. In the second step, we compare the results to an advanced calculation method of ATR100 for completeness. The results for the advanced calculation method for EGWP100 are similar to those of ATR100 and are not presented here.

7.2 Methodology of the study

Climate impact of CO_2 emissions can be directly calculated from an almost linear relationship with the amount of fuel used. Including the impact of non-CO_2 effects, which is of similar size to or even greater than that of CO_2, is more complex, since it depends on the location of emissions and physical conditions of atmosphere. The European Emission Trading System (ETS) currently uses a single measure, typically CO_2 equivalent (Sect. 2.3) to account for all greenhouse gas emissions, including both CO_2 and non-CO_2 emissions. The GWP of a pulse emission over time horizon of 100 years is generally accepted metric to evaluate the equivalents (IPCC AR4). In the simplified method, the total climate impact of an aviation technology is estimated by summing CO_2 emissions with the CO_2 equivalents of non-CO_2 emissions, which are derived by multiplying the emissions by their respective GWPs. This approach relies on estimates of radiative forcings of various emissions and effects by the *global aviation* (Lee at al. 2009; Lee at al. 2021). An alternative approach to assess climate

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effects of aviation considers spatial and temporal distributions of emissions with the use of climate response models. For an advanced method to calculate the climate impact of a given emission using various climate metrics, we use the climate response model AirClim (Grewe and Stenke, 2008, Dahlmann et al. 2016), as this is the only response model available that resolves climate effects depending on the location of the aircraft emission for all relevant species. Since the general response of AirClim, e.g. with respect to fight altitude changes (Dahlmann et al. 2016, their Figure A.6) or general evolution of the climate impact (Grewe et al. 2021) is well represented by AirClim, we do not expect principal differences in the here shown differences between simple and advanced methods. For given emission distributions, we use AirClim to calculate the changes in atmospheric composition, the associated radiative forcings and the climate response to these radiative forcings, e.g. as change of the near-surface temperature. AirClim models combines emission data with pre-calculated climate response data obtained from detailed climate-chemistry simulations. The pre-calculated data is altitude- and latitude-dependent and for contrails in addition longitudinal dependent, which means that the model considers where emissions occur to provide a more accurate climate impact assessment in contrast to the simplified calculation methods for climate metrics that are based on global mean values, only.

Figure 7.1 compares the radiative forcings of CO_2, NO_X, H_2O emissions and contrails from the global aviation radiative forcings derived by Lee et al. (2021) for year 2018 and the values from AirClim response model calculated by Grewe et al. (2021). The RF values for the relevant aviation terms in work by Lee et al (2021) were compiled from multiple published studies, and normalised and scaled to be consistent with emissions of the regarded year 2018. This process involves accounting for differences in air traffic inventories, integration of emissions along flight tracks, and assumed jet-engine emission indices. Both approaches yield similar values of the net radiative forcings, 156.8 vs 150.74 Wm^{-2}, respectively, and similar impacts from CO_2 and water vapor emissions. The difference in the NO_x impacts is caused by a larger NO_x-O_3 sensitivity in the climate-chemistry model that was used for the development of AirClim compared to the mean value adopted by Lee et al. (2021). Additionally, AirClim model includes the saturation effects in contrail formation where the formation of contrails reduces the ambient water vapour, thereby lowering the possibility of additional contrails forming in the same region. This effect has also been considered in individual studies that were summarised in Lee et al., but not for the scaling to the respective considered year

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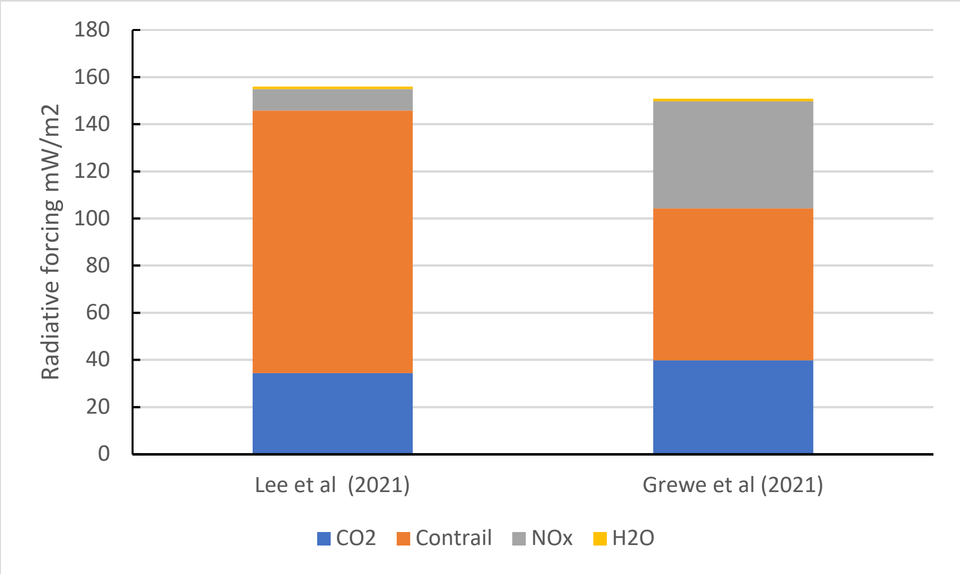

Figure 7.1: The aviation radiative forcing in the year 2018 for CO_2, NO_x, H_2O and contrails estimated by Lee et al (2021) and the values from AirClim model derived by Grewe et al. (2021).

2018. This effect is important in areas with dense air traffic, such as the North Atlantic Flight Corridor (NAFC). This effect decreases the contrail impact value shown in Fig. 7.1.

To analyse the difference between advanced and simplified calculation methods for climate metrics we use three different show cases. These show cases represent three different technologies: one regional aircraft, and two long-range aircraft, comprising one single-aisle and one twin-aisle aircraft. The respective network and typical cruise altitudes (described in detail Section 7.2) are based on data from the AS4D project (cooperation between Airbus, DLR institutes PA (Institute of Atmospheric Physics) and LV (Institute of Air Transport)).

The choice of the climate metric is based on Megill et al. (2024) and the outcome of the CLAIM Climate metrics workshop (Section 6). For the comparison of the three show cases, we select the ATR100 as the climate metric calculated with advanced method. Additionally, since GWP100 is the most commonly applied climate metric in international climate policy, we use it here for comparison. We have chosen the Business-as-usual (BAU) scenario (Grewe et al., 2021) for the temporal development of emissions for our show cases. This evolution scenario represents a future where some technological improvements in aviation are implemented, but without any specific aims to reduce climate impact. The BAU scenario is used as a reference to compare the impact of other scenarios that include more aggressive measures for climate mitigation. In the climate impact assessment, the background atmosphere is expected to follow the Shared Socioeconomic Pathway SSP2-4.5 as used in the sixth Assessment Report (Intergovernmental Panel on Climate Change, 2021).

Together with the technology scenarios, we consider two cases for aviation fuel: pure kerosene fuel and sustainable aviation fuels (SAF) assuming a reduction of the life-cycle CO_2 emissions of 95%. Recent research suggests that SAF can substantially reduce particulate

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matter emissions from aviation compared to traditional fossil fuels. We therefore reduce emission of particulate matter by 50% in the SAF case which leads to a reduction in contrail formation.

