

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. This variation is attributed to the regional and altitudinal dependence of the non-CO₂ aviation effects, such as contrail formation and ozone production from NO_x 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.

Keywords

non-CO₂ 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 alternative fuels



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1. INTRODUCTION

1.1 Objective of the deliverable

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 (see Section 2.2.) and how climate metrics are used to derive equivalent CO_2 emissions before a description of candidate physical climate metrics is given (see Section 3).

Requirements for climate metrics are given in Section 4 and the climate metrics are tested against these requirements to provide an objective basis for a choice of appropriate climate metrics to be used in CLAIM.

In June 2024 a workshop was held in Hamburg to obtain feedback and recommendations from international stakeholders from industry and academia on the procedure outlines 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 better understand the pros and cons of simplified versus advanced calculation methods for climate metrics Section 7 outlines some principle differences including explanations for different aircraft/fuel combinations.

1.2 Aviation climate impact

Aviation contributes to climate change via emissions of CO_2 and non- CO_2 emissions and effects. Slide 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 and methane), 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. Slide 1 shows how the various emissions are influencing the atmospheric composition and cloudiness and thus have a direct (emitted species are greenhouse gases) or indirect (emitted species alter greenhouse gases or cloudiness) impact on the climate.



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Slide 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 (Slide 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 , which differs for different climate species.



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Slide 2 Overview on the principle relation between radiation imbalance (radiative forcing, RF) and future temperature changes.

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 disturbance of the atmospheric composition. While a part of the emitted CO_2 remains in the atmosphere for several centuries, the lifetime of contrails is only a few hours (Slide 3). 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.



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Slide 3 Overview on the lifetime of atmospheric perturbations and the temporal evolution of near-surface temperature changes due to a one-year pulse emission (lower right).



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2. MEASURING CLIMATE EFFECTS BY APPLYING A PHYSICAL CLIMATE METRIC

2.1 Overview

The different climate species affect the climate in very different ways. They differ in terms of sign, lifetime and spatial dependencies. For this reason, it is important to use a measure that considers these effects when assessing the climate impact of technologies or scenarios. A climate metric represents a direct link between the emission and the impact. What is considered as climate impact depends on the question being asked. The further down the process chain you go from emissions to damage (Slide 4, lower right), the larger is its relevance, but the larger is also the associated uncertainty. 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.



Slide 4 Overview of purpose of climate metrics and process chain from emissions to damage.

2.2 Choice of a climate metric

An example from Shindell et al. (2010) shows why it is important to consider the choice of climate metrics carefully (Slide 5)¹. Looking at the radiative forcing of a newly built coal-fired power plant over time, the coal-fired power plant initially has a cooling effect, as the cooling effect of the direct and indirect sulphate effect is stronger than the warming effect of CO₂ emissions. However, due to the long lifetime of CO₂, the CO₂ accumulates in the atmosphere

¹ For further discussions see e.g. Ocko et al. (2017)



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and the warming contribution becomes larger. After about 20 years, the warming effect of CO₂ predominates. If only the radiative forcing after 20 years of use were considered, a coal-fired power plant would be wrongly categorised as climate-friendly.



Slide 5 Temporal development of Radiative Forcing of a coal power plant as an example how important the choice of climate metrics is.

The choice of metric depends on the question to be answered and consists of three subaspects: the emissions development, the climate indicator and the time horizon (Slide 6). Here in this example the emission development is a constant emission over time as the power plant is constantly used, the climate indicator is RF, and the time horizon in the example is 20 years. One think about a reasonable question concerning the climate impact of a power plant as follows:

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

From this an adequate emissions development, climate indicator and the time horizon can be deduced (see also Grewe and Dahlmann, 2015):

Choice of emissions development

Since a mean useful life of a powerplant is 50 years, a sustained (constant) emission scenario for 50 years seems to be a reasonable choice.

Choice of time horizon

The question refers to a *future climate impact* resulting from *its useful life*. Hence, this refers to a minimum time horizon of also 50 years or even longer, considering that *resulting future climate impacts*, refer to a time after end of use, e.g. 100-year time horizon. Note that there is no strict solution and anything between 50 and 100 might be a reasonable choice. (More on time horizons: see slide 17)



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Choice of climate indicator:

The question addresses future climate impact, therefore an indicator based on the near-surface temperature change might be a reasonable choice. Considering that the sign of the temperature response changes in this example, a temporal mean may be 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) might also serve the purpose.

Choice summary:

These considerations lead to selecting climate metric 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.

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

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

For the assessment of this technology, for example, the impact of this technology on temperature change over its typical lifetime over the next 100 years can be analysed. Then, for example, 32 years is taken as the emission development and the average temperature change (ATR) over a time horizon of 100 years is taken as the climate indicator.



