CEAS Aeronautical Journal
https://doi.org/10.1007/s13272-026-00980-0

REVIEW PAPER

Review of methods for assessing the climate impacts of aviation technologies and the resulting best practices

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Received: 24 September 2025 / Revised: 2 April 2026 / Accepted: 28 May 2026

Abstract

The climate impact of aviation resulting from both CO_2 emissions and non-CO_2 effects is gaining attention from aviation stakeholders seeking to identify potential mitigation options. There is a need to consolidate the use of assessment methods and climate metrics, which are required to convert aviation non-CO_2 effects into CO_2-equivalent emissions. We provide an overview of the operational, technological and scenario-based climate impact assessment methods that have been applied in literature as well as considerations and requirements for the choice of climate metric. We propose a four-layer technology climate impact assessment methodology, which includes: (1) the technology parameters, such as entry into service and temporal and spatial network use; (2) the calculation of three-dimensional aircraft trajectories and emission inventories; (3) the calculation of radiative forcing and induced temperature change time series; and (4) the overall climate impact, measured using a climate metric. We recommend two climate metrics that best fulfill the requirements, the Average Temperature Response (ATR100) and the Efficacy-weighted Global Warming Potential (EGWP100), both over 100 years. Additionally, we discuss further steps, such as the understanding of the most sensitive parameters in this approach, how uncertainties can be included to provide robust estimates, aspects of verification and update possibilities for new findings in research.

Keywords Aviation climate impact · Aviation emissions · Climate impact technology assessment · Climate metrics · Contrails · Nitrogen oxides

Abbreviations

AS4D	AirClim Surrogate Model for Design
CiC	Contrail induced cloudiness
CM	Climate metric
CO_2-Eq	Equivalent CO_2 emission
EF	Energy forcing
EI	Emission index
EIS	Entry-into-service
EU ETS	European Union Emissions Trading System
GRIDLAB	Global Air Traffic Emission Distribution Laboratory
HER	Hybrid-electric regional
IPCC	Intergovernmental Panel on Climate Change
ISO	Intermediate-stop operations
LCA	Life cycle assessment
MDO	Multidisciplinary design optimization
MF-BWB	Multi-fuel blended wing body
NM	Nautical miles
REG	Regional jet market segment
SA	Single-aisle market segment
SAF	Sustainable aviation fuel
SMR	Short-medium range market segment
SRL	Scientific readiness level
TA	Twin-aisle market segment

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1 Introduction

The climate impact of aviation results from both CO_2 emissions and non-CO_2 emissions and effects. The latter comprise the emission of NO_x, H_2O, particulates and the formation of persistent contrails [1]. These emissions and effects alter the atmospheric abundance of species and the cloudiness, leading to changes in the Earth's radiation budget, which is quantified by the concept of Radiative Forcing (RF). RF was introduced as the change in the net (downward–upward) flux of energy at the top of atmosphere caused by perturbations in the Earth system, calculated before the climate system responds. As a consequence, the climate is changing, affecting near-surface temperatures as well as other atmospheric parameters such as precipitation patterns and extreme weather events. Among these, the near-surface temperature change is a frequently used and a well-accepted indicator of climate change [2, 3] which is addressed by the Paris Agreement [4].

While the assessment of the climate impact of the aviation sector is based on a well-established method, including the choice of a climate metric, this is not the case for the climate impact assessment of individual future aviation technologies. Aviation climate impact assessments [1, 5–7] mostly apply a backward-looking approach, using RF and Effective Radiative Forcing (ERF) to analyse the impact of aviation emissions from roughly 1940 to "present" (at the time of the respective publication). ERF is calculated after rapid adjustments in atmosphere, e.g. changes in clouds, continental temperature which affect radiative transfer, have been accounted for. A few studies also refer to temperature changes, which additionally use the concept of efficacy to include slow feedback processes such as changes in ocean temperatures [e.g. 2, 8, 3]. The efficacy parameter r_i for aviation impact species *i* is defined as the ratio of its climate sensitivity λ_i (i.e. temperature response per unit radiative forcing, in $\mathrm{K}/(\mathrm{W\ m^{-2}})$) to the climate sensitivity of CO_2.

The main differences of these aviation climate impact assessments, as compared to the technology climate impact assessments, stem from the following factors: (1) historical evolution of aviation emissions is well constrained due to availability of data and long-term records as compared to our knowledge of future technology scenarios; (2) the focus is on the effects of past, accumulated impacts on the present day (backward-looking approach), rather than on impacts from future technologies on the climate at a later point in time; (3) the background conditions, e.g. impact from other sectors, are well constrained, whereas for future conditions different scenarios exist.

In Sect. 2, we provide an overview of climate impact assessments of aviation mitigation options. Section 3 then presents and discusses requirements for the choice of climate metrics for aviation. Based on this broad, though certainly not exclusive overview, we derive a best practice for a technology climate impact assessment workflow (Sect. 4.1), present examples of its application (Sect. 4.2), and discuss knowledge gaps in both the sensitivities in the workflow and the uncertainties in the assessment itself (Sect. 5).

This work was performed within the CLAIM project (Clean Aviation Support for Impact Monitoring, https://www.claim-project.eu/) funded by European Union, where a best practice for a climate impact assessment was developed and presented in two workshops to stakeholders from industry, academia and policy. The detailed and fruitful feedback is incorporated here in the recommended methodology (Sect. 4).

2 Climate impact assessments

In this section, we provide an overview of the literature and projects that described and performed climate impact assessments. We focus on the methods that have been applied rather than the findings. The metrics used in assessments are defined in Table 1 and main characteristics of these methods are summarised in Table 2. We consider three main areas: operational mitigation options (Sect. 2.1), technological mitigation options (Sect. 2.2), and analysis of various scenarios, i.e. projections for future air traffic (Sect. 2.3). We summarise the methodological approaches in Sect. 2.4.

2.1 Operational climate mitigation options

The avoidance of climate sensitive regions (e.g. contrail avoidance) is one of the most promising operational climate mitigation options. The modelling concept for the approach in the EU projects REACT4C [29], ATM4E [30] and FlyATM4E [31] is presented in Grewe et al. [9]. They calculated the impact of a local emission, assuming specific weather situations, resulting in 4D datasets (three spatial coordinates and time), so-called climate change functions that describe expected climate impacts per aviation emission or flown distance for CO_2, NO_x, H_2O emissions and contrails. By multiplying the datasets with 4D emissions of planned flights, trade-off between CO_2 and non-CO_2 climate effects for climate optimized routing could be analyzed. They considered a pulse emission and several pathways of projected future emissions (emission scenarios). In their Table 7, they summarised the research question as "What is the short/long-term climate impact of the REACT4C re-routing strategy?" and concluded that there is the need to focus "on the metrics F-ATR20, F-ATR100, P-GWP20 and P-GWP100 in future applications". Here and throughout the paper the first

Table 1 Metrics used for evaluation of climate impact of aviation technologies

Metric	Acronym[1]	Description
Radiative forcing	RF	The change in the average net radiative flux induced by emissions at a specific time horizon
Global warming potential	GWP	The time-integrated RF over a specific time horizon, relatively to the integrated forcing from an equal mass of CO_2
Efficacy-weighted global warming potential	EGWP	The GWP multiplied by the corresponding efficacy. Introduced as a derivative of the GWP to align more closely with temperature-based metrics
Global temperature change potential	GTP	the change in global mean surface temperature at a specific time horizon, relative to that of CO_2
Integrated GTP	iGTP	The time-integrated GTP over a specific time horizon proposed as a temperature-based alternative to GWP
Average temperature response	ATR	The average global surface temperature change over a specific time horizon ($ATR=\frac{1}{H}iAGTP$). Designed for comparing aviation technologies
GWP starred	GWP*	A modification of the GWP designed to compare the effect that short-lived pollutants such as CH_4 in terms of CO_2 warming equivalent
Efficacy-weighted GWP starred	EGWP*	GWP* multiplied by the corresponding efficacy of the species

[1]These climate metrics in absolute form are denoted with 'A' in front of the metric. This does not apply to the ATR metric, which is in the absolute form

letter F and P denote future scenarios and pulse emissions, respectively, and the numbers following the metric acronyms denote the adopted time horizons in years.

Teoh et al. [10] investigated trade-offs in climate effects resulting from contrail avoidance in the Japanese air space. They concentrated on pulse emissions and calculate the Energy Forcing (EF), defined as the total energy loss or gain by the Earth system caused by the contrail during its lifetime. EF is essentially equivalent to GWP100 with other units (see supplement of Irvine et al. [32] and Borella et al. [33]). GWP100 is also used directly for the CO_2 climate impact and then recalculated into EF. Hence, we regard GWP100 as the basic underlying metric in this study. Similar approaches were used in Quante et al. [34], Borella et al. [33] and others.

Besides those operational measures that take advantage of the day-by-day variation in the weather system and the large variability in aviation climate effects, additional strategic operational measures were examined. Linke et al. [11] and Zengerling et al. [12] analysed the climate impact mitigation potential for intermediate stop operations (ISO), which refers to one or more stops at airports between the origin and final destination of an aircraft allowing it to transport less fuel over a long distance and thus to reduce the amount of fuel burnt over the mission. They used 3D inventories of aviation emissions that either include or exclude ISO. The studies adopted an increasing emission evolution together with the ATR20 and ATR100.

Similar to this approach, the potential for reducing the climate impact through the use of aerodynamic formation flight was analysed in Dahlmann et al. [13]. They also employ ATR100 to quantify the climate impact. Emission inventories were calculated for the most popular airport pairs assuming that the emissions increase according to the future Fa1 scenario as defined in IPCC [35].

Frömming et al. [14] investigated general flight altitude changes that are implemented from the year 2000 and follow a future aviation scenario with various variations (lasting for 15 years, constant after 2050, following the future scenario). The aviation emissions are based on detailed 3D-inventories for the year 2000. The RF and the temperature change 100 years after the start of the implementation (i.e. 2100) of this strategy is used as a climate metric (RF100, AGTP100). Here and throughout the paper, "A" in front of the metric denotes an absolute climate metric (e.g. AGTP, AGWP, AEGWP), with exception of the ATR metric. Similarly, Matthes et al. [15] investigated general cruise altitude changes with an updated 3D-emission inventory and using annual historic emissions form 1940 to 2006 (66 years) to analyse RF and temperature changes (AGTP) for the year 2006.

2.2 Technological climate mitigation options

Svensson et al. [16] investigated lower flying liquid hydrogen-driven (LH_2) aircraft in comparison to a kerosene-driven aircraft. They combined atmospheric modeling results to provide an altitude-dependent GWP response function for NO_x and H_2O emissions. Schwartz-Dallara and Kroo [17] applied an optimisation approach to derive aircraft designs that minimise their climate impact. They used a typical mission, i.e. a typical aircraft trajectory and emissions along that trajectory and combined it with pre-calculated atmospheric RF responses of aviation NO_x, H_2O emissions and contrails that were obtained by using a 3D-inventory [36, 37]. They considered a 30 year service life of the aircraft (lifetime emission, L) and analysed the averaged temperature response over 500 years, where the temperature change after the aircraft use is weighted by a discount rate r (ATR_r). Schwartz-Dallara and Kroo [19] used the same methodology, though concentrated on sustained emissions and the global temperature potential over 100 years (S-GTP100).