7.2 Description of show cases used for metric evaluation

We adopt three technologies as our show cases: a regional aircraft, a twin aisle aircraft (TA) and a single aisle aircraft (SA) (Table 7.1). The aircraft are used on two different networks: a regional network (Show Case *Regional*), a long-range network for SA and a different long-range network for TA (Show Case *Long-range SA* and *Long-range TA*, respectively). The cruise altitude differs between the networks: The regional flights cruise at FL200 whereas the long-range aircraft cruise at a higher altitude of FL360. The climb angle for all cases equals to 3.5°. Emission inventories for these three cases are taken from the AirClim Surrogate Model 4 Design (AS4D). AS4D was developed to evaluate the climate impact of various aircraft technologies. It combines route networks for three aircraft categories (regional, TA, and SA) with emission inventories calculated for each flight segment (climb, cruise, decent) as a function of flight altitude and angle of climb. Table 7.1 summarises the yearly emissions for these inventories. Note that the values in Table 7.1 should not be taken as reference for regional and long-range aircraft as they represent only one of many climb angles and trajectories. The show cases are calculated for different engine specifications for *hypothetical* TA and SA (the same as Regional) aircraft. The methodology described here will be applied for specific technologies in WP3, in particular, in D3.3.

Table 7.1: Overview of the show cases.

Show Case	Network	Flight level	Climb angle	Fuel use	CO_2 Emis.	NO_x Emis.	Flown Distance	EI NO_x
Units		hfeet		Tg/yr	Tg/yr	$Tg(NO_2)/yr$	10^8 km	$g(NO_2)/kg$
Regional	Regional	200	3.5°	23.3	73.45	0.433	85.8	18.6
Long-range SA	Long-range	360	3.5°	215.1	678.18	4.02	803.3	18.7
Long-range TA	Long-range	360	3.5°	246.7	777.9	3.24	404.4	13.1

Vertical distributions of emission inventories for all show cases are shown as pressure altitude profiles in Fig. 7.2 and clearly indicates the large differences with the emissions located at lower altitudes for the show case Regional and the broader maximum for the show case Long-range TA compared to SA, since the cruise altitude is only reached at the end of the aircraft trajectory due to weight constraints. Figure 7.3 depicts two-dimensional projections of yearly fuel use on the longitude and latitude grid. Both long-range cases, SA and TA, have similar cruise levels, but very different flight distances and route networks. The fuel map indicates that the long-range TA show case covers the longest routes, hence most of emissions occurs

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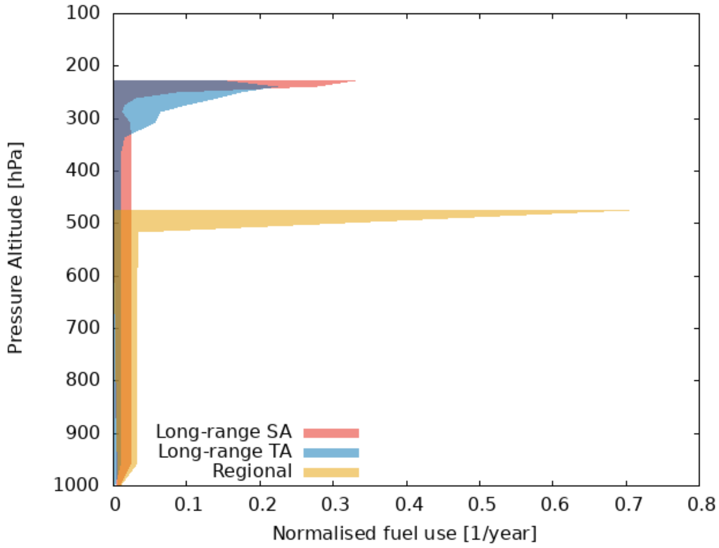

Figure 7.2: Vertical distribution of fuel use for the use cases *Regional*, *Long-range SA* and *Long-range TA*. Since we are interested in the flight path conditions and not absolute values of fuel use, we normalise each profile by the corresponding yearly fuel use (Table 7.1).

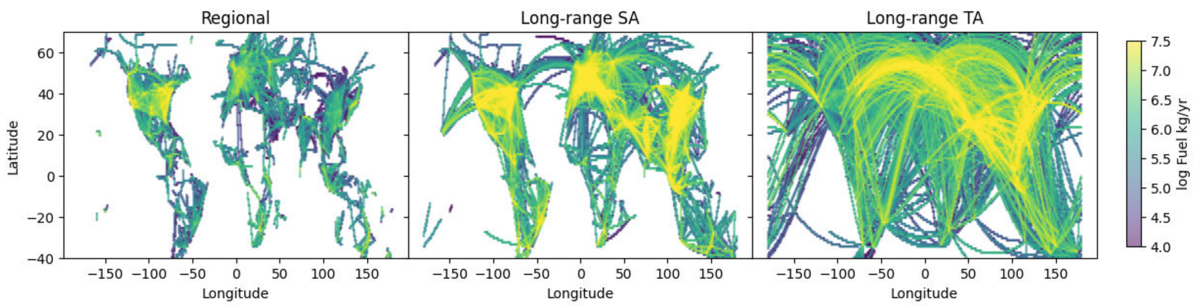

Figure 7.3: Fuel use map for the Regional, Long-range TA and Long-rang SA show cases. The maps project three-dimensional emission distribution data on the latitude and longitude grid.

at high altitude (87% above the altitude that relates to the pressure of 350 hPa). The Long-range SA show case has shorter missions and consume 72% of fuel above this level. The show case Regional has the lowest cruise levels and the shortest flight distances among the three cases.

We combine the emission inventories (on an annual basis) described above with the BAU scenario for temporal emission development to calculate the yearly amounts of fuel use, CO_2, H_2O, and NO_x emissions and climate responses with the AirClim model. Year 2020 is adopted as the start of emissions. Figure 7.4 shows resulting annual CO_2 emissions for all three show cases and for each of the two fuel types.

CO_2 emissions for the Long-range SA and TA cases are substantially higher than that for the Reginal case owing to many flights on their routes. In terms of CO_2 emissions per flown

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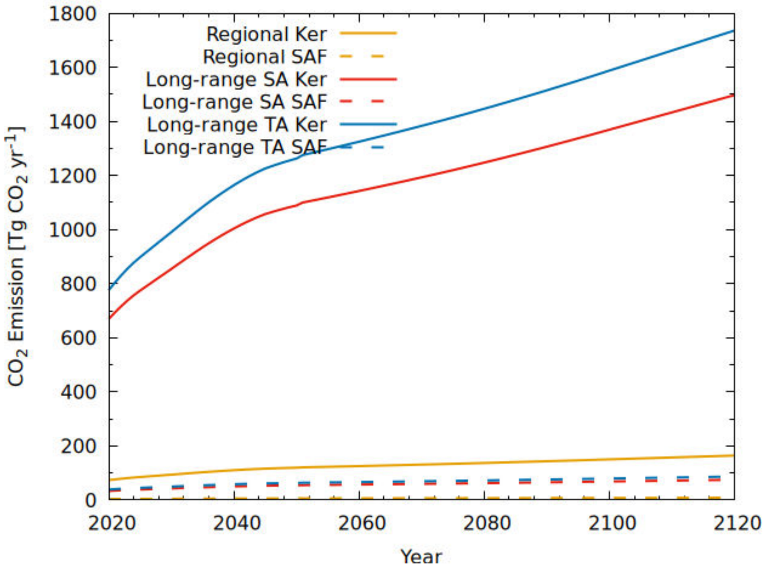

Figure 7.4: Annual CO_2 emission for three selected use cases for the BAU emission scenario. Solid and dashed lines indicate the emissions for traditional fossil fuels and effective CO_2 emissions for the SAF, corresponding to 95% reduction of CO_2 life-cycle emissions, respectively.

distance, the Long-range TA show case has the highest fuel consumption of 6.1 kg/km, in contrast to 2.7 kg/km for the Long-range SA and Regional cases.