Slide 6 Overview of how the choice of Metrics is composed and an metric choice example for technology assessment.



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2.3 Equivalent CO₂ 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 CO₂ emission. The conversion of any emission into CO₂ 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 CO₂ emission of e.g. 1 ton of CO₂ ($CM_{norm}^{CO2} = \frac{CM^{CO2}}{CO2}$) and the total value can be determined that includes all CO₂ and non-CO₂ effects (*CM*^{fot}), which leads to a conversion factor and equivalent CO₂ emissions (*eqCO2*) of the regarded technology with the CO₂ 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 CO₂. Therefore, this approach is equally applicable for technologies that do not emit CO₂, 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, respectively². For the hydrogen case we get a H₂ emission of 14 ktons and a value of the ATR100 of 4 mK. Hence for the kerosene aircraft we obtain:

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

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

which gives a CO₂ equivalent emission of

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

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

which gives a CO₂ equivalent emission of

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

² Numbers are for illustrative purpose, only



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3. EXISTING CLIMATE METRICS

There are many different climate metrics in the literature. Slide 7 provides a schematic overview of the most commonly used climate metrics for aviation. In the following slides (Slide 8 to Slide 14) the individual climate metrics are presented in more detail.



Note: "A" = Absolute climate metric, e.g. AGWP, AGTP ATR is absolute; rATR is relative

Slide 7 Schematic overview of the most commonly used climate metrics

3.1 Radiative Forcing (RF)

Radiative Forcing (RF, slide 8) describes an annual mean change in the atmospheric radiation budget that eventually will lead an equilibrium temperature change (Δ T). The RF definition has evolved over time to best fit the linear relation between RF and the resulting equilibrium temperature change (Δ T). Nowadays, rapid atmospheric adjustments, such as stratospheric 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 feedback is considered in the term efficacy.



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Slide 8 Overview of the Radiative Forcing concept and on the right various types of Radiative Forcing (instantaneous, adjusted, and effective radiative forcing)

3.2 Global Warming Potential (GWP)



Slide 9 Overview of Global Warming Potential (GWP)



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3.3 Efficacy-weighted Global Warming Potential (EGWP)



where r_i is the efficacy taken from Ponater et al. (2006) - see the Table (right).

members.

t₀+H

Slide 10 Overview on Efficacy-weighted Global Warming Potential (EGWP)

3.4 Global Temperature Change Potential (GTP)



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3.5 Average Temperature Response (ATR)







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3.6 GWP* and extended GWP*

GWP* (1)

- RF from SLCPs depends on the emission rate and atmospheric lifetime
- Equivalence has been shown between a step change in SLCP rate and a pulse emission of CO₂
- GWP* (<u>Allen et al. 2018</u>) defines CO₂-e* emissions that achieve temperature stabilisation when net zero.

$$E_{\rm CO_2-e^*} = \rm GWP_H \times \frac{\Delta E_{\rm SLCP}}{\Delta t} \times H$$



Slide 13 Principle concept of GWP^{*}. The blue line shows examples of SLCP emissions and the red line respective eq. CO_2 emissions derived by using the climate matric GWP^{*} with dt=20 years.



Slide 14 Extension of GWP* considering short- and longer-term climate pollutants. On the right: Figure from Cain et al.: Methane emissions (dotted line) and calculated respective temperature change (dashed line) is given in black for three future scenarios (a-c). The coloured lines represent the estimated temperature change based on climate metrics, showing that the extended GWP* (magenta) represents the temperature change best compared to GWP100 (cyan) and GWP* (orange).



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4. REQUIREMENTS OF A CLIMATE METRIC

A metric for assessing the climate impact of aviation emissions should fulfil various requirements. An overview from Megill et al., 2024 is shown in Slide 15. More details about the requirements and the results for the different metrics are provided in Slides 15 to 18.

Climate Metric Requirements



Climate metrics shall:

- 1. Neuturally represent the chosen climate indicator;
- 2. Be temporally stable;
- 3. Be compatible with existing climate policy;
- 4. Be simple to understand and implement

Slide 15 Overview of Climate metric requirements



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4.1 Climate metric neutrality

The first requirement is the neutral evaluation of the climate metric meaning 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 a 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. 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 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.

To assess climate metric neutrality, a Monte Carlo simulation was carried out in which the following parameters were randomly varied within the specified limits (see Slide 16 for details) to mimic different technologies: Fuel consumption, NO_x emission, flight altitude, contrail distance, fuel, year of fleet introduction and background concentration.



Slide 16 Parameter ranges for Monte Carlo simulation to investigate climate metric neutrality

The peak temperature and the climate metric are then compared for arbitrary pairs. If both values have the same sign (upper right and lower left box, Slide 17), a neutral evaluation is assumed. If they have different signs (upper left and lower right box), the result is an incorrect fleet pairing.