Table 2 Overview of the characteristics of climate impact assessments approaches described in the literature

Project/institution	Spatial emission	Temporal emis	Climate metric	Time horizon H [yr]	Topic	References
Operational						
REACT4C, ATM4E, FlyATM4E	4D trajectory data	F-ATR, S-ATR, S-AGTP, P-GWP		20, 100	Climate-optimised routing	[9]
Imperial college/DLR	4D trajectory data	P	GWP (EF)	100	Contrail-optimised routing	[10]
DLR/ClimOP	3D inventories	F	ATR	20, 100	ISO	[11, 12]
FormIC	3D inventories	F	ATR	50, 100	Formation flight	[13]
TRADEOFF	3D inventories	Var. F	RF, AGTP	100	Cruise altitude changes	[14]
REACT4C	3D inventories	H	RF, AGTP	66	Cruise altitude changes	[15]
Technological						
CRYOPLANE	Mission	P	GWP	100	LH_2-fuelled aircraft	[16]
Stanford	Mission + response from 3D inventory	L	ATR_r^1	500	Aircraft design	[17]
GLOWOPT/TU Delft	As above	L	GTP	100	Aircraft design	[18]
TUM, AIRBUS	As above	S	GTP	100	Aircraft design	[19]
MTU	As above	S	GTP	100	Aircraft design	[20]
CATS	3D inventory	L	ATR	100	Aircraft design	[21, 22]
AHEAD	3D inventory	F	ATR	100	MF-BWB	[23]
WeCare/ FrEACs	3D inventory	F	ATR	100	Strut-braced wing aircraft	[24]
EXACT	3D inventory	L	ATR	100	Synthetic kerosine and green hydrogen powered mid-range aircraft	[25]
EXACT	3D inventory	P	GWP, ATR	100	LCA of LH_2-aircraft design	[26]
MINIMAL	3D inventory	F	ATR	100	Engine climate optimisation	[27]
Scenario						
ETH	Global means	F	GWP*	100	Pathways to climate neutrality	[28]
IMPACT	Global means	F	RF, dT	n.a	Future aviation CO_2 impacts	[2]
ECATS	3D inventories	F	RF, dT	n.a	Aviation, Paris agreement	[3]

The assessments were performed for a pulse (P), sustained (S), lifetime (L), future(F) and historic (H) temporal evolution of emissions; ISO, MF-BWB and LCA stand forintermediate-stop-operations, multi-fuel blended wing body and life-cycle assessment, respectively

[1]This version of ATR includes a discount rate r after the aircraft is taken out of service. Note that for $r = 0$ the definition is identical to ATR used in other studies

Similar approaches were used by Proesmans and Vos [18] who relied on a linearisation of the same response functions [17], but used a slightly changed temporal evolution of the emissions with a ramp-up phase, a maximum use of 5 years and a phase-out that leads to 65 years of emissions. Pouzolz et al. [20] applied the same atmospheric response functions for the climate optimisation of aircraft design and an aircraft propelled by a water-enhanced turbofan engine, respectively. However, they used a pulse emission and GWP as the underlying climate metric.

Koch et al. [21] and Dahlmann et al. [22] investigated the relation between changes in climate impact and operational costs when changing cruise speed and altitude. They optimised an aircraft for an eco-efficient setting of altitude and speed. The climate impact assessment uses 3D inventories for each of the considered settings of cruise speed and altitude and assumes a lifespan of 32 years where emissions take place (L) and applied the climate metric ATR100. Grewe et al. [23] investigated the climate impact of a multi-fuel blended wing body. The engine featured two combustion chambers: the first burns hydrogen, the second sustainable aviation fuel using flameless technology. A 3D inventory was calculated for this aircraft. The temporal evolution of the emissions was characterised by an entry into service in 2050 with a constant increase of the fleet size until 2075. After 2075 the overall aviation emissions were assumed to increase (F) and the market share of the AHEAD aircraft remained constant. A comparable approach was used in Grewe et al. [24] for the assessment of a strut-braced wing. Both studies based the climate impact evaluation on ATR100. While the above studies assessed emissions during flight, only, Ramm et al. [26] investigated the whole life cycle and based their estimates on a pulse emission combined with GWP100. For the emissions, they based their assessment on a 3D European emission inventory, while Silberhorn et al. [25] investigated the impact of synthetic kerosene and green hydrogen powered mid-range aircraft using ATR100 for a lifetime emission.

2.3 Scenario assessments

For completeness, several scenario assessments are included in Table 2 to provide a more comprehensive understanding of assessment strategies. All these studies have in common that future temporal changes in aviation emissions and their impacts are the main objectives, whereas operational and technological assessments utilize the temporal evolution of emissions as merely a means for calculating the impact of a mitigation option. Therefore, the temporal evolution of the emissions is marked with an F (Table 2).

Climate metrics are then often used to convert the impact of non-CO_2 effects into equivalent CO_2 emissions. For this conversion, Brazzola et al. [28], for example, used the climate metric GWP* [38] that includes a time horizon and is sensitive to changes in the emission scenario. Note that the star-metrics are generally evaluated to be suitable for scenario calculations, but unsuitable as an emission metric [39, 40] or for technology assessments [41, see also Sect. 3]. Terrenoire et al. [2] concentrated on the impact of future CO_2 emissions and hence a detailed 3D inventory is not necessary, as the location of the emission is not relevant for its impact in this case. They investigated the temporal evolution of the associated RF and temperature changes with the OSCAR model and discussed changes for 2050 and 2100 in more detail, without the necessity to apply climate metrics, although the discussion of the temperature change in the year 2100 can also be interpreted as AGTP(2100). Similarly, Grewe et al. [3] analysed top-down and bottom-up emission scenarios and tested the alignment with the Paris Agreement. Since also non-CO_2 effects were included, detailed 3D emission inventories were calculated and the discussion concentrated on temperature changes, and identified time horizons when a temperature change is surpassing a certain limit.

2.4 Summary on assessment characteristics

The overviews of both operational and technological mitigation options, discussed in Sects. 2.1 and 2.2, share a common feature: they both incorporate a detailed 3D emission analysis that takes into account the location of the emissions. Figure 1 presents an overview of climate indicators and respective time horizon values adopted in the operational (blue), technological (red) and scenario (orange) assessments listed in Table 2. It shows that that for technology climate impact assessments, ATR was frequently combined with life-cycle (L) or future increasing emissions (F)

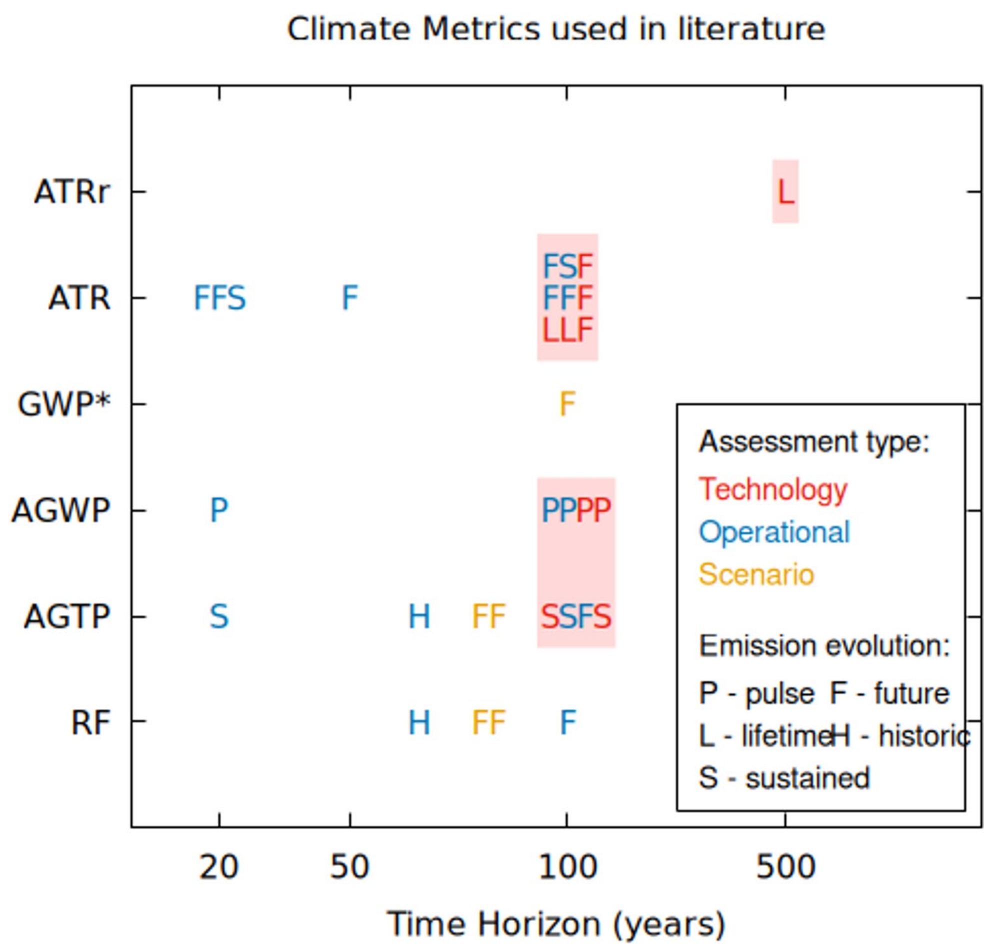

Fig. 1 Overview of the climate metrics used in climate impact assessment studies (see Table 2). The temporal evolution of emissions are abbreviated with letters P, S, L, F, H for pulse, sustained, lifetime, future and historic aviation evolution, respectively. The colors blue, red and orange represent operational, technological and scenario measures, respectively. For visibility reason, the symbols are slightly displaced. The red shaded area indicated climate metric combination used for technology climate impact assessments

to describe the temporal evolution of the technology's emissions and AGWP and AGTP were combined with pulse (P) and sustained (S) emissions. On the other hand, the selection of the climate metrics in operational climate impact assessments varies much more. This might be seen as obvious, since a technology option requires a much longer time for implementation and hence short-term climate metrics are seen as inappropriate.

3 Choices for climate metrics in technology climate impact assessments

3.1 Introduction

A climate metric provides a common scale for comparison of the relative impacts of various atmospheric species with vastly different timescales such as CO_2, NO_x, contrails and contrail-cirrus (contrail induced cloudiness, CiC). In particular, climate metric are used to convert the impact of non-CO_2 emissions and effects into CO_2 equivalents serving as a single measure for mitigation strategy development and in single-basket schemes, e.g. the European Union Emission Trading System (EU ETS).

There is no consensus in the climate and atmospheric modeling community on the most suitable climate metric to objectively compare impacts of using different strategies for aviation fuel burdens [e.g. 42]. Climate metrics proposed in the literature for aviation impact assessments are presented in Table 1 (see Fig. 1 for an overview of the climate metrics used across different assessments and their respective time horizons). RF is the earliest climate metric, which quantifies the perturbation of Earth's energy balance induced by anthropogenic emissions (see [43] for an overview). The concept of RF has been refined over time to account for rapid atmospheric adjustments and to distinguish instantaneous, stratosphere-adjusted, and effective forcing components. Here, we adopt the stratosphere-adjusted RF defined as the change in the average net radiative flux at the tropopause after allowing stratospheric temperatures to readjust to a new radiative equilibrium, while holding surface and tropospheric temperatures fixed at their unperturbed values.