Note that we intend to show the fundamental mechanisms that lead to differences between simple and advanced calculation methods. We believe that the choices are reasonably representative and show a sufficient variation in the assumptions for this specific purpose.

7.3 Climate impact of simple show cases

This Section highlights the dependence of climate response on the emission location based on the show cases described in Section 7.2 and Table 7.1. We assess climate impacts of non-CO_2 species using CO_2 equivalents, which are the climate impacts of each climate species relative to the climate impact of one kg CO_2 (Sect. 2.3). The climate responses are calculated with AirClim model that combines 3D emission inventories and BAU emission scenario introduced in Sections 7.1 and 7.2.

Figure 7.5 shows proportions of CO_2, NO_x, H_2O emissions and contrails in the total CO_2 equivalent emissions calculated using ATR100 as climate metric. The climate impacts are shown for flights with traditional fossil fuels (upper row) and SAF (lower panels). The most notable feature of Fig. 7.5 is that CO_2 emissions dominate the climate impact in the show case Regional with tradition fuels and contribute 71% to the climate impact. NO_x emissions and contrails constitute the remaining 29% of the total eqCO_2. At the higher cruise altitude of the Long-range TA and SA show cases, temperatures are lower leading to more efficient contrail formation. This is reflected in the larger impacts from contrails. The climate effects of NO_x emissions from aviation also increase with altitude, as illustrated by the Long-range show cases (Fig. 7.5). CO_2 emissions contribute about one third to the total impact in these cases.

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The climate impact of NO_x is slightly higher than that of CO_2 in the case Long-range SA, while for twin-aisle it is the opposite. It is explained by the higher emission index of NO_x for the SA compared to the TA (Table 7.1). Note that the relative impact of NO_x compared to CO_2 is higher for a continuous emission scenario adopted here compared to a pulse scenario. In a pulse scenario, the NO_x emissions have a short-term effect, while long-lasting CO_2 dominates the impact. In a continuous scenario, the short-term effects of NO_x emissions are maintained, while warming effect of CO_2 is more spread out over time.

In fact, NO_x emissions from aviation have a complex climate impact with both warming and cooling effects. The net radiative forcing of NO_x can be positive or negative depending on the location of the emission, background concentrations, and photo-chemical reaction rates. On one hand, NO_x emissions increase the formation of ozone (O_3) in the upper troposphere and lower stratosphere. Ozone is a greenhouse gas and contributes to warming. On the other hand, NO_x emissions also lead to the depletion of methane (CH_4), another greenhouse gas. The reduction of CH_4 also leads to the lower production rate of O_3 known as the primary mode ozone effect (PMO), which together causes a net cooling effect. Figure 7.6 illustrates how the role of these main components of the NO_x climate impact (CH_4, O_3 and PMO) differs for our show cases in terms of their CO_2 equivalents per emitted kg CO_2. For example, the impact of NO_x emissions on the ozone RF increases with altitude and hence is the lowest for the show case Regional.

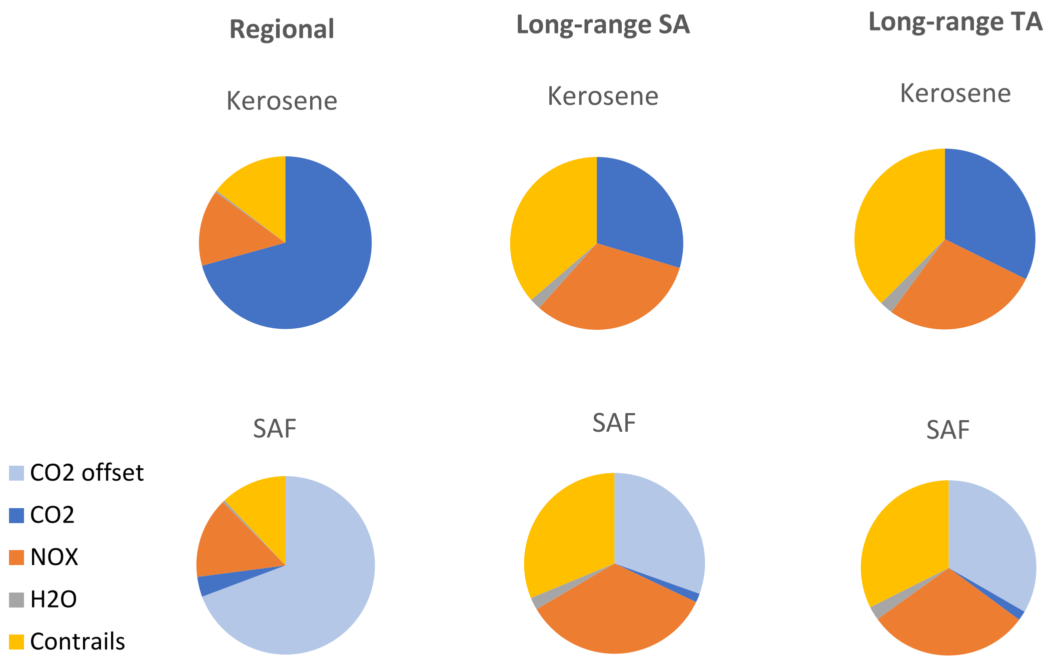

Figure 7.5: Pie charts of CO_2 equivalent emissions for CO_2, NO_x, H_2O and contrails calculated for the ATR100 climate metric with the AirClim model for the three show cases (Table 7.1). Upper panel shows the values for kerosene fuel and lower panel for 95% SAF, respectively. The offset CO_2 emissions are shown with light blue colour.

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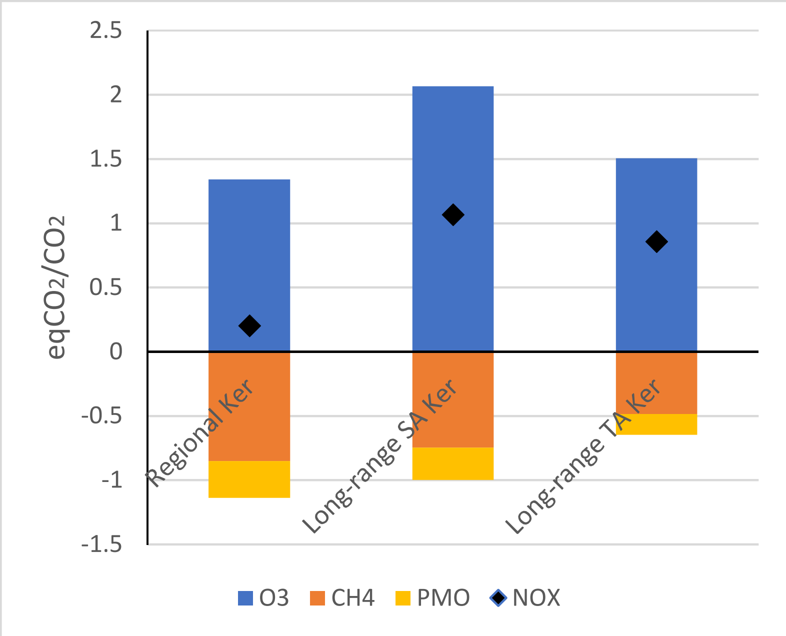

Figure 7.6: The climate impacts of three main components (ozone (O_3), methane (CH_4) and primary mode ozone (PMO)) that determine the net climate effect of NO_x (black symbols). The climate impact is expressed as equivalent emissions per emitted kg CO_2 for ATR100 as climate metric.

