



A novel reduced-order model for climate impact assessment of aircraft engines: Climate Functions for Engine Design (CFED 1.0)

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Abstract. The aviation industry is anticipated to grow in the future, with high demand for air travel coming from emerging markets. Consequently, the climate impact attributable to aviation will grow, which is largely driven by non-CO₂ emissions and their associated effects. The role of propulsion systems is critical in reducing the aviation climate impact, as the various species relevant for climate impact are mostly produced during combustion. In this research, we present a novel reduced-order model for climate impact assessment of aircraft engines applicable during the preliminary engine cycle optimization stage. All information that is necessary to estimate the climate impact of combustion emissions is transparently built into the model, such as aircraft type, fleet characterization, route network and fuel type. First, a baseline emission inventory considering global coverage of short-medium range flights by A321neo-like aircraft operating on a Sustainable Aviation Fuel (SAF) in 2050 is generated. Second, the performance parameters of the inventory in terms of fuel burn and emissions are scaled on a one-at-a-time basis within predefined ranges to generate a wide array of inventories, corresponding to variation in cruise altitude. Third, the impact of each variation is analyzed using the climate assessment model OpenAirClim (version 0.16) for a fixed set of boundary conditions. The sensitivity of the climate metric ATR₁₀₀ for each species, i.e., CO₂, NO_x, H₂O and contrail-induced cloudiness, CiC, is analyzed with respect to the variation in the fuel burn, emissions and cruise altitude. This leads to closed-form analytical expressions describing the impact of each species as a function of engine performance parameters, namely the Climate Functions for Engine Design (CFED) version 1.0, which constitute the model. We find that CFED is able to reproduce relevant metric sensitivity trends due to emission and altitude variation across species with a mean error of 2.71%. Further, for a set of 100 randomly selected combinations of the variation in the fuel burn and emissions across all species and altitudes, the mean error of the CFED prediction relative to the full methodology was found to be within 0.25%. The CFED equations are suitable for integration in the engine cycle design framework as they effectively capture the climate sensitivity during conceptual phase, and are computationally inexpensive. They enable climate assessment of new engine designs and allow for engine cycle optimization to include the climate impact of engine emissions.

1 Introduction

Aviation is one of the key pillars of modern society, allowing for mobility and global economic activities. It is expected to grow in the future, with strong demand from emerging markets. A recent estimation by the International Air Transport Association (IATA) suggests that the Revenue Passenger Kilometers (RPK) is forecast to grow at a Compounded Annual Growth Rate (CAGR) of 2.9% to 3.3% between 2024 and 2050 (IATA, 2026). However, with growing demand, the climate impact resulting from aviation is expected to increase as well. Almost two-thirds of the total impact from aviation is due to the relatively short-lived non-CO₂ emissions, which are dependent on the location and the altitude (Frömming et al., 2021). The main climate forcers of aviation are CO₂, NO_x, H₂O and non-volatile particulate matter (nvPM) emissions. Among these, CO₂ and water vapor are direct greenhouse emissions that cause a radiative imbalance, resulting in a positive Radiative Forcing (RF), i.e., warming effect. NO_x emissions lead to tropospheric O₃ enhancement, along with a long-term reduction in CH₄, as well as a small long-term reduction in O₃, resulting in a net positive RF. nvPM emissions can serve as ice-nucleation sites leading to contrail formation under favorable conditions, which may lead to increased cloud cover, resulting in a positive RF as well. In addition, other effects include aerosol radiative effects and cloud interactions, however the physical understanding of these phenomena remain low (Lee et al., 2021). The evaluation of aviation emission scenarios by Grewe et al. (2021) shows that although aviation is on track to meet emission targets of the Paris Agreement, the associated climate impact will very likely not meet these goals, with the efficiency improvement trends not fully able to offset the impact due to increased demand.

As a result, research in the field of climate impact assessment of aviation has been growing. There are different approaches researched simultaneously to mitigate the climate impact from aviation, while keeping up with the global demand. These include operational aspects like aircraft re-routing to avoid climate sensitive regions (Simorgh et al. (2022); Castino et al. (2023); Yamashita et al. (2021)) or to consider the impact during the aircraft design stage. (Schwartz and Kroo (2009); Grewe et al. (2017); Thijssen et al. (2022), see also Grewe et al. (2026) for an overview). Radhakrishnan et al. (2022) implemented Climate Functions for Aircraft Design (CFAD) in the form of a response surface that relates aircraft parameters at design stage with the estimated climate impact considering the aircraft network and 3D fleet inventories for optimizing the next generation of A350-like aircraft for minimum climate impact. Similarly, Grewe et al. (2026) applied the AirClim Surrogate model for Aircraft Design (AS4D) that relies on pre-calculated climate impact calculations for various networks and aircraft related parameters, like cruise altitude, fuel use and emission characteristics to estimate climate effects of aircraft in the regional and short- to-medium range market segments. These studies considered the global emission distribution combined with detailed location and altitude dependent climate response of different species as part of the methodological framework for sensitivity analysis. In contrast, Proesmans and Vos (2022) considered the climate impact in aircraft design optimization by implementing simplified Radiative Forcing (RF) calculations in the form of analytical equations for the different aviation-relevant species, analyzing design tradeoffs between operational cost and climate impact.