The GWP metric is defined as the time-integrated RF for either pulse or sustained emissions relatively to that from an equal mass pulse of CO_2 over a specific time interval (*H*) [44]. It has been traditionally used in policy-making, for example, in single-basket schemes such as EU ETS and in the recently established aviation non-CO_2 Measurement, Reporting, and Verification framework. An advantage of the GWP for a pulse emission is that it can be calculated with a simple analytical approach, for which data are readily available. However, the GWP has been criticised over years, especially when considering aviation effects that do not depend on emissions alone [42, 45] and due to its sensitivity to the time horizon [e.g. 46]. Moreover, this metric does not fully capture the complex interactions and feedback mechanisms in the climate system that influence actual temperature changes and climate impacts [42, 47]. Many alternative physical metrics have been proposed in the literature such as the end-point metrics RF and GTP, and integrated metrics EGWP, iGTP, and ATR (see Table 1 for details). Furthermore, flow-based metrics GWP* and EGWP* metrics have been introduced recently to include the effect of short-lived climate pollutants.

The choice of a climate metric strongly influences the outcome of the impact evaluation and potentially affects decision making. It involves decisions on the emission evolution scenario (pulse, sustained, etc.), the time horizon and the climate indicator (AGWP, ATR, etc.). Because of the different timescales of CO_2 and non-CO_2 effects, the chosen time horizon influences the perceived importance of different emissions [42, 48]. Additionally, the temporal emission evolution weights short-lived effects more when considering scenarios rising over time, compared to declining scenarios or pulse emissions [49]. Hence, different metrics can yield values with varying signs, highlighting the importance of selecting the most appropriate metric for policy decisions [42]. Analysis of potential contrail avoidance strategies indicates that climate benefit from flight rerouting depends on both the time horizon and metric definition [33]. Applying new metrics like GWP* within existing climate policy contexts should be approached with caution, as their use in interpreting the Paris Agreement goals leads to inconsistencies in the mitigation framework and potentially undermine the net-zero CO_2 emissions target [50].

Selecting an appropriate climate metric thus involves decisions regarding the physical indicator represented by the metric (e.g. radiative forcing or temperature), the choice between end-point and integrated metrics, the adopted time horizon and the underlying emission scenario. For aviation emissions, a further challenge with the choice of a metric is that the emission effects vary with altitude, location, and emission time. A method that accounts for this dependence as well as changes in the background relies on simple climate response models which we will discuss in Sect. 4.3.

In summary, the multiplicity of climate metrics for aviation imposes a perceived ambiguity that potentially leads to a hurdle in the acceptance of a climate impact technology assessment. Grewe and Dahlmann [51] stress that not all climate metrics are equally suited for addressing a specific research question, and the careful framing of such questions significantly reduces this perceived ambiguity. Megill et al. [41] further narrowed down the climate metric selection process by defining requirements that are for the most part taken from literature and testing climate metrics against those requirements by contrasting a scenario analysis and the climate metrics values for 10,000 potential aircraft fleets. In the following, we summarise and discuss these results as a basis for a recommendation and best practice given in Sect. 4.

3.2 Requirements for climate metric evaluation

To evaluate the applicability of existing physical metrics to the aviation industry, Megill et al. [41] formulated main requirements for physical climate metrics based on the primary needs of aviation, including trajectory optimisation, aircraft design, and policy development. Performance of both traditional and new climate metrics was then evaluated against these requirements. The proposed set of requirements stipulates that a climate metric must be

- *Neutral* (i.e. free of normative or technology-specific bias), which includes two aspects: first, that a climate metric objectively represents results from a respective scenario assessment and second, that there is no bias and value judgement towards a specific technology or design;
- *Temporally stable*, which refers to its ability to represent climate impacts consistently over different periods of time and be insensitive to small variations of the time horizon;
- *Compatible* with existing climate policy;
- *Simple to understand and implement* for non-specialists (requirement of the climate metric transparency).

Below, we briefly discuss each requirement and summarise the outcome of evaluation of physical metrics (see Table 2 in Megill et al. [41] for definitions of the metrics) against these requirements. Note that the integrated GTP (iGTP) and the ATR metric are in principle the same, differing only by a factor of H and expressed in units of mK yr and mK, respectively.

Climate metric neutrality. The first requirement implies that a climate metric should neutrally represent the chosen climate indicator, which describes the climate change caused by the considered technology. In practice, it means that the climate metric should be unbiased towards any specific aircraft concept changes. The peak temperature was selected as an indicator of climate change for evaluation of metric neutrality (see Sect. 3.4 for a discussion of this choice). A metric correctly represents the temperature change when the difference in the climate impacts of two technological options 1 and 2 evaluated with this climate metric (CM) has the same sign as the difference in their temperature changes (ΔT)

$$(CM_1 - CM_2) \times (\Delta T_1 - \Delta T_2) > 0. \quad (1)$$

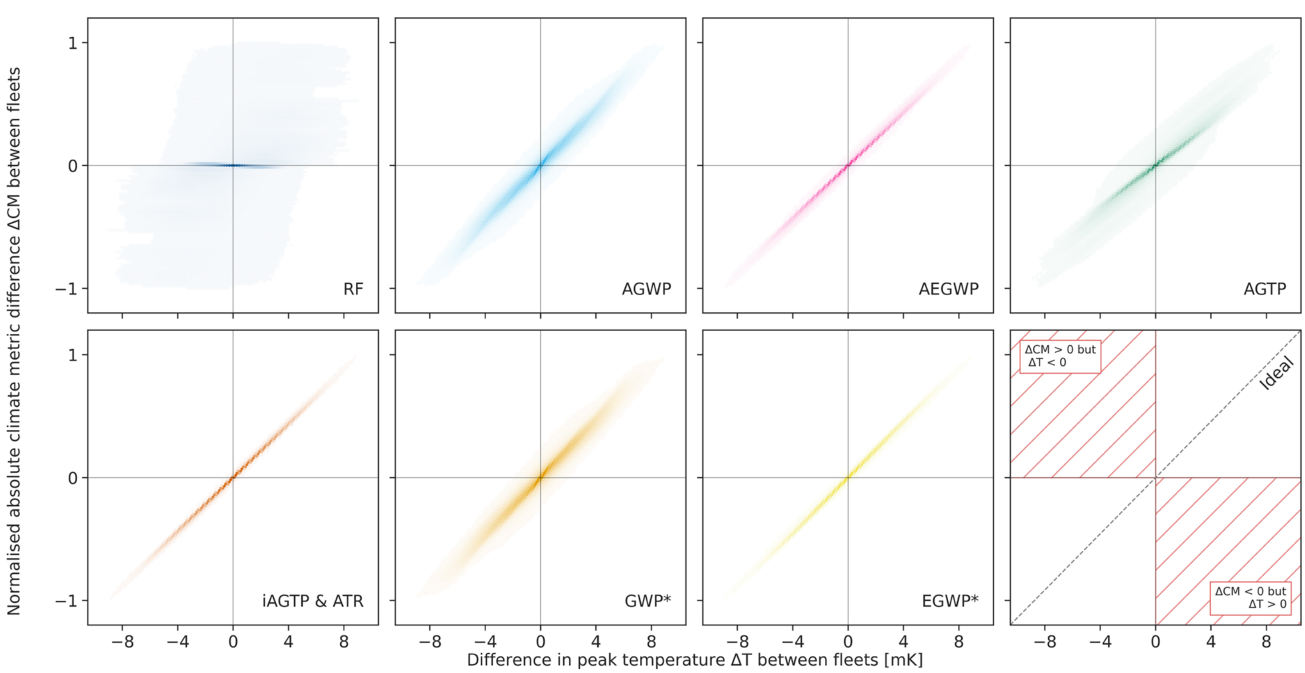

Fig. 2 The peak temperature change $\Delta T_1 - \Delta T_2$ vs. the difference in the climate metric $CM_1 - CM_2$ for randomly selected fleet pairs. The lower right panel shows the areas enclosing the incorrect fleet pairs (red quadrants), which do not fulfill the condition given by Eq. 1. The proportion of fleet pairs within these areas determines the neutrality of a metric. Adopted from the supplement of Megill et al. [41]

In order to test the neutrality of climate metrics, Megill et al. [41] perform fleet pairing analysis on a large set of future aircraft fleets. Each fleet is generated with the Monte Carlo method by varying the fuel type, CO_2 and non-CO_2 emissions and effects, flight altitude, year of fleet introduction, and background concentration. The response model AirClim is used for the climate impact assessment [52, 53].

Figure 2 shows the differences in the peak temperature changes for randomly selected fleet pairs vs. the corresponding differences in the climate metric values for the selected climate metrics. The fleet pairs in the red quadrants in Fig. 2 are incorrect fleet pairs that do not satisfy the condition given by Eq. (1). Generally, climate metrics with the lowest scatter of fleet pairs such as ATR, AEGWP, EGWP* are representative of the temperature changes and have high neutrality and vice versa.

Temporal stability. The requirement of temporal stability ensures that the impact assessment with a climate metric remains accurate and consistent over different time periods. This requirement is particularly relevant for monitoring purposes in aviation policy. The stability of climate metrics was assessed by analysing the temporal developments of CO_2-eq emission in two future aviation emission scenarios, CORSIA and FlightPath2050 [3]. The analysis shows a poor performance of the GWP* and EGWP* metrics with respect to this requirement, whereas the rest of the metrics show relatively similar trends.

Compatibility with climate policy. The compatibility of a climate metric with existing climate policy requires that the metric aligns with policy goals and is easily integrated into existing reporting and monitoring systems used by governments, organisations, and industries. We evaluate compatibility of a climate metric with climate policy in terms of its functionality: it is considered compatible if it provides similar functionality as the most commonly used GWP. In the context of the aviation industry, this implies that a metric should be able to calculate (1) the temporal evolution of CO_2-eq emissions and (2) a single value for a given time horizon for fleets and individual flights for application in the EU ETS. All conventional climate metrics – RF, GWP, GTP, iGTP and ATR – provide this functionality and hence can be used in existing climate policy. Temperature-based metrics are however considered more policy-relevant due to their link to temperature change targets. The GWP* and EGWP* metrics have difficulties with the condition (2). The GWP* method is designed to provide a continuous assessment that reflects ongoing changes in emissions and their immediate impacts. The GWP* and EGWP* metrics effectively have a second time horizon that corresponds to the time span during which change in the emission rate is considered.

Schleussner et al. [50] find that applying GWP* directly to interpret the goals of the Paris Agreement can lead to profound inconsistencies in its mitigation architecture. The Paris Agreement focuses on the evolution of annual emission rates over time, whereas GWP* is better suited for linking cumulative CO_2-equivalent emissions to global mean temperature.