In the show case Regional, the magnitude of the warming effect of O_3 is 17% higher than the net cooling by PMO and CH_4 (Fig. 7.6). As the result, NO_x emissions have a relatively small net warming effect compared to that of CO_2. At FL360 in the Long-range SA and TA show cases, the warming from O_3 is higher, while the net cooling effect is lower compared to the show case Regional. The CO_2 equivalents of O_3 for both Long-range show cases are about twice as large as the combined effects of CH_4 and PMO. This explains large climate impacts of NO_x in the Long-range show cases illustrated in Fig. 7.5.

The climate impact of water vapour also increases with altitude; hence it is the lowest for the show case Regional. It constitutes 2% for the Long-range SA and TA show case, but it can be substantially higher at higher altitudes.

The climate impact of aviation emissions for the show cases with SAF, also shown in Fig. 5, differs compared to those with conventional kerosene in two ways. Firstly, the impact of CO_2 emissions is lower due to the reduction of the life-cycle CO_2 emissions for SAF. The net reduction of the climate impact is most pronounced in the Regional case (70%), where CO_2 is the dominant climate agent, and it is lower in the Long-range SA and TA cases (36% and 39%, respectively. Secondly, the climate impact of contrails is reduced owing to a lower soot number emission that, respectively, shorter contrail lifetimes and changes in the optical properties. This also results in the somewhat higher ratios of CO_2 equivalents for NO_x to that of contrails for all three cases with SAF compared to the corresponding show cases with kerosene.

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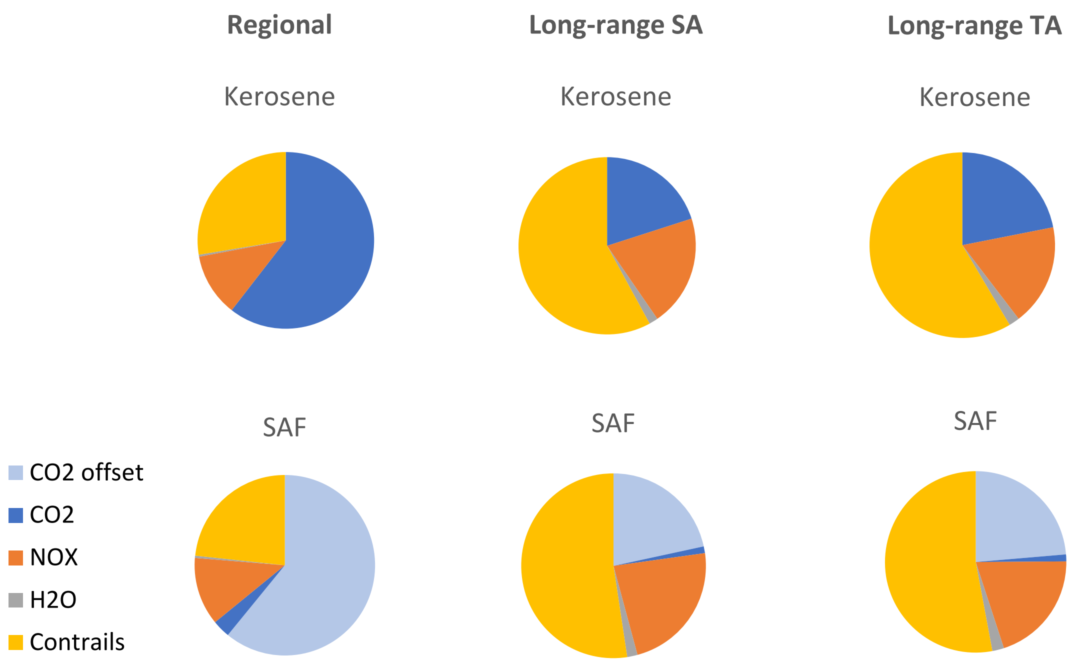

Figure 7.7: The same as in Figure 7.5, but for the GWP100 climate metric.

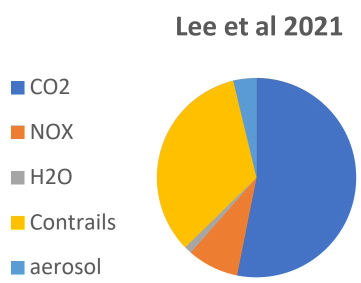

Figure 7.8: Pie chart of CO_2-equivalent emissions for CO_2, NO_x, H_2O, aerosols and contrails estimated for 2018 aviation emissions and cloudiness using a simplified global mean version of GWP100 as climate metric based on data from Lee at al. (2021).

Pie charts of CO_2 equivalent emissions calculated using GWP100 as the climate metric are shown in Fig. 7.7 for kerosene and SAF fuels. The main differences compared to the estimates derived with the ATR100 metric are lower eqCO_2 fractions of CO_2 and NO_x and larger fractions for contrails in all three cases. These differences demonstrate how sensitivity parameters included the climate impact assessment with the ATR metric affect the outcome compared to an assessment using the GWP, which accounts only for radiative forcings. Climate sensitivity of an emitted species refers to the degree to which the Earth's temperature will change in response to a given radiative forcing. Efficacy is simply the ratio of species' sensitivity to that of CO_2. Since we apply an efficacy of contrails of 0.43, their impact relative to CO_2 emissions is higher with the GWP100 metric than with the ATR100 metric. It is the opposite for NO_x

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emissions, owing to the efficacies of O_3 and CH_4 of 1 and 0.86. The combined effect of the efficacies leads to higher contrails-to-NO_x ratios in Fig. 7.7 compared to those assessed with ATR100 (Fig.7.5) for all three cases.

Note that the magnitude of the climate impact reduction thanks to SAF depends on the adopted metric. It is most noticeable for the case Regional. The total CO_2 equivalent is reduced by 70% with the ATR100 metric and by 63% with the GWP100 metric. The reduction of $eqCO_{2,tot}$ for the Long-range SA and TA cases are 31% and 33%, respectively. The largest effect of SAF is observed in the case where the relative impact of CO_2 is the largest with traditional kerosene fuel, as in the show case Regional.

7.4 Comparison with simplified methods for climate metrics

Including non-CO_2 climate effects of aviation into the emission trading and mitigation framework has increasing importance given that they can have the same or even greater impact as CO_2. Market-based measures like the ETS apply the single-basket approach where a single price for CO_2-eq emissions is established, rather than separate prices for each gas. The GWP of a pulse emission over time horizon of 100 years is commonly used to express the impact of various emissions to the CO_2 equivalents.

The ratio of the total CO_2 equivalent emissions of all climate species to CO_2 emission expresses the climate impact relatively to that of CO_2 alone. These ratios are called CO_2 equivalent factors or 'multipliers', as they are then used to estimate the climate impact of non-CO_2 emissions in single-basket schemes and carbon footprint compensation schemes. The constant 'multipliers' based on radiative forcings for the global aviation provide the easiest way to estimate the impact of non-CO_2 effects on the environment. It does not however consider how the impact of emissions measured relative to CO_2 varies with the mission parameters. It may strongly underestimate or overestimate the climate impact of non-CO_2 emission effects. We compare the CO_2 equivalent factors derived for the show cases (Table 7.1) with AirClim response model and with the values from the comprehensive evaluation by Lee et al (2021) for GWP100 as climate metric that is based on a standard emission distribution, referring to a whole fleet.