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REQ 1: Climate Metric Neutrality (2)



• Climate metric "neutrality" is judged by:

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

- ΔT is the climate objective, here the peak/average temperature change
- Climate metrics are compared for different time horizons by counting the number of "incorrect fleet pairings", i.e. those in the top-left and bottom-right quadrants



Slide 17 Illustration of which fleet pairings are identified as incorrect

The number of incorrect fleet pairings in dependency of the time horizon can be seen on the picture on the right-hand side of Slide 18.



Slide 18 The number of incorrect fleet pairings in dependency of the time horizon



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4.2 Temporal stability

Another requirement for a climate metric is stability over time, which refers to whether its ability to accurately represent climate impacts remains consistent over different time periods. Here, we analyse how the CO₂ equivalents of two different scenarios (CORSIA and FP2050) change over time (Slide 19). RFI, GWP, EGWP, GTP and ATR show relatively similar trends, while GWP* and EGWP* show significantly decreasing CO₂ equivalents for CORSIA from 2035 and even clearly negative values for FP2050 (Slide 20). This would suggest that aviation is contributing to cooling here, although only emissions are falling.



Slide 19 Principle of temporal Stability



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Slide 20 Temporal development of metrics for CORSIA and FP2050 scenario



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4.3 Compatibility with climate policy

It is important that climate metrics are compatible with current climate policy framework. While this is the case for all conventional metrics, it is not the case for GWP* and EGWP*, as these metrics effectively have a second time horizon (Slide 21).



Slide 21 Compatibility with current climate policy framework



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4.4 Climate metric transparency

For climate metrics to be accepted, they should be as easy to understand and transparent as possible. While endpoint metrics like RF and GTP are easiest to understand, integrated metrics are a bit more complex (Slide 22). In-depth understanding is necessary for GWP* and EGWP*.

REQ 4: Climate Metric Transparency



- Endpoint climate metrics RF and GTP are easiest to understand and implement.
- Integrated climate metrics GWP, EGWP, iGTP and ATR and more complex and it can sometimes be difficult to ascertain the impacts of individual species
- Least transparent and simple are the GWP* and EGWP*. Use of these climate metrics requires in-depth understanding of the equivalency between SLCP emission rates and CO₂ pulses. It can be difficult to understand the response even to simple emission profiles.

Slide 22 Climate metric transparency



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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).

All climate metrics have inherent trade-offs and favour certain aircraft designs over others. Therefore, the choice of climate metric is always the result of a trade-off. Slide 23 gives a summary of how well the different metrics fulfil our requirements. An overview of the performance of the considered physical climate metrics with respect to the identified requirements is presented in Slide 23. It shows rating of how well each metric satisfies respective criteria. Additional tests, such as comparing responses to a pulse versus a constant emission, influenced the final ratings. Overall, this table indicates that both ATR and EGWP represent options that meet all four requirements with at least an "acceptable" result (three "0" and one "++"). Therefore, we evaluate ATR and EGWP as overall good compromise. Based on this analysis, we recommend ATR and EGWP metrics, depending on what policymakers require.

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, in that it can more accurately represent the 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 right time horizon remains a challenge. However, as the sensitivity decreases for larger time horizons – we thus in general recommend using time horizons above 70 years. To be consistent with existing policy, 100 years 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.



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Overview: Choice of Climate Metric*



Climate Metric	REQ 1 Neutrality	REQ 2 Stability	REQ 3 Compatibility	REQ 4 Simplicity	Notes
RF		-	-	+	
GWP (reference)	0	0	0	0	
EGWP	++	0	0	0	Best overall (radiative forcing)
GTP	-	-	0	+	
iGTP	++	0	-	0	Unit more complex than ATR
ATR	++	0	0	0	Best overall (temperature)
GWP*	0				
EGWP*	+++				

*trade-off only representative

Slide 23 Overview how well the different metrics fulfil the above-mentioned requirements. Evaluation of how well a metric satisfies the respective criterium ranges from +++ ("very high") to "---" (very low).

Recommendation:

As stated above, there is no general best climate metric, nevertheless the trade-off analysis allows a choice of a metric to be recommended for the use in Clean Aviation impact 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 CO₂ and non-CO₂ 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
- 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, "not sensitive 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-CO₂ 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 twodimensional 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 CO₂ optimizations? What would be the acceptable limit of uncertainty or associated risk?



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Challenging the technology impact

- All CO₂ and non-CO₂ emissions and impacts should be regarded, including NO_X, nvPM, H₂O, 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 CO₂, even though CO₂ is not emitted, as it better fits into current considerations. (Note that for a given climate metric, the equivalent CO₂ emission can be calculated for H₂).
- Climate metrics should also be able to consistently estimate climate impacts of subfleet 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 Conclusion

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.