Climate metric transparency. The transparency requirement evaluates how difficult it is for non-specialists to understand the metric and implement it into climate frameworks. Endpoint metrics such as RF and GTP are the most straightforward to understand, while integrated climate metrics show more complex behaviour. Their calculation requires to average or integrate over a dedicated time horizon. Among integrated metrics, the GWP is the most simple to understand since it represents cumulative RF. The simplicity in understanding together with an easy calculation method and availability of data needed for its calculation are the reasons for its continuous use in climate policies and assessments.

Compared to metrics based on radiative forcing, temperature-based metrics (GTP, iGTP, and ATR) and EGWP are more complex to implement. These temperature-based metrics incorporate efficacy values of radiative forcing derived with global coupled ocean–atmosphere general circulation models (coupled GCMs) and hence uncertainties associated with climate modelling. These uncertainties should however be integrated in the climate impact assessment (see Sect. 5 for details).

The GWP* and EGWP* metrics are the least transparent and simple as they require an understanding of the relationship between emissions from short-lived climate pollutants and CO_2 pulse emission. Additionally, their implementation can be complicated by the fact that these metrics require a temporal emission profile 20 years prior to the considered instance as well as a value of the AGWP for a CO_2 pulse that has to be calculated for each background scenario.

Table 3 Performance evaluation of climate metrics against respective requirements

Metric	Neutrality	Stability	Compatibility	Transparency
RF	−−−	−	−	+
GWP	0	0	0	0
EGWP	++	0	0	0
GTP	−	−	−	+
iGTP	++	0	0	−
ATR	++	0	0	−
GWP*	0	−−−	−−−	−−−
EGWP*	+++	−−−	−−−	−−−

Performance is ranked from − − − (very low) to + + + (excellent)

3.3 Down-selection of climate metrics for the use in climate impact technology assessments

Table 3 summaries the performance of the climate metrics against the requirements. Performance is ranked from

"– – –" (very low) to + + + ("excellent") based on a revised version of Table 1 from [41]. In the context of technology impact assessments, the neutrality requirement is given the highest priority, as reflected in the highest ratings compared to other requirements for the metrics that perform well against this criterion. The end-point metrics RF and GTP have generally low ratings, mainly owing to their strong dependencies on the time horizon and temporal emission profile (scenario), resulting in low neutrality and stability. Also, end-point metrics are limited to a single point of time in the future (H) and hence do not preserve an indication if the technology caused a rise in temperature prior to the time horizon. In contrast, integrated metrics accumulate the effect of increasing temperature (or RF). Among the considered metrics, the EGWP* shows "excellent" neutrality, but at the same time it has poor performance against the rest of the requirements and therefore is not recommended. The ATR and EGWP metrics show high neutrality and the highest overall ratings in Table 3, making them a good overall compromise. Note that the conclusions of the selection procedure are applied for both relative and absolute metric forms.

The ATR, as a temperature-based metric, has the potential to include more climatic processes, aligns better with Paris agreement and thus is more relevant for temperature-based policy targets than the GWP. The EGWP, by incorporating efficacy values, allows its RF basis to more closely align with temperature-based metrics, thus more accurately representing the climate impact of aviation while retaining the GWP's methodological structure. Although the iGTP and the ATR differ only by a factor of H, the units of the ATR are more straightforward to understand, making this metric our choice.

As discussed in Sect. 3.1, choice of the time horizon plays an important role in the assessment of climate impacts and cannot be determined from first principles. A longer value (longer than 70 years) is recommended for several reasons: (1) metrics demonstrate a decreasing sensitivity with time horizon, (2) a longer timescale is necessary to capture the full impact of long-lived gases, and (3) long horizons are more appropriate for policy goals when the eventual magnitude of climate change and long-term risks are the primary concerns. For consistency with existing policy, H of 100 years is appropriate.

3.4 Discussion of climate metric choice

The choice of a climate metric often involves subjective value judgments that can affect the final decision, as has been noted during the stakeholder workshops. To address this issue, the neutrality requirement offers an objective weighting of metrics based on a quantitative estimate of how effectively a metric represents a chosen physical indicator. This requirement was therefore deemed to be the most important at the stakeholder workshop. Moreover, stakeholders proposed that the neutrality requirement could be renamed to "being representative of temperature change". However, we point out that the evaluation procedure can be also applied with another physical indicator representing climate change such as RF. The choice of physical indicator for metric evaluation should align with existing policies.

Fuglestvedt et al. [54] noted that the problem with identifying an alternative to the GWP metrics is "the lack of a well-pronounced goal for combating climate change that a metric is to serve". In 2015, the Paris Agreement specified limiting the global average surface temperature raise to 1.5 °C above pre-industrial levels as such a goal. This makes temperature-based metrics more relevant for climate policies. Since the Paris Agreement does not specify the year when this goal has to be met, its goal can be interpreted as limiting the peak temperature. In this context, the peak temperature is a preferable physical indicator and thus superior to radiative forcing. We note that a climate assessment of any technology assuming a limited technology life time yields a peak in temperature response.

In contrast to the peak temperature, selecting a temperature change measured for a certain time horizon as an alternative climate indicator introduces a potential issue that the sign of the temperature change could reverse, depending on future emission scenarios. Therefore, the GTP metric, which was proposed and extensively discussed in the literature as an alternative to the commonly used GWP, under-performs w.r.t. the neutrality requirement in comparison to integrated temperature-based metrics such as the ATR. As expected, the GTP metric, similar to the other end-point metric RF, indicates a higher frequency of the incorrectly identified fleet pairs (lower neutrality) and is less representative of the peak and average temperature changes.

The second requirement using a quantitative approach is metric stability over time. It was ranked second in importance at the stakeholder workshop, which underscored that metrics should be insensitive to small changes in the time horizon. Nonetheless, this criterion is broader and also ensures accurate and consistent assessments over different time periods, a point that, as Megill et al. [41] argue, is relevant for policy monitoring.

As mentioned in Sect. 3.2, the temperature-based metrics introduce additional uncertainties in the climate impact assessment through uncertainties in modelling of efficacies of aviation climate forcings. However, these uncertainties can be integrated in the climate impact assessment, together with other uncertainties discussed in Sect. 5. The primary advantage of these metrics lies in their clearer alignment with the objectives of the Paris Agreement, which significantly

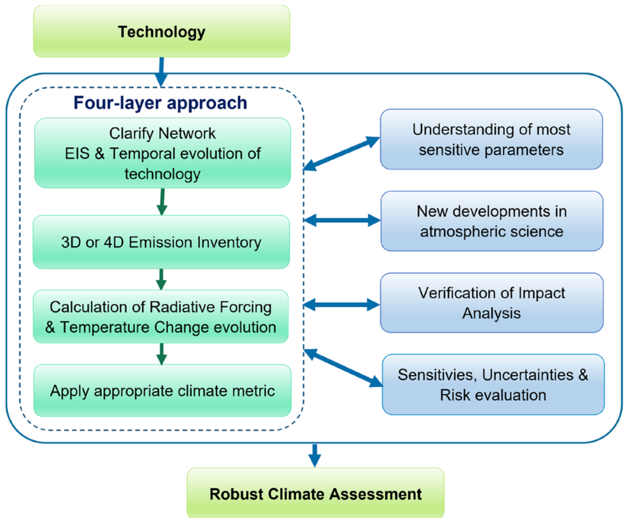

Fig. 3 Sketch of the four-layer approach for the technology climate impact assessment (green part, see Sect. 4.1 for details) and the consideration of consequences from gaps and uncertainties in the assessment approach (blue part, see Sect. 4.3 for details)

enhances their applicability. The feedback received in the stakeholder workshop corroborates the importance of this argument.

4 Resulting best practice for a technology climate impact assessment

In the following, we combine the results from the literature study on technology impact assessments (Sect. 2.4) with the findings from selection of climate metrics presented in Sect. 3 to derive a best practice for a technology impact assessment (Sect. 4.1) and provide an example in Sect. 4.2.

4.1 Description of four-layer approach

In this section, we suggest the following four-layer approach as a best practice for a technology climate impact assessment (Fig. 3). A new technology may encompass an entire aircraft or a component, such as a new engine. In the first layer, we consider in detail where this technology is used by specifying the network. This is combined with an expected entry-into-service and temporal evolution (see Sect. 2.4 for various scenarios of temporal evolution). Note that there might also be a relationship between the entry into service and the network. This forms the basis for a detailed calculation of a 3D or 4D emission inventory (second layer). Using these emission inventories, the non-CO_2 impacts are assessed by using an appropriate model (third layer). Here a more detailed atmospheric 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 forcing and temperature changes. Finally, these time series are used to calculate the climate metrics ATR100 and EGWP100 (Sect. 3.3).

It is important to note that although the end result of the climate impact assessment is a single value of the climate metric, the understanding of how this value is derived is key in the application of this procedure. This requires a detailed diagnostics parallel to the four-layer approach that enables a deeper understanding of the assessment of the individual steps. Those are for example total emissions and emission indices for the second layer, atmospheric composition changes, contrail flight kilometers, and time series of RF and temperature changes in the third step, and some alternative metrics in the last step.

4.2 Use cases based on AS4D

4.2.1 Description of the use cases

In this section, we present two practical applications that demonstrate how the four-layer assessment is applied to evaluate specific aircraft designs expected to enter service in the mid-2030s.

We employ the AirClim Surrogate Model for Design (AS4D) that incorporates the four-layer approach by using a dedicated aircraft-dependent network, estimating multi-dimensional emissions, the spatial atmospheric impact of emissions and using ATR100 as climate metric, to quantify the climate response of potential aircraft concepts at the preliminary design stage (see Appendix A for description and verification of AS4D). AS4D enables benchmarking of various technological configurations against one another, which is applied here to analyse the climate impact of two future concept technologies relatively to the impacts of respective state-of-the-art technologies at present time (baselines). A baseline technology provides a common reference point for comparing both the CO_2 and non-CO_2 climate impacts of advanced technologies – for example, by evaluating their mitigation potentials (the ratio of a technology's CO_2 -equivalent emissions to those of the baseline).

The first assessment layer of a given technology identifies its route network, EIS and temporal development of emissions. The present study evaluates the impact of two future concept technologies expected to enter into service around 2035 compared to 2020 state-of-the-art technology. AS4D assumes Airbus traffic growth forecasts to model temporal evolution of emissions, as described in App. A.2.

The use cases are selected from two market segments: (i) from the regional and (ii) from the short- to medium-range (SMR) segment, reflecting current research and innovation priorities, and for which AS4D provides dedicated modeling capabilities. Baseline aircraft, which represents the regional market segment, was characterized by a reference design similar with the top-level aircraft requirements and performance characteristics of the ATR72-600 [55]. For the SMR segment, baseline aircraft was represented by a configuration similar to the A321neo [55]. The selected cases differ in the cruise altitudes: while baseline aircraft for the regional segment operates at the cruise altitudes below 20000 ft, baseline aircraft for the SMR segment operates above 30000 ft, leading to more pronounced non-CO_2 effects.