First, we show CO_2 equivalents for CO_2, NO_x, contrails, aerosols and water vapour calculated using GWP100 by Lee at al. (2021) for 2018 aviation emissions and contrails, relatively to the total CO_2 equivalent emission from all CO_2 and non-CO_2 effects (Fig. 7.8). With the large impact from CO_2 and second in importance from contrails, the distribution of CO_2 equivalents estimated by Lee et al (2021) resembles that of the show case Regional (Fig. 7.7).

Figure 7.9 presents CO_2-equivalent factors ('multipliers') derived with AirClim for the show cases Regional, Long-range SA, and Long-range TA and the values evaluated by Lee et al (2021). First, we compare the multipliers derived with advance metric calculation methods for the use cases with kerosene fuel and the simplified approach. The total CO_2-equivalent factor of 1.81 for Lee et al. (2021) is slightly higher than the published value of 1.73 because we do not consider aerosols for simplicity reasons. We also test how replacing the NO_x emission index of 15.4 g(NO_2)/kg from Lee at al. (2021) with the values for each show case listed in

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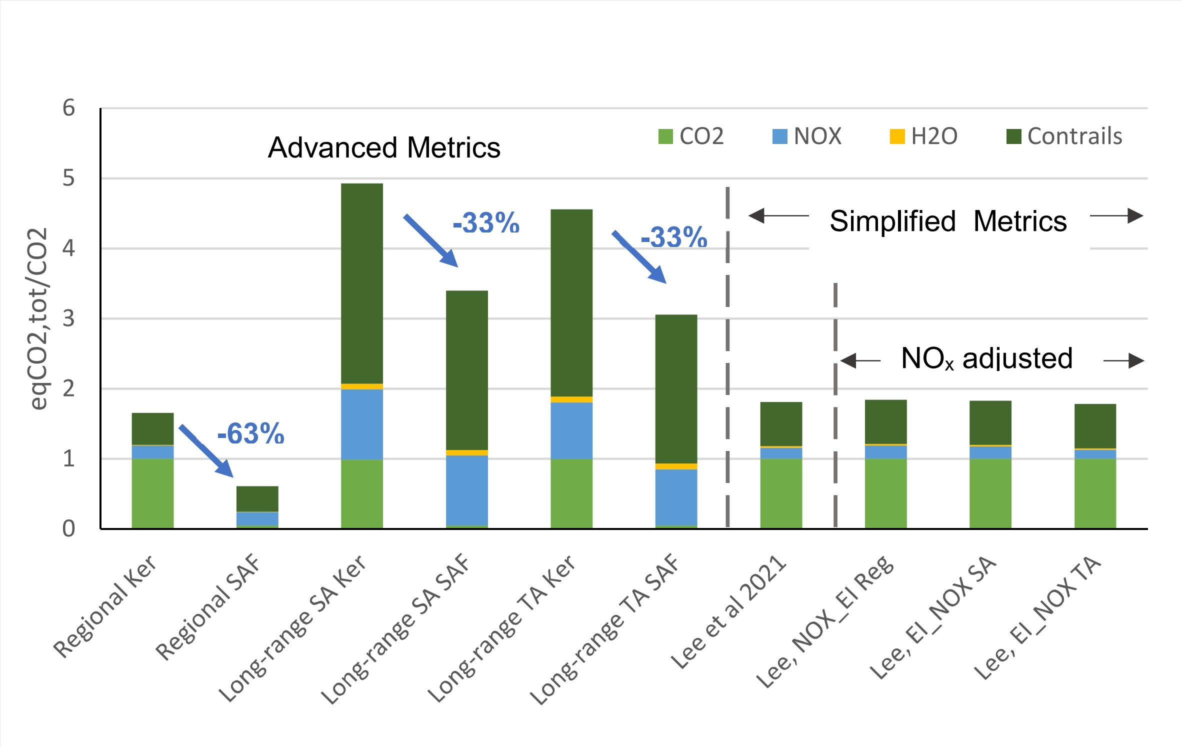

Figure 7.9: Total CO_2-equivalent emissions relatively to CO_2 calculated using GWP100 climate metric for our three show cases and two fuel types using the AirClim model and considering the location of the emission (first six bars). The bar chart shows a value calculated with a simplified method for 2018 global aviation emissions presented by Lee at al. (2021) in their Table 5 for comparison. The three stacked bars on the utmost right show CO_2-equivalent emissions from Lee at al. (2021) with the NO_x emission index updated accordingly to the value in each show case listed in Table 7.1. Colours indicate relative contributions of CO_2, NO_x, H_2O and contrails.

Table 7.1 affects the estimates of the CO_2-equivalent factors. These adjusted CO_2-equivalent factors are also shown in Fig. 7.9. The comparison reveals the following features:

- The total CO_2-equivalent factor of 1.7 for the show case Regional is the closest to the value from Lee et al (2021). However, this is purely coincidental, as the values of multipliers depend on the time horizon and scenario. As discussed in Sect. 7.2, the relative impact of CO_2 compared to the short-term effects such as NO_x and contrails is lower for the continuous emission than for a pulse emission. The values of multipliers for these technologies are therefore higher than they would be for a pulse emission.
- The values of the total CO_2-equivalent factor are 4.6 and 4.9 for the Long-range TA and SA cases, respectively. This is mainly owing to the higher cruise altitude and thereby larger impact from NO_x and contrails compared to the show case Regional as

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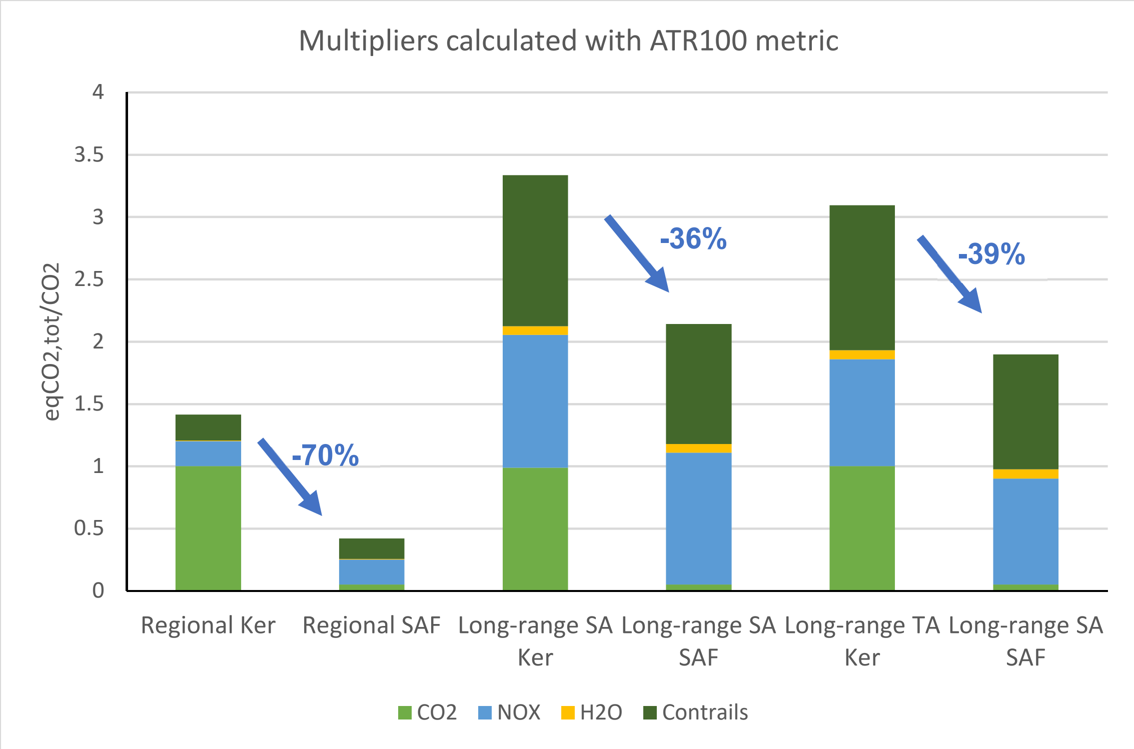