<u>*Response:*</u> 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 "Not sensitive 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.

<u>Response</u>: 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.

 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.

<u>Response</u>: 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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<u>*Response:*</u> 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

<u>*Response:*</u> 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

<u>Response</u>: 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

<u>Response:</u> 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 <u>Response</u>: 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 <u>Response:</u> 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 Methodology of the study

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. Climate impact of CO₂ emissions can be directly calculated from an almost linear relationship with the amount of fuel used. Including the impact of non-CO₂ effects, which is of similar size to or even greater than that of CO₂, 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-CO₂ 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 CO₂ equivalents of non-CO₂ 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 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). 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 precalculated 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 CO₂, NO_x, H₂O 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 CO₂ and water vapor emissions. The difference in the NO_x impacts is caused by a larger NO_x-O₃ 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 longrange 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.

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

Table 7.1: Overview of the show cases.

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 Longrange 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.



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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.

 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 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.

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 CO₂, NO_x, H₂O emissions and contrails in the total CO₂ 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 CO₂ 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 eqCO₂. 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). CO₂ 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 CO₂ 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 CO₂ 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 CO₂ dominates the impact. In a continuous scenario, the short-term effects of NO_x emissions are maintained, while warming effect of CO₂ 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 (O₃) 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 (CH₄), another greenhouse gas. The reduction of CH₄ also leads to the lower production rate of O₃ 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 (CH₄, O₃ and PMO) differs for our show cases in terms of their CO₂ equivalents per emitted kg CO₂. 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 CH₄ (Fig. 7.6). As the result, NO_x emissions have a relatively small net warming effect compared to that of CO₂. At FL360 in the Long-range SA and TA show cases, the warming from O₃ is higher, while the net cooling effect is lower compared to the show case Regional. The CO₂ equivalents of O₃ for both Long-range show cases are about twice as large as the combined effects of CH₄ 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 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 contrail climate impact is reduced owing to a lower soot number emission that lead to 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 CO₂-equivalent emissions for CO₂, NO_x, H₂O, 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 eqCO₂ fractions of CO₂ 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 CO₂. Since we apply an efficacy of contrails of 0.43, their impact relative to CO₂ 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-CO₂ 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 CO₂. Market-based measures like the ETS apply the single-basket approach where a single price for CO₂-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 CO₂ 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(NO₂)/kg from Lee at al. (2021) with the values for each show case listed in



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Figure 7.9: Total CO₂-equivalent emissions relatively to CO₂ 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 CO₂-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 CO₂, NO_x, H₂O 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 CO₂-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 CO₂ 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 CO₂-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 CO₂-equivalent emissions relatively to the emitted CO₂ calculated with AirClim model using the ATR100 climate metric. Colours indicate the relative contributions of CO₂, NO_x, H₂O and contrails to the total. CO₂ 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 CO₂ 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 CO₂-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 CO₂-equivalent factors based on GWP100 are estimated relatively to the emitted CO₂, before the offset is subtracted, i.e. <u>not</u> relative for the life-cycle CO_2 emissions³. For the assessment of the climate impact, we consider effective CO_2 emissions reduced by the offset corresponding to the SAF fraction. The CO₂-equivalent factors for CO₂ 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 CO₂-equivalent factor falls below 1. Additionally, the non-CO₂ effects on 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).

³This is a technical detail, only, that is not influencing the climate assessment, but keeps the range of the CO₂-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 emissions 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 that leads to an assumed 95% reduction of CO_2 lifecycle emissions 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 Longrange 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 CO₂-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 CO₂ 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



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SAF, respectively. The corresponding values of multipliers derived with the ATR100 metric for 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. 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-CO₂ 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.



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APPENDIX

A.1 Supporting material for World Café on requirements

World Café Requirements for climate metrics



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 Meqill et al.



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Question 3

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Workshop on climate metrics Hamburg, 17-18 June 2024





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A.2 Supporting material for World Café on evaluation

World Café **Evaluation of climate metrics**



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

 Question 1

 Consider a teach individual requirement. Is it possible to evaluate the climate metrics against this requirement?

 Eg. when is a requirement fulfilled/met?

 Eg. Is it possible or necessary to identify limits?

 Eg. is there a unique calculation method?

Question 2

Construction 2 in Megili 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 (-7 - 70 + 7 + 1) (Sebaution 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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A.3 Supporting material for World Café on gap analysis

World Café Gap analysis: climate metrics



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 <u>selection</u> 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 <u>use</u> 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 **of** Climate metrics & technology impact



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-CO2 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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