The future aircraft concepts were modeled through fully iterated design studies to capture the potential performance and climate benefits of advanced configurations. For the regional market, a plug-in hybrid-electric configuration was selected, operating fully electric for missions up to 300 NM, followed by hybrid-electric propulsion using a kerosene or SAF-powered gas turbine [56]. The concept for this use case and segment is referred to as the Hybrid-Electric Regional 2035 (HER-2035) aircraft. For the SMR segment, a conventional configuration with a high-aspect-ratio wing was chosen, also powered by kerosene or SAF, and incorporating an ultra-high bypass ratio turbofan engine, along with advanced structural components and aircraft systems (SMR-2035) [57].

After future concepts and baseline technologies were defined, emission inventories (the second layer) and respective climate responses (the third layer) were calculated for each technology using AS4D. Finally, the impacts of CO_2, NO_x, H_2O emissions, and CiC were quantified with the ATR and EGWP metrics recommended in Sect. 3 over time horizon of 100 yr. To illustrate the effect of fuel choice, we perform the assessments for two distinct fuel scenarios: one with conventional fuel and one with SAF, assuming an 80% reduction in soot emissions and 80% CO_2 life-cycle savings through the use of CO_2-neutral fuel.

4.2.2 Climate impacts of the use cases

The results of the four-layer assessment for SMR and HER cases evaluated for two fuel scenarios (conventional and SAF) and two metrics (ATR100 and EGWP100) are presented in Figs. 4 and 5, respectively.

Figures 4a and 5a show CO_2-eq emissions for the individual climate agents (CO_2, H_2O, NO_x, and contrails) and

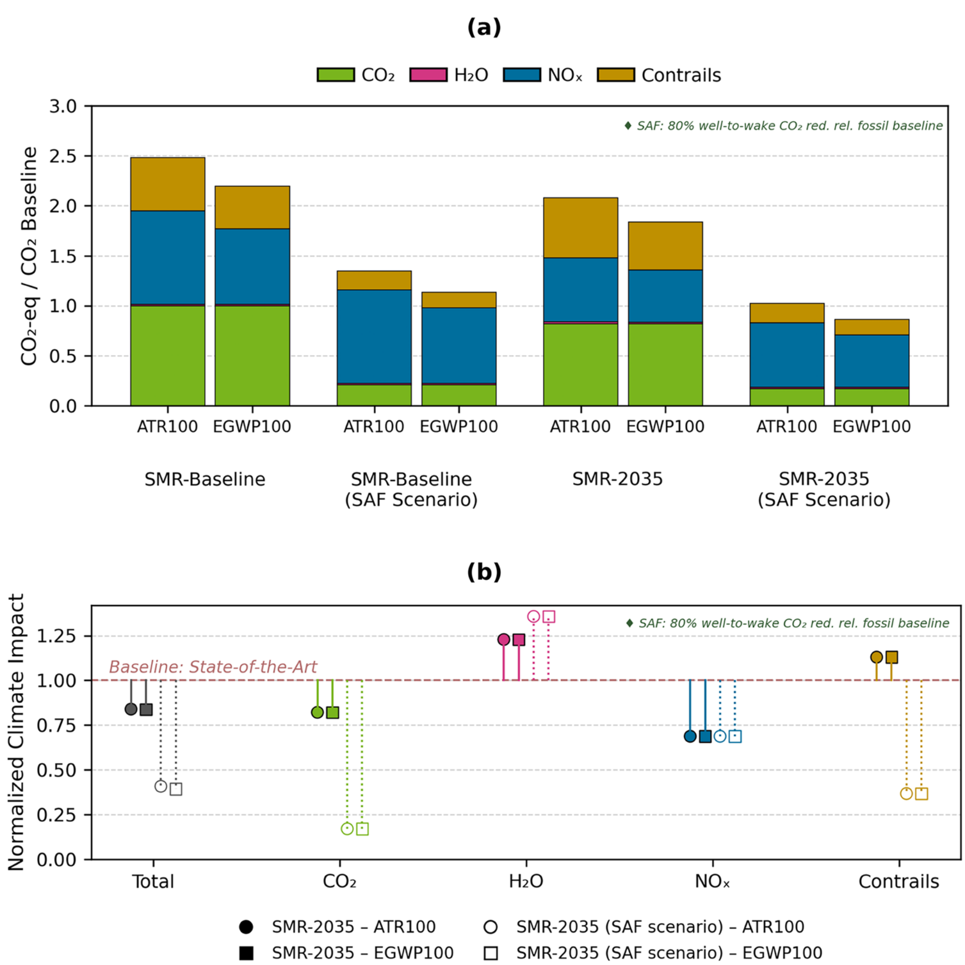

Fig. 4 Climate impact in the short-to medium-range (SMR) use case under conventional fuel and SAF scenarios, evaluated using ATR100 and EGWP100: **a** CO_2-equivalent emissions for both 2020 state-of-the-art (baseline) and 2035 concept aircraft relatively to 2020 baseline CO_2 emissions. **b** Total and individual climate agent mitigation potentials (CO_2-eq emissions for SMR-2035 normalized to CO_2-eq emissions of baseline)

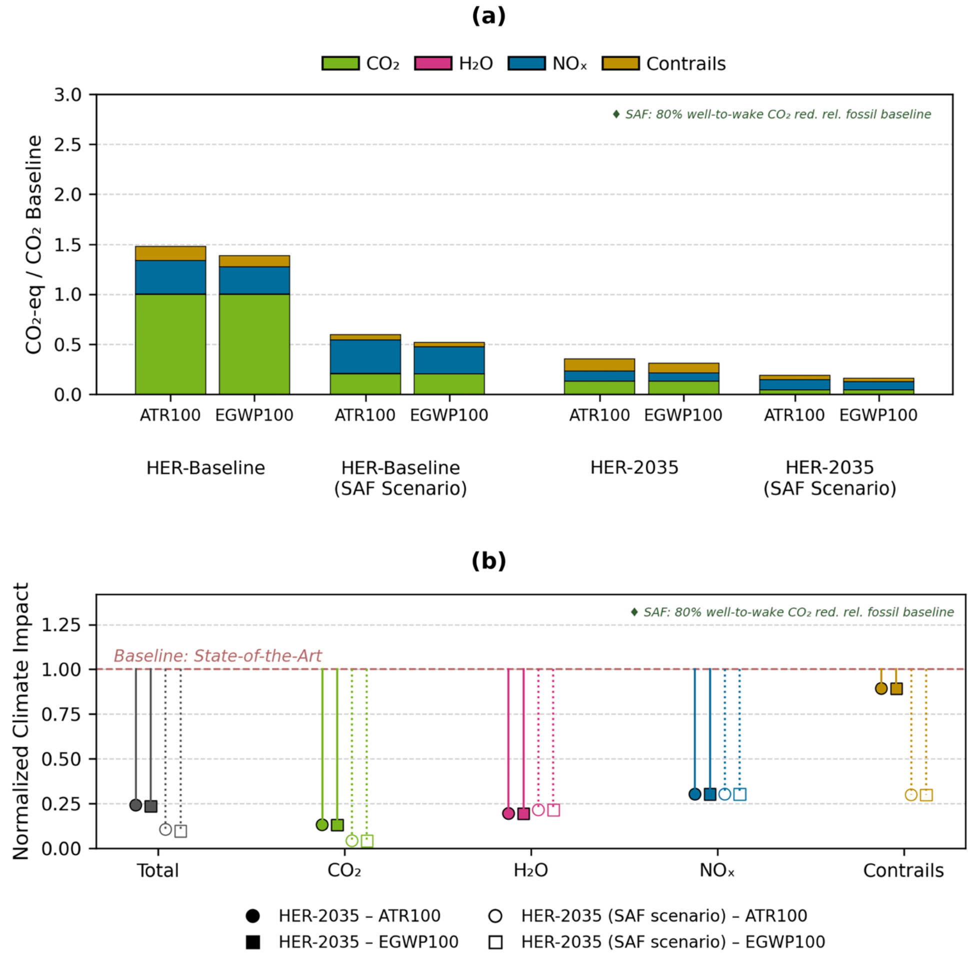

Fig. 5 Climate impact in the hybrid-electric regional (HER) use case under conventional fuel and SAF scenarios, evaluated using ATR100 and EGWP100: **a** CO_2-equivalent emissions for both 2020 state-of-the-art and 2035 concept aircraft relatively to 2020 baseline CO_2 emissions. **b** Total and individual climate agent mitigation potentials

Table 4 CO_2-eq emissions for the SMR-baseline and SMR-2035 technologies relatively to SMR-baseline CO_2 emissions, calculated using ATR100 and EGWP100 metrics for conventional and SAF fuels

	SMR-baseline		SMR-baseline (SAF)		SMR-2035		SMR-2035 (SAF)	
	ATR	EGWP	ATR100	EGWP	ATR	EGWP	ATR	EGWP
CO_2	1	1	0.2	0.2	0.82	0.82	0.17	0.17
H_2O	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01
NO_x	0.94	0.76	0.94	0.76	0.64	0.52	0.64	0.52
Contrails	0.53	0.43	0.11	0.09	0.6	0.48	0.2	0.16
Total	2.48	2.2	1.26	1.06	2.08	1.84	1.03	0.86

Table 5 The same as in Table 4, but for HER-baseline and HER-2035 technologies

	HER-baseline		HER-baseline (SAF)		HER-2035		HER-2035 (SAF)	
	ATR	EGWP	ATR100	EGWP	ATR	EGWP	ATR	EGWP
CO_2	1	1	0.2	0.2	0.2	0.2	0.04	0.04
H_2O	0.01	0	0.01	0.01	0	0	0	0
NO_x	0.33	0.27	0.33	0.27	0.1	0.08	0.1	0.08
Contrails	0.14	0.05	0.05	0.04	0.12	0.1	0.04	0.03
Total	1.48	1.33	0.59	0.52	0.43	0.38	0.18	0.16

the total CO_2-eq (stacked value) normalized against CO_2 of the respective 2020 baselines. The values of the normalized CO_2-eq emissions are included in Tables 4 and 5 for SMR and HER, respectively. This normalization enables a comparison of individual contributions of climate species to the total impact and quantification of the CO_2 emission reduction achieved by advanced technologies. For SAF scenarios, the CO_2 normalization values are taken without account of life-cycle savings. Figures 4b and 5b show the total CO_2-eq and CO_2-eq for the individual climate agents relatively to the respective values of baseline CO_2-eq emissions, characterising the mitigation potentials of SMR-2035 and HER-2035 for each climate agent.

First, we briefly illustrate the dependence on emission location using baseline aircraft as example. For baseline, Tables 4 and 5 show that the ratio of total CO_2-eq emissions to CO_2 emissions is 2.5 for SMR and 1.5 for regional market segments (for the ATR100 metric and conventional fuel). These ratios derived for global aviation are used as 'multipliers' to estimate the impact from non-CO_2 emissions and effects. As expected, the non-CO_2 contribution for SMR-baseline case operating at higher altitudes is substantially higher than that for HER-baseline. In fact, both CiC and NO_x effects are lower in the regional segment, with higher a NOx-to-contrail ratio than in the SMR (2.5 vs. 1.8, respectively).