Figure 7.10: Total CO_2-equivalent emissions relatively to the emitted CO_2 calculated with AirClim model using the ATR100 climate metric. Colours indicate the relative contributions of CO_2, NO_x, H_2O and contrails to the total. CO_2 fraction is always equal to one for the kerosene fuels.

discussed in Sect. 7.3. It means that the total climate impact of the Long-range show cases relatively to CO_2 is actually 2.6-2.7 higher than that estimated with the constant multiplier.

- In case of the SAF fuels, the effective CO_2 is considered with the corresponding fraction of 0.05.Since the individual show cases differ in their NO_x emission, replacing the emission index of NO_x used by Lee at al. (2021) with the values for each show case only slightly increases the values of the total CO_2-equivalent factor and does not improve the agreement.

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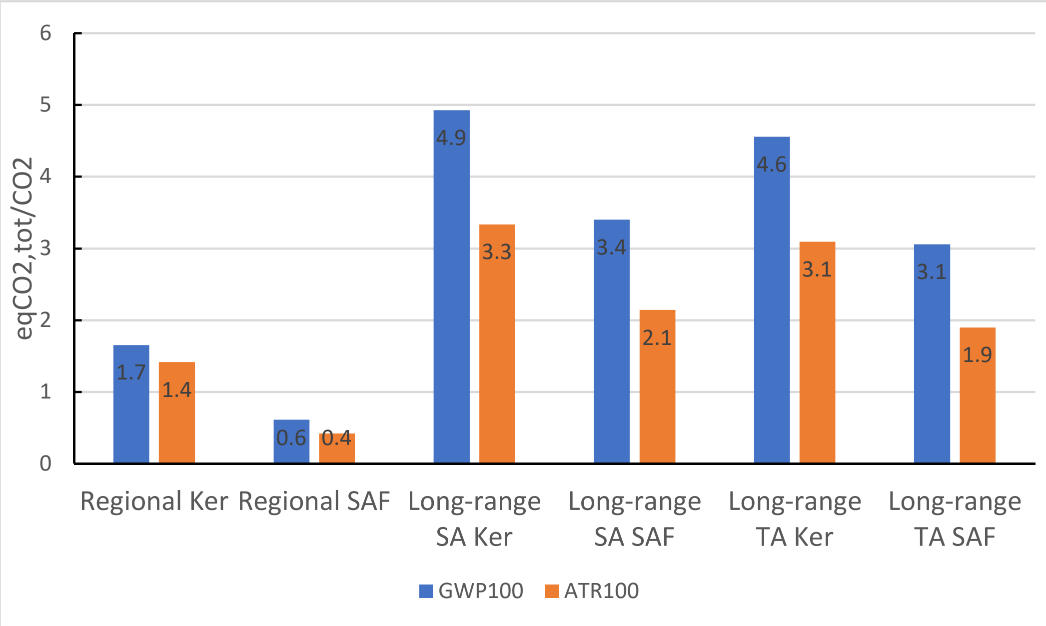

Figure 7.11: Total CO_2-equivalent emissions relatively to the emitted CO_2 calculated with AirClim model using the ATR100 and GWP100 climate metrics.

In the case of SAF (Fig. 7.9), the CO_2-equivalent factors based on GWP100 are estimated relatively to the emitted CO_2, before the offset is subtracted, i.e. not relative for the life-cycle CO_2 emissions[5]. For the assessment of the climate impact, we consider effective CO_2 emissions reduced by the offset corresponding to the SAF fraction. The CO_2-equivalent factors for CO_2 emissions for the show cases with SAF are therefore reduced by 95%. The SAF effect on the climate impact is most pronounced for the Regional SAF case, where the total the CO_2-equivalent factor falls below 1. Additionally, the non-CO_2 effects on climate and hence multipliers for the show cases with SAF are reduced due to lower contrail climate impacts for SAF. The total equivalent factors (multipliers) for Regional, Long-Range SA and TA cases with SAF are 0.6, 3.4 and 3.1, respectively, which corresponds to the reduction of the climate impact by about 63% and 33% (see also Sect. 7.3).

As we discussed in Sect. 7.3, the contribution of CO_2 emissions to the total CO_2 equivalent emission is higher when they are estimated with the ATR100 metric than with the GWP100 metric. Consequently, the total CO_2-equivalent factors evaluated with the ATR100 are lower compared to the assessment with the GWP100 metric (Fig. 7.10 and 7.11). The values derived using the ATR100 metric are 1.4, 3.3, and 3.1 for cases Regional, the Long-range SA and TA cases with traditional fuel, respectively. The multipliers for these show cases with SAF are 0.4, 2.14, and 1.9, respectively, what corresponds to the reduction of the total climate impact relative to the CO_2 by 70% for the case Regional and 36% (39%) for the case Long-range SA (TA) (Fig. 7.11).

[5]This is a technical detail, only, that is not influencing the climate assessment, but keeps the range of the CO_2-equivalent factors smaller and avoids a division by zero for cases when the life-cycle emissions of SAF would be zero.

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7.5 Conclusions and Recommendations

In this section, we showed the differences between simplified and advanced calculation methods for climate metric. For that, we select three show cases from AS4D that include 3 arbitrary aircraft types (regional, single aisle and twin aisle) and 2 networks (regional and long-range). Differences in geography, mission lengths and cruise altitudes between the cases are used to demonstrate variations in the climate impacts of CO_2 and non-CO_2 (NO_x, water vapor and contrails) aviation emissions with the climate metric ATR100 derived with advanced method. This approach employs AirClim, a non-linear response model, and incorporates three-dimensional emission inventories and an emission scenario, for which we adopted a continuously increasing temporal development (the Business-as-usual). In addition to pure kerosene fuel, we discuss how using SAF reduces the climate impact of the show cases.

We find large differences between the climate impacts assessed with AirClim for the Regional and Long-range show cases. CO_2 contributions to the total equivalent emission estimated using the ATR100 metric is 70% in the show case Regional and it falls down to about 30% in the Long-range show cases. While contrails dominate the impact in the Long-range cases, NO_x emissions contribute about one third to the total equivalent emission. The main difference between the Long-range SA and TA show cases is that the impact of NO_x emissions is higher than that of CO_2 emissions in the former case and the opposite in the latter case.