Next, we compare the impact for advanced technologies across the proposed climate metrics. For the short- to medium-range segment, EGWP100 attributes a lower relative contribution of non-CO_2 effects to the total climate impact than ATR100. This trend is evident for both the SMR-Baseline and SMR-2035, although the differences remain small (Fig. 4a). For the regional segment, a similar trend is visible, with overall non-CO_2 impacts being lower than in the SMR segment (Fig. 5a), primarily attributable to the operational characteristics of these aircraft, such as operating at lower flight levels. Especially, the integration of advanced technologies leads to further reductions in both CO_2 and non-CO_2 impacts for both metrics. The hybrid-electric configuration shows a pronounced mitigation of climate impact, as battery-electric operation on missions up to 300 NM covers a substantial share of the operational spectrum and thereby significantly reduces in-flight emissions.

For the SMR-2035, by contrast, the use of SAF, providing benefits in terms of soot emissions and CO_2 life-cycle reductions, has a more pronounced effect compared to HER-2035. This is partly because the HER-2035 already achieves substantial reductions through its advanced propulsion system, whereas the SMR-2035 exhibits comparatively greater additional mitigation potential from SAF use. This is attributable to its operational characteristics, which make non-CO_2 effects, particularly contrail contributions, more prominent for the SMR case.

To further investigate the implications of climate metric choice and fuel options on the assessment of advanced technologies, we compare total climate impact reductions and individual contributor effects relative to the state-of-the-art baseline for both segments (Figs. 4b and 5b). First we examine the isolated effects of individual contributors, providing a clearer basis for interpreting the total mitigation potential.

For the SMR-2035 with conventional fuel shown in Fig. 4b, the comparatively higher climate impact from H_2O and contrails results mainly from its higher cruise altitudes and improved propulsive efficiency, both of which increase the likelihood of forming thicker and more persistent contrails. Under the SAF scenario, H_2O-related impacts increase further due to the higher hydrogen content properties of SAF [e.g. 58], while contrail impacts decrease as a result of reduced soot emissions. Additionally, life-cycle savings from the use of CO_2-neutral fuel further reduce overall CO_2 emissions, and thereby the associated CO_2-related climate impact. It is worth noting that, in the current setup, AS4D uses wingspan as a proxy for aircraft mass, and thus for vortex generation and descent speed. Larger wingspans typically produce stronger vortices that descend more rapidly into warmer layers, thereby reducing the likelihood of persistent contrail formation. In the case of the aircraft studied here, however, the high-aspect-ratio wing would generate weaker vortices that descend more slowly, potentially leading to isolated vorticed induced contrail effects similar to or even greater than those of the baseline.

Apart from this, the effect of technology and performance characteristics differ across the individual contributors. However, the choice of climate metric does not affect these isolated effects, as they only reflect changes within each contributor and, in this case, depend solely on the selected scenario. For the total climate impact, the choice of metric can in principle have an effect, as it may weight the contributions of individual climate agents differently. In the present analysis, however, the results indicate that the overall climate impact is very similar for both ATR100 and EGWP100. In particular, for the SMR-2035 (conventional fuel) a reduction of about 17% is observed for both metrics, while for the SAF case higher mitigation potentials of around 59% are achieved, again accounting additionally for CO_2 life-cycle savings. The consistent mitigation results across both metrics indicate that their underlying weightings are comparable, leading to similar trends when benchmarking different technology options without favoring specific technologies in the SMR market segment.

For the HER use case, very similar trends are observed (Fig. 5b). As with SMR, the isolated mitigation potentials of individual contributors depend only on the scenario and not on the choice of climate metric. The relatively high reductions in CO_2, H_2O, and NO_x compared to the SMR case can be primarily attributed to lower fleet-level fuel burn enabled by the fully- and hybrid-electric operations of the HER-2035, as concluded previously. In particular, for the HER-2035 with conventional fuel, a total mitigation potential of around 76% is achieved, while with SAF this increases to about 88%. Again, both metrics show similar trends and robustness, confirming that the ATR100 and EGWP100 metrics, recommended in Sect. 3 do not bias the benchmarking of technologies.

To conclude, across all scenarios a comparable total climate impact reduction is observed for both metrics, with variations remaining below 1%. Consequently, both climate metrics demonstrate very similar overall trends. When interpreting the presented overall mitigation potentials, however, it should be noted that this use case represents an academic exercise, with outcomes highly dependent on the specific study setup, including the choice of reference and baseline aircraft, engine type, forecast scenario, network configuration, and operational assumptions.

4.3 Discussion of the best practice

The example in Sect. 4.2 nicely shows the applicability of the four-layer approach, presented in Sect. 4 even at the stage of a pre-design. Although the results are eventually summarised in two climate metrics, the additional diagnostics, such as the contribution of individual emissions to the climate metric value, allows for a deeper analysis of the results. The four-layer approach relies on the experience from earlier work, such as Terekhov et al. [59], Linke et al. [11] and Grewe et al. [24] for the individual steps from the aircraft type to the emission inventory and combines those with ideas on the integration of uncertainties in the assessment [e.g. 53]. Even if the four-layer approach is demanding, since it requires the calculation of networks, emission inventories and climate impact, the example shows the feasibility, moreover the integration of climate impact assessment in a multidisciplinary design process is assured (Fig. 8).

5 Uncertainties

The principles of the four-layer approach that we proposed in Sect. 4 have been already applied in the literature (see Sect. 2). However, there are still uncertainties and knowledge gaps and their impacts require better understanding. They refer to both the associated science and the approach itself. In Sect. 5.1, we briefly discuss them and, in Sect. 5.2, outline how these uncertainties can be addressed in the four-layer approach.

5.1 Description of uncertainties

Atmospheric science. Assessments of the current knowledge in climate science [60] and especially aviation related atmospheric science [1, 7, 42, 61] nicely present the state-of-art in aviation related science that is evaluated in terms of the level of scientific understanding (LOSU) that comprises both the theoretical knowledge and the amount of data available. Along the process chain from emissions to atmospheric composition changes, radiation budget to climate metrics, all processes are described in approximations that include uncertainties. A detailed description and assessment are beyond the scope of this paper and we limit ourselves to a more general description.

The calculation of emissions is based on assumptions of the aircraft trajectory, thrust settings and fuel composition, which are accompanied by uncertainties. The emitted species experience transformation in the plume and are further advected with the general circulation and again experience chemical and micro-physical transformation processes, which also affect other species, before they are removed from the atmosphere, i.e. by dry deposition at the Earth's surface or wet deposition by rain. For example, contrail plume processes are important since they influence the characteristics of a contrail like ice crystal number densities and thereby its lifetime and radiative effects [e.g. 62, 63]. The plume processes also affect the soot and sulphate processing that eventually may affect natural cloud processes [e.g. 64, 65] and the NO_y partitioning [e.g. 66, 67].

The atmospheric background conditions in form of chemical composition including greenhouse gases, aerosols and cloudiness are important not only since they impact those transformation processes, but also because they impact radiative processes and especially calculation of radiative forcing. The changes in atmospheric composition and radiation eventually lead to temperature changes that can be described by the climate sensitivity parameter. The changes in composition, radiation temperature also trigger feedback processes. The concept of the effective radiative forcing includes fast feedbacks, also called adjustments, such as changes in natural clouds due to the contrail induced water budget changes [68, 69] and slow feedbacks via changes in ocean temperatures [70]. The level of the scientific understanding is very different from process to process. For example, the conditions when a contrail forms are well established and there is a wealth of data from measurements and modeling available, whereas the impact of aerosol emissions on natural clouds is highly uncertain. Data for efficacies are sparse, especially for aviation-related effects.

To cover all these uncertainties in an assessment is extremely difficult and either multi-model estimates or expert judgements are often used [1]. Dahlmann et al. [53] and Grewe et al. [3] used more aggregated estimates of uncertainties covering the entire chain from emissions to temperature changes by introducing uncertainties in the atmospheric lifetime of a composition change, an uncertainty in the radiative effect and an uncertainty in the temperature effect.

Aircraft trajectory and emission modeling. Uncertainties associated with aircraft trajectory and emission modeling are generally smaller than those arising from meteorological inputs and climate response modeling. Aircraft fuel consumption is estimated during flight planning and subsequently monitored and recorded during operation to ensure efficiency, safety, and operational reliability. Trajectory calculations based on the EUROCONTROL Base of Aircraft Data (BADA), particularly with the improvements introduced in BADA 4, typically reproduce fuel burn with a mean deviation below 5% [71].

The accuracy of emission estimates depends on the pollutant and the applied calculation method. NO_x form from atmospheric nitrogen at high temperatures and are highly sensitive to combustion conditions (pressure, temperature, humidity) and fuel flow, which controls thrust. Several fuel-flow-based estimation methods exploit this correlation, differing in complexity, accuracy, and data requirements. These methods use certified sea-level engine emission indices and fuel flow data from ICAO's Engine Exhaust Emissions Database (EDB) for each engine type, requiring the engine UID. Common approaches for inventory purposes include the Boeing Fuel Flow Method 2 and the DLR Fuel Flow Method. More detailed methods, such as the P3T3 method, rely on combustor entry temperature and pressure to achieve higher accuracy but use data that are typically confidential. For rich-burn engines, the uncertainty of these fuel-flow-based NO_x models is estimated to be approximately ± 10% [72]. For lean-burn combustors, the current Landing and Take-Off (LTO) metric implicitly interpolates cruise NO_x emissions from ground-based measurements (30–85%), which may not accurately represent modern engines. To address this, the ICAO Committee on Aviation Environmental Protection (CAEP)/13 work programme is developing a new cruise NO_x metric system to improve the quantification and control of cruise NO_x emissions.

Assessment methodology. In addition to the uncertainties described above, the four-layer method (Sect. 4) also include uncertainties. In the first layer both the network and the temporal evolution of the technology usage (e.g. entry-into service (EIS)) include various uncertainties. These uncertainties are associated with such questions as:

- How many city pairs are required to obtain a robust result?
- How sensitive is the assessment to changes in the network?
- How sensitive is the assessment to the choice of the EIS?

Furthermore, the temporal evolution affects the assessment. Although the choice between a life-cycle emission evolution and an evolution similar to a future scenario (see Sect. 2 for details) may have only a small impact on the assessment, a quantification has not yet been done. Regarding the second and third layers, which include calculations of the 3D emission inventory and of RF and temperature change time series, all uncertainties discussed in the previous paragraphs apply. In the fourth layer, selection of the climate metric is obviously limited (Sect. 3), but still some choices can be made concerning, e.g. the details of the temporal development of emissions and time horizon. The sensitivity of the assessment outcome to the choice of the climate metric is likely not essential as we have already limited the number of climate metrics [9, 33, 51]. However a good understanding of all the assumptions of the assessment is lacking.

5.2 Best practice in dealing with uncertainties and knowledge gaps

The previous section clearly indicated a need to integrate gaps and uncertainties into the technology climate impact assessment. We identify four main areas that we discuss briefly in the following and that are indicated in blue in Fig. 3.

Understanding of the most sensitive parameters. As a first step, we recommend establishing 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. As described above the uncertainties from both atmospheric science and the four-layer approach itself (Sect. 5.1) will translate into uncertainties in the climate impact assessment of a specific technology. This can be addressed by defining probability density functions to each parameter of the four-layer approach and perform a Monte-Carlo simulation to allow the understanding of the propagation of uncertainties. Dahlmann et al. [53] give an example for such an approach and stressed the importance of analysing the difference in technologies within 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 towards 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 indirect cloud effects, refer to processes where the understanding is not mature enough to be integrated into the four-layer approach. Here it is necessary to allow updates to the assessment approach, whenever consolidated research leads to a sufficient maturity level. ESTEC [73] has proposed a grading for a scientific readiness level (SRL), though for the maturity of evolving science with respect to a mission concept, satellite mission, or satellite instrument activity. However, as a concept it might help to develop a similar SRL for deciding when a process should be integrated in the technology climate impact assessment.

Verifying the assessment procedure. The four-layer approach integrates complex interdisciplinary processes from aeronautical engineering to climate science. As for any model, the proof of applicability is necessary. While for the individual layers individual processes can be validated against observational data, there is no possibility to validate the entire approach against observational data. However, a verification with higher fidelity models, for example, using a modelling chain from large-eddy simulations to climate-chemistry models [23], for selected independent use cases is mandatory.

6 Summary and conclusion

We present an overview on methods that were applied in aviation climate impact assessments and summarise requirements for climate metrics. Based on this literature review, we derive a best practice for technology climate impact assessment that comprises four layers: (1) temporal and spatial technology use; (2) three-dimensional aircraft trajectory and emission inventories; (3) time series of radiative forcing and induced near-surface temperature changes; and (4) the climate metrics ATR100 and EGWP100. The four layers are necessary to obtain a ratio between non-CO_2 and CO_2 effects that is in line with the respective scenario assessment and considers the spatial sensitivity of the non-CO_2 effects.

We discuss two examples of the four-layer assessment, in which the AirClim Surrogate model for Design is employed to evaluate specific aircraft designs expected to enter service in 2035. The use cases are chosen from the Regional and the SMR market segments, characterised by different route networks—particularly with respect to cruise altitude. The differing emission locations in the use cases lead to distinct non-CO_2 effects. For example, the derived total CO_2-eq-to-CO_2 ratio is 1.5 for the 2020 state-of-the-art aircraft (baseline) in the regional segment and 2.5 in the SMR segment. Dependence on the emission location manifests even stronger when comparing the relative roles of NO_x and contrails in these cases.

We chose hybrid-electric technology (HER-2035) as a future concept. Both HER-2035 and SMR-2035 engines can be powered by SAF and we use these examples to demonstrate how different is the effect of SAF compared to conventional kerosene fuel on these cases. For HER-2035, the total mitigation potential is rather high for conventional fuel, therefore the reduction due to SAF is relatively small (76 vs. 88%). In contrast, the total mitigation potential for SMR-2035 increases from 17 to 59%, when aircraft is powered by SAF. Assessments using different metrics (ATR100 or EGWP100) show similar trends for both metrics, illustrating that the metric choice among these two options has low influence on the outcome, in contrast to the fuel options.

Finally, for further steps in application of the four-layer assessment, it is important (1) to improve the understanding of the most sensitive parameters in this approach; (2) to test the approach of including uncertainties that stem from both the method itself and atmospheric science in order to obtain robust estimates; (3) to provide a verification on the basis of higher fidelity models; and (4) to provide a consolidated framework for incorporating new findings into (atmospheric) research depending on the level of scientific understanding or the scientific readiness level.

Appendix A AirClim surrogate model for design–AS4D

The AirClim Surrogate Model for Design (AS4D) enables assessment of an aircraft's potential climate impact at the pre-design stage by integrating non-CO_2 effects into the multidisciplinary design (MDO) process. AS4D relies on the response model AirClim that is briefly described in Sect. 7.1. The AS4D model and its underlying pre-calculations are described in detail in Sect. 7.2. Based on these simulations, AS4D provides response surfaces that allow designers to rapidly evaluate fleet-level climate impacts of design trajectories, as demonstrated in Sect. 7.3. This approach supports efficient exploration of design options and trade-offs between performance metrics such as fuel consumption and climate effects. An overview of model verification, demonstrating how accurately AS4D reproduces AirClim results, is provided in Sect. 7.4.

Non-linear aviation emission response model AirClim

AirClim combines 3D aircraft emission data, such as emission inventories, with a temporal evolution of those emissions and a set of pre-calculated non-linear emission–response relations to obtain temporal evolutions of the associated radiative forcing. Using this information, it estimates temporal evolutions of the near-surface temperature changes. By using these response functions, a climatological approach is applied for the estimation of aviation climate effects, meaning that the calculated responses represent a mean over all weather situations. AirClim includes the effects of the climate agents CO_2, H_2O, CH_4, O_3 and primary mode ozone (PMO) (the latter three result from NO_x emissions), as well as contrail-cirrus. For deriving the atmospheric responses for H_2O and NO_x-induced changes, 85 steady-state simulations for the year 2000 were performed with the chemistry climate model E39/CA [74], prescribing normalized emissions at various atmospheric regions [75]. For the effect of contrail-cirrus, the Schmidt-Appleman criterion in conjunction with ice-supersaturated regions is considered and combined with non-linear responses of the contrail coverage and radiative forcing based on simulations with ECHAM4-CCMod [76].

AirClim is verified against independent modelling data from ECAHM-CCMod for contrail-cirrus, as well as several other climate-chemistry models for the NO_x and H_2O effects. For this, the REACT4C emission data set is used to calculate a base case, an inventory where aircraft fly 2000 ft higher and lower [53]. The results show a good agreement with respect to the mean values as well as the tendencies with respect to altitude changes. AirClim results are also compared to aviation assessments [3, 77].

AS4D model development

Quantifying the climate impact of aviation, particularly from non-CO_2 effects, requires extensive simulation of global emission inventories and their interaction with atmospheric processes, which are computationally intensive. To enable climate assessments during early design stages, AS4D uses a surrogate modeling approach based on pre-calculated data from Global Air Traffic Emission Distribution Laboratory (GRIDLAB) [11, 78] and the climate response model AirClim [52, 53] simulations (Fig. 6). DLR's GRIDLAB generates global 4D aviation emission inventories from flight plans and aircraft data, simulating trajectories with a total energy model that accounts for thrust, drag, and aerodynamics, or alternatively by applying pre-processed, high-fidelity 4D trajectory datasets. Non-CO_2 emissions are derived from ICAO LTO indices and fuel correlation methods. Trajectories can be aligned with either actual flight paths or great circle routes and mapped here onto a 3D grid, producing inputs for AirClim (e.g., in netCDF format).

In addition to GRIDLAB, several models are used to calculate global aviation emission inventories. AERO-MS [79] is a top-down, policy-oriented model that uses macro-level economic and traffic data to compute emissions from average aircraft operations, without simulating individual flights. At a higher resolution, AEIC [80, 81] is a bottom-up, model-driven framework generating gridded inventories from flight missions, aircraft performance, and engine data, though it does not capture full flight path detail. The GAIA model [82] provides the highest spatial and temporal resolution, using observed flight trajectories and engine data, making it suitable for high-fidelity climate studies, but it is not openly available.

Using these pre-calculated data, AS4D bypasses high-resolution modeling by generating fast-access response surfaces that estimate the climate effects of a full route network from typical aircraft design trajectories (Fig. 7a), requiring only typical aircraft design trajectories as an input. The following section describes the AS4D model structure and the setup of its pre-calculations.

To construct the AS4D surrogate model, an extensive set of pre-calculations was performed using representative aircraft design trajectories. These simulations span a

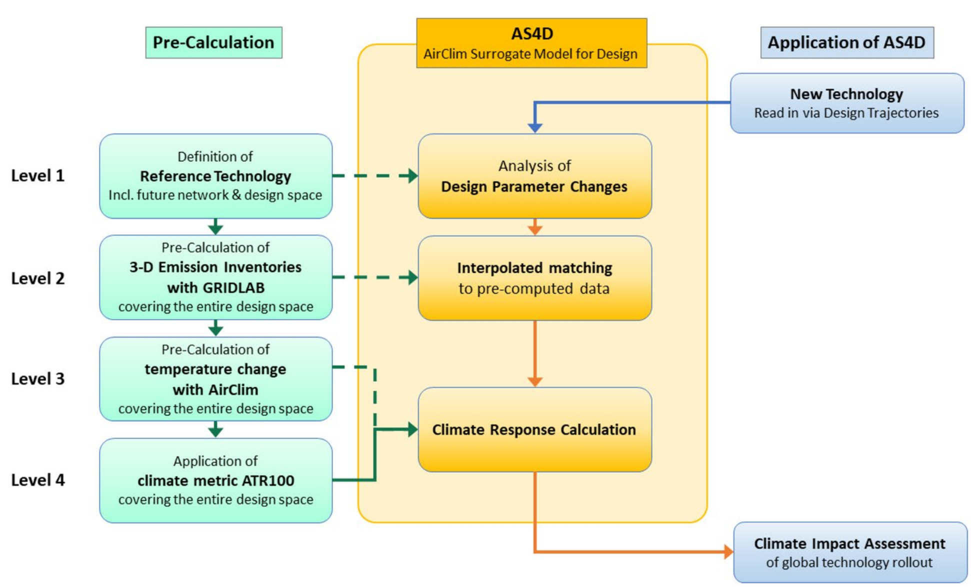

Fig. 6 Surrogate modeling approach of AS4D: bypassing high-resolution emission and climate simulations via fast-access response surfaces to assess the aviation climate impact of global technology rollout. The four-layer approach is applied to provide pre-calculated input data (green, left part) for AS4D. The user perspective is shown in yellow (middle) and input–output data are given in blue (right)

Table 6 Key design parameters in AS4D

Design parameter	Range	Variations
Market segments [-]	REG; SA; TA	3×
Initial cruise altitude [ft]	20,000–45,000	10×
Climb angle [deg]	2.00–8.00	5×
Improved propulsion efficiency [-]	1.00–1.40	5×
G*-slope [kg(H_2O)/J]	0.04–0.12	9×
Total number of parameter combinations		**6750**

five-dimensional parameter space designed to capture key drivers of aviation emissions and their atmospheric impact (see Table 6). We define a set of

(1) *Market segments* (regional jet, single-aisle, or twin-aisle denoted as REG, SA, and TA, respectively), determining the route network as well as fuel and emission flows of the corresponding reference aircraft;
(2) *Initial cruise altitudes*, reflecting the altitude sensitivity of non-CO_2 effects such as contrail formation and ozone chemistry;
(3) *Climb rates* to that initial cruise altitude, represented by climb angles, in combination with market segment to capture different engine and mission configurations;
(4) *Improved overall propulsion efficiencies*, defined relative to the reference aircraft of the market and influencing contrail effects;
(5) *Mixing line slopes (G*-slopes)* in the Schmidt–Appleman criterion, affecting the likelihood of contrail formation based on the aircraft and fuel-dependent parameters (EI-H_2O, overall propulsion efficiency η and lower heating value of the fuel).For each setting, flight trajectories are calculated, and the resulting emission inventories are split into three parts: climb, cruise and descent (Fig. 7b–d)

The choice of market segment (regional jet, single-aisle, or twin-aisle) affects the underlying flight network and reference aircraft performance, resulting in differences in total emission volumes and their geographic distribution. For each market segment, city-pair connections and flight frequencies were extracted from current global flight schedules and scaled to the year 2050 using Airbus traffic growth forecasts. This scaling reflects the temporal evolution of air traffic demand, with annual growth rates gradually declining from 2018 to 2130, consistent with the business-as-usual scenario described by Grewe et al. [3]. For the introduction of new aircraft configurations and technologies, an EIS in 2030 is assumed, followed by a 5 year production ramp-up phase until 2035, a 10 years renewal of older aircraft until 2045 and a constant market share of 75% until 2129.