The total CO_2-equivalent factor ('multiplier') estimated for the case Regional with AirClim using the GWP100 metric is 1.7, which is three times lower than the values derived for the Long-range TA and SA cases (4.6 and 4.9, respectively). Using a constant multiplier of 1.8 derived with the simplified approach for the global aviation emissions would underestimate the total impact by the factor of about 2.6 for the Long-range show cases. Note that the relatively high multiplier values in the show cases are caused by continuous emissions, which reduce the relative impact of CO_2 compared to the short-term effects of NO_x and contrails over the considered time horizon.

Replacing the emission index of NO_x used by Lee at al. (2021) with the values for each show case does not improve the agreement between the total CO_2-equivalent factors evaluated with advanced and simplified calculation methods for climate metrics. The discrepancies are caused by dependence on the location, selected emission scenario and atmospheric conditions of individual flight networks rather than engine characteristics.

The CO_2-equivalent factors calculated using the ATR100 metric are smaller compared to the values for the GWP100 metric owing to different sensitivities of contrails and NO_x included in the ATR100 assessment. For example, for the Long-range SA case, the CO_2 equivalent factor evaluated using the ATR100 is 37% lower and for the case Regional is 14% lower than that calculated using the GWP100 metric.

Using SAF with a 95% reduction of lifecycle CO_2 emissions decreases the values of the total CO_2-equivalent factors (multipliers) estimated with the GWP100 metric to 0.6, 3.4 and 3.1, for cases Regional, Long-Range SA and TA, respectively. In cases such as Regional, where CO_2 has a large contribution to the total impact, using SAF may lead the values of multipliers below one, because the impact is measured relatively to the emitted CO_2 before the offset is applied. Comparison with the values derived for pure kerosene fuel reveals that the climate impact is reduced by about 63% for the case Regional and 33% for the Long-range cases with SAF, respectively. The corresponding values of multipliers derived with the ATR100 metric for

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the same use cases with SAF are 0.4, 2.14, and 1.9. This implies a larger reduction of the multipliers due to SAF compared to the GWP100 metric, namely a 70% reduction in the case Regional and a 36%-39% reduction in the case Long-range.

Based on these findings it is recommended to:

- prefer advanced climate metric calculation methods that account for emission location over simplified multipliers, even when they include certain adaptations, such as adjustments for variations in the NO_x emissions index.
- have a decomposition of the climate metric into the contributions from individual effects to allow a deeper analysis

Additionally, based on the feedback from the climate metrics workshop (Sect. 6), it is recommended to:

- allow updates to the climate metrics in line with the latest and more consolidated research
- cross-check the outcome of climate metrics with time series of the effects and evaluate them using higher-fidelity models on a sample basis
- include a framework for uncertainties that supports risk analysis

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8. The Four-Layer Climate Impact Technology Assessment as a Best Practice

8.1 Description of four-layer approach

In this section, we propose a four-layer approach as a best practice for technology climate impact assessment (Fig. 8.1, middle part). This assessment applies to new technologies, which may be an entire aircraft or specific components, such as a new engine. In the first layer, we examine in detail where this technology is utilized in order to clarify the network. Next, we consider when this technology will enter into service and how the temporal evolution may unfold. Note that there might also be relations between the entry into service and the appropriate network. These considerations form the basis of a detailed calculation of a 3D (spatial) or 4D (spatial and temporal) emission inventory (the second layer). In the third layer, all the components from the preceding layers are combined to assess non-CO_2 impacts of the technology. To this end, a more detailed atmospheric model (e.g., a response climate model) that considers the sensitivity of non-CO_2 effects with respect to geographical location and altitude is used to calculate the temporal evolution of the radiative forcings and temperature changes. Finally, these timeseries are used to calculate the climate metrics ATR100 and EGWP100 that were down-selected in Sect. 5.

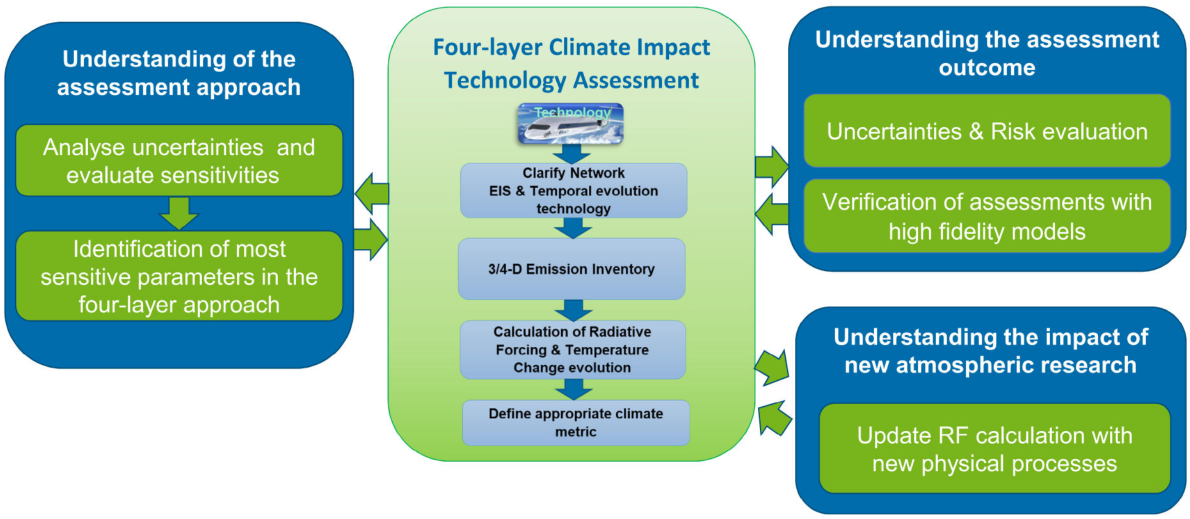

Figure 8.1: Workflow showing the four-layer approach to the Climate Impact Technology Assessment (central panel) and its relation to the three elements that ensure the integration of knowledge gaps and uncertainties in this method.

8.2 Best practice in dealing with uncertainties and knowledge gaps

Discussions with various stakeholders during the CLAIM workshops highlighted the importance of understanding knowledge gaps and uncertainties for a reliable assessment of

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climate impact of aviation technologies and the need to integrate uncertainties into four-layer methodology outlined in Sect. 8.1. Integration on systematic level requires (1) understanding the sensitivities of the ingredients of all four layers of the method, (2) understanding the assessment outcome, including risk evaluation and verification procedure, and (3) understanding advances in atmospheric research and updating the models to include relevant physical processes (see side blocks in Figure 8.1). Below we briefly discuss four main steps necessary for a robust climate impact assessment.

Identifying the most sensitive parameters

As a first step, we recommend to establish a good understanding of the impact of uncertainties in all of the four steps of the approach on the final outcome. Identifying the most sensitive parameters is key to understanding the robustness of the methodology. Note that for different technologies, such as long-range and regional or SAF-driven and hydrogen-driven aircraft, the sensitivities might change. Nevertheless, a general overview would help in prioritising future research activities.

Developing robustness metrics

The uncertainties from both atmospheric science and the four-layer approach itself (Sec. 8.1) will translate into uncertainties in the climate impact assessment of a specific technology. This issue can be addressed by defining probability density functions for each parameter of the four-layer approach and perform a Monte-Carlo simulation to understand the propagation of uncertainties. Dahlmann et al. (2016) provided a relevant example for such an approach for comparing technological options, in which they stressed the importance of analysing the difference in technologies with the Monte-Carlo simulation to take advantage of possible correlations of uncertainties that equally apply to either technology. They found that the uncertainty ranges of relative differences between technologies are the most effective robustness metrics.

Updating based on new consolidated research findings

As described above, the processes that are included in the four-layer approach are associated with uncertainties that can be characterised. In contrast, knowledge gaps, such as the indirect cloud effects, refer to processes where the understanding is not mature enough to be integrated in the four-layer approach. In this regard, it is necessary to allow updates to the assessment approach whenever consolidated research reaches a sufficient level of maturity. In 2015, European Space Research and Technology Centre (ESTEC) proposed a grading for a scientific readiness level (SRL) to characterise the maturity of evolving science with respect to a mission concept, satellite mission, or satellite instrument activity. It might be useful to establish a similar measure in the technology climate impact assessment to aid decision-making regarding when a process should be integrated in the procedure.

Verifying the assessment procedure

The four-layer approach integrates complex interdisciplinary processes from aeronautical engineering to climate science. As with any model, the proof of applicability is necessary. While individual processes in each layer can be validated against observational data, there is no possibility to validate the whole approach against observational data. However, a verification with higher fidelity models for selected independent use cases is mandatory.

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9. CONCLUSION

In this deliverable, we have introduced commonly used climate metrics and provided an assessment of these climate metrics against formulated requirements for climate metrics. A CLAIM workshop was held to obtain feedback on this approach from stakeholder, representing academia, aviation industries and authorities. The outcome of this workshop is summarised in this document. It basically approves the requirement and procedure for testing climate metrics with some recommendations for renaming the requirements to more tangible wordings. By using a world café approach, the stakeholder weighted the importance of the requirements with a clear priority of the requirement “neutrality” which refers to the ability of a climate metric to rate two mitigation options similar to a more detailed assessment with a scenario-based approach and not being biased to a specific technology. Other recommendations with respect to the impact of choices on the climate metrics will deliver an important input to the 3rd CLAIM workshop on technology assessments. In order to illustrate the importance of the use of more advanced methods for climate metrics calculation, several show cases were presented. They clearly show that the climate impact of individual fleets, such as regional aircraft or long-range single aisle aircraft differ significantly from that of a global fleet of aircraft. This is due to the regional and altitudinal dependence of the non-CO_2 aviation effects such as contrail formation or the ozone production from NO_x emissions. The examples clearly show that simple calculation methods are not able to capture these differences and are hence not recommended for the use in assessing technology climate mitigation options.

Based on the work in CLAIM, we propose a four-layer climate impact technology assessment that also enables the use of uncertainties to translate them into robustness metrics.

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APPENDIX

A.1 Supporting material for World Café on requirements

World Café
Requirements for climate metrics

claim
Workshop on climate metrics
Hamburg, 17-18 June 2024

Introduction

CLAIM aims at providing a methodology for the assessment of the climate impact of technologies (aircraft design, engine, etc.). Hence a climate metric has to be chosen to assess CO_2 and non-CO_2 climate effects on the same scale.

For the choice of the climate metric, we would like to define requirements and use the work of Megill et al. as a starting point.

The next questions serve as a basis for the feedback on those requirements. Are they helpful/useful, serve the purpose and complete? How important are they?

Note that later, those requirements are discussed with respect to the possibility to evaluate the climate metrics against those requirements.

Feedback

Question 1
Are the requirements in Megill et al. well-defined, helpful and useful?

Question 2
Would you add requirements?

Question 3
How would you weigh the requirements? (Pairwise comparison on next page)

Available Material
Fact sheet on the definition of climate metrics

Fact sheet on requirements and evaluation approach by Megill et al.

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Question 3
How would you weigh the requirements? (Pairwise comparison on next page)

than / more important	Neutrality	Temporally stable	Compatible with policy	Simple to understand and implement				Sum
Neutrality								
Temporally stable								
Compatible with policy								
Simple to understand and implement								
Sum								

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A.2 Supporting material for World Café on evaluation

World Café
Evaluation of climate metrics

Workshop on climate metrics
Hamburg, 17-18 June 2024

Introduction

In the first world café round, requirements for climate metrics were discussed. Here, we would like to get feedback on the evaluation of climate metrics against those requirements.

Feedback

Question 1

Consider at each individual requirement. Is it possible to evaluate the climate metrics against this requirement?

- E.g. when is a requirement fulfilled/met?
- E.g. Is it possible or necessary to identify limits?
- E.g. is there a unique calculation method?

Question 2

In Megill et al. there is a summary table for the evaluation of every individual climate metric. For those requirements that you feel comfortable with to evaluate, can you try to assess it (-- / - / o / + / ++) (Evaluation table on next page)
It would be helpful to us, if you could provide arguments for your choices.

Question 3

Are there already metrics that can be excluded based on the answer to question 2

Question 4

Are there elements of the climate metrics definition (emission/time horizon/indicator/reference) that can already be selected/excluded?

Available Material

Fact sheet on the definition of climate metrics

Fact sheet on requirements and evaluation approach by Megill et al.

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Question 2 - Rating

Workshop on climate metrics
Hamburg, 17-18 June 2024

Please fill in (-- / - / o / + / ++)

Requirement	Neutrality	Temporally stable	Compatible with policy	Simple to understand and implement			
RF							
GWP							
EGWP							
GTP							
ATR&iGTP							
GWP*							
EGWP*							

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A.3 Supporting material for World Café on gap analysis

World Café
Gap analysis: climate metrics

Workshop on climate metrics
Hamburg, 17-18 June 2024

Introduction

In the first world café round, requirements for climate metrics were discussed. Here, we would like to get feedback on knowledge gaps for the selection or the use of climate metrics.

Feedback

Question 1

What gaps can be identified that may limit the **selection** of a suitable climate metric?

E.g. with respect to assumptions, future scenarios, etc.

Question 2

What gaps can be identified that may limit the **use** of a suitable climate metric?

E.g. with respect to the calculation of the metrics?

Question 3

Each climate metric is weighting the individual CO_2 and non-CO_2-effects in a specific way, e.g. for ATR100 to represent the average temperature response.

Is this approach sufficient to represent the different time horizons?

Question 4

What research should be conducted to fill the gaps in question 1 - 3?

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A.4 Supporting material for World Café on technology impact

World Café
Climate metrics & technology impact

Workshop on climate metrics
Hamburg, 17-18 June 2024

Introduction

In the first world café round, requirements for climate metrics were discussed. Here, we would like to get feedback on possible technology assessments with respect to their climate impact.

Consider that new aircraft/engine concepts and new technologies are developed and tested. To assess their (climate) benefit, their introduction needs to be assessed with a climate metric compared to a reference aircraft.

Feedback

Question 1

Which non-CO_2 emissions/effects should be assessed when technologies are evaluated?

Question 2

How can a non-CO_2 evaluation be coupled to typical technology metrics like weight reduction, fuel burn reduction and others?

Question 3

How to identify win-win opportunities and handle opposing effects (trade-offs) of climate effects of new technologies?

Question 4

How can technologies with different entry-into-service (EIS) be compared? (e.g. should a technology A with EIS 2025 be compared with the same metric (incl. time horizon) like a technology B with EIS 2050?

Question 5

The talk by Feijia Yin showed that location dependent non-CO_2 effects can be considered by using an appropriate network and estimating an emission inventory for a new technology. Would that be an appropriate way to consider the location of emission of different or new technologies? Are there alternatives?

Question 6

How can hydrogen aircraft (combustion or fuel cell) be assessed with the climate metrics? What will be the reference technology?

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