To account for the altitude sensitivity of non-CO_2 effects (particularly contrail formation and ozone chemistry) in cruise altitude optimization during aircraft pre-design, pre-calculations were conducted across ten different average

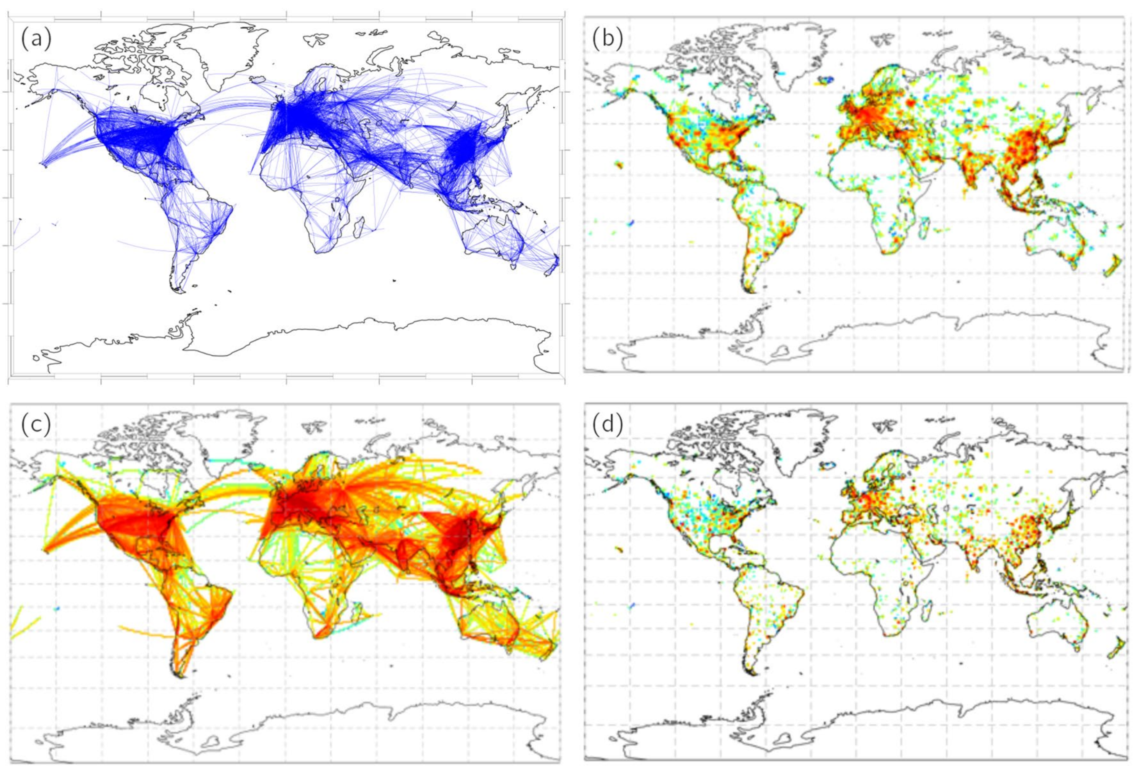

Fig. 7 Forecasted single aisle data for 2050: **a** route network, **b** emissions during climb (**b**), cruise (**c**), and descent (**d**)

cruise levels ranging from flight level 20,000 ft (FL200) to FL450. Emissions and 3D emission inventories were calculated assuming an idealized flight profile for each flight, with idealized emission flows throughout the main flight phases. For single- and twin-aisle missions, cruise was simulated as continuous climb, while regional missions assumed a constant cruise altitude. To capture the influence of engine configurations (e.g., turbojet, turboprop) on climb rate and emission rate, pre-calculations were conducted across five different climb angles ($2° - 8°$), which affected cruise length as well as emission volumes and distribution. If a cruise segment of at least five minutes was not feasible at the target altitude, the cruise altitude was gradually reduced down to a minimum of FL200.

The climate impact for each emission inventory was evaluated with AirClim, which computes the temporal evolution of radiative forcing and temperature change, and the respective ATR over H of 100 years (ATR100) as the climate metric. The EGWP100 metric is calculated using conversion coefficient from [49]. During these simulations, we systematically varied the overall propulsion efficiency and the mixing line slope (G*) in the Schmidt–Appleman criterion to account for different contrail-related impacts and the likelihood of contrail formation.

In total, 6750 parameter combinations were evaluated using GRIDLAB and AirClim to generate the response surfaces that underpin AS4D.

Model application

As visualized in Fig. 8, AS4D has been developed to be integrated into the MDO process of aircraft design. For its application, users must provide a set of design trajectories representing emission flows along predefined mission lengths, along with an assumption file containing key input parameters. These include the lower heating value (LHV) [MJ/kg] of the fuel, emission index of water vapor (EI_{H_2O}) [kg H_2O/kg fuel], CO_2 intensity of fuel production [kg CO_2/kg fuel], fraction of CO_2-neutral fuel [-], soot emission index (EI_{Soot}) [-], aircraft size [pax], and wingspan [m].

Each design trajectory is then analyzed and segmented into the three flight phases: climb, cruise, and descent. For each phase, changes in design parameters or input values are compared against the set of pre-calculated emission inventories (see Fig. 6). To best represent the input trajectories, an optimal linear combination of the pre-calculated data is calculated and scaled with improvement factors based on the design parameter changes. The same linear combination is used to calculate the resulting climate response.

To account for changes in aircraft size on contrail climate impact (f_{ACsize}), we apply the Bruder et al. [83] parameterization, which is based on the work of Unterstrasser and Görsch [84], using wingspan (b) as a proxy for aircraft size. To model the reduction in contrail climate impact due to decreased soot number emissions ($f_{\Delta\mathrm{pm}}$), we apply the formulation established in Grewe et al. [3], which are based on simulations by Burkhardt et al. [62]. In this adaptation, the relative change in the number of emitted soot particles, Δ pm, is modeled as a function of mass flow (m_f) and the soot emission index (EI_{Soot}).

$$f_{\mathrm{contrail}}(b, \mathrm{EI}_{\mathrm{soot}}, m_f) = f_{\mathrm{ACsize}}(b) \cdot f_{\Delta\mathrm{pm}}(\mathrm{EI}_{\mathrm{soot}}, m_f) \qquad (2)$$

AS4D outputs the climate impact of a global rollout of a user-specific technology introduced in 2030. The impact is expressed as the ATR100 in millikelvin (mK), with individual contributions from CO_2, H_2O, NO_x, and contrail induced cloudiness (CiC). It also reports fleet emissions in kilograms for CO_2, H_2O, and NO_x, along with operational data such as total flight and contrail distances in kilometers. The analyzed design trajectories and assumptions are also saved for verification purposes to prevent misinterpretations.

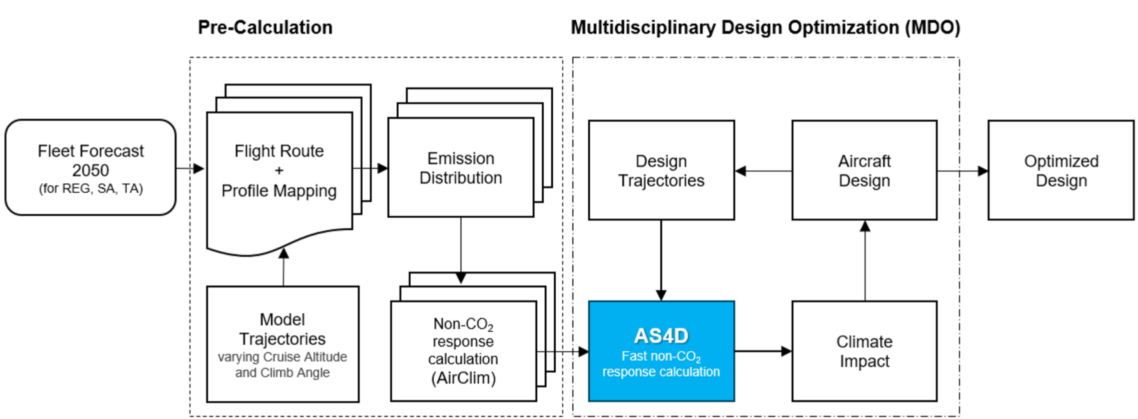

Fig. 8 AS4D integration into MDO process of aircraft design

Table 7 Validation of AS4D response surfaces: mean deviation compared to AirClim

Market segments	CO_2 (%)	H_2O (%)	O_3 (%)	CH_4 (%)	CiC (%)	CiC distance (%)
Regional jet	0.4	0.5	0.1	1.2	1.0	0.01
Single aisle	0.3	5.7	1.0	0.7	0.1	1.1
Twin aisle	0.2	3.7	0.7	0.6	0.25	0.4

Model verification

Verification of AS4D was conducted in two steps. First, the response surfaces generated by AS4D were validated by comparing their mean deviations against results from the detailed AirClim model. This means the generic trajectories of those three aircraft were anaylsed using AS4D and compared to the results of a simulation with AirClim based on an inventory of those aircraft generated with GRIDLAB. The results are summarized in Table 7.

Second, a detailed verification was carried out for the single-aisle market segment, using a set of four representative aircraft that were characterised by different shapes of design trajectories and distinct emission compositions of H_2O, CO_2 and NO_x. For these aircraft, detailed emission inventories were calculated with GRIDLAB and evaluated with AirClim, forming a test dataset for model comparison. The same design trajectories were then evaluated with AS4D, resulting in a systematic underestimation of the climate metric value by 1.0–2.3%.

Both verification steps indicate that the AS4D model sufficiently well represents the behaviour of the AirClim model.

Acknowledgements The research received funding by the Clean Aviation Joint Undertaking and its members by the CLAIM (Clean Aviation Support for Impact Monitoring) project under Grant Agreement No 101140632.

Author contributions All authors contributed to the manuscript. The first draft of the manuscript was written by VG, SZ and PB. Two workshops were held to obtain stakeholder feedback that was included here. All authors contributed to the preparation and execution of the workshops. PB and PR prepared the results for the use cases with AS4D. VG, MN, BL, KD, FL and SM developed the AS4D model.

Funding Open Access funding enabled and organized by Projekt DEAL. The research received funding by the Clean Aviation Joint Undertaking and its members by the CLAIM (Clean Aviation Support for Impact Monitoring) project under Grant Agreement No 101140632.

Data availability No datasets were generated or analysed during the current study.

Code availability Not applicable.

Materials availability Not applicable.

Declarations

Conflict of interest The authors declare no conflict of interest.

Consent for publication Not applicable.

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