The International Civil Aviation Organization (ICAO) has introduced the Carbon Offsetting & Reduction Scheme for International Aviation (CORSIA), a market-based measure to enable net-zero carbon emission growth after 2020 in aviation (ICAO, 2023). One of the ways to offset carbon emissions is the use of Sustainable Aviation Fuels (SAF) by aircraft operators. These

are viewed as a drop-in solution towards reducing in-flight CO₂ emissions in the immediate future. SAF also shows a reduction in particle emissions relative to the conventional jet fuels due to reduced cyclic aromatic hydrocarbons, polycyclic naphthalene, and sulfur content, leading to lower contrail ice formation and its associated effects (Märkl et al., 2024). Boerboom et al. (2025) investigated the climate impact of well-to-wake emissions for several SAFs, comparing the equivalent CO₂ emissions based on core lifecycle as well as induced land use change emissions due to growing SAF demand.

In addition to aircraft design and SAF, another important field is aircraft propulsion, when it comes to understanding and mitigating the climate impact of aviation. Interest has been steadily growing in identifying key propulsion-related parameters most sensitive towards the impact. Zink and Unterstrasser (2026) analyzed the sensitivity of engine-related aspects on exhaust plume characteristics formed on entrained ambient aerosols to investigate the contrail formation process for hydrogen combustion. Callard et al. (2026) investigated the sensitivity of engine design and operational condition changes on contrail formation for a representative engine in the short-to-medium range class. Khan et al. (2022) compared the change in the climate impact due to differences in these emissions from a H₂-powered aircraft relative to the conventional Jet-A1 aircraft in a global atmospheric chemistry and transport model. In addition to these sensitivities, focus has also been on better understanding of the existing design v/s non-CO₂ emission tradeoff for civil aircraft engines, and its implications for climate impact. Historically, civil turbofan engine design trends have focused on improving the fuel consumption of the conventional gas-turbine architecture by increasing the thermal and propulsive efficiencies, leading to ever-efficient engines (Yin and Rao, 2017). While this has led to a decrease in the CO₂ emissions over time, the trends of the non-CO₂ emissions are not so straightforward, depending on the overall design of the engine and the combustor (Perpignan et al., 2018), thus resulting in a tradeoff. Saluja et al. (2023) carried out a holistic assessment of turbofan engine design parameter sensitivities by considering CO₂, NO_x, H₂O and contrails responses in terms of the Average Temperature Response (ATR) of these species using the climate response model, AirClim (Grewe and Stenke (2008); Dahlmann et al. (2016)). Research on novel propulsion technologies aimed at moving away from the design v/s non-CO₂ emission tradeoff have also been gaining attention. Some of these include, the Water-Enhanced Turbofan (WET) engine concept (Kaiser et al., 2022) aimed at reducing NO_x emissions, a hybrid engine for a multi-fuel blended wing body aircraft incorporating technologies such as boundary layer ingestion (Yin et al., 2018), and the Composite Cycle Engine (CCE) concept with pressure ratios greater than 100, showcasing fuel consumption improvements upto 15-17%, depending on the mission length (Kaiser et al. (2016); Lin et al. (2026)).

In general, assessing the climate impact of an aircraft engine would involve a four-layer approach to include operating network aspects, temporal evolution of air traffic and three dimensional emission inventory calculations resulting in temporal RF and temperature change trends which serve as a basis for an adequate climate metric (Grewe et al., 2026). While these aspects complicate a climate impact assessment, they are necessary to represent the large inhomogeneity of the atmosphere's response to aviation emissions. During the engine design phase, each iteration would lead to a different emission inventory for identical boundary conditions, indicating differences in emissions at the same geographical locations. However, it is usually complex and computationally expensive to generate a representative inventory. It can easily involve simulating millions of flights across different airport pairs for the fleet, where the relevant emissions need to be calculated at each way point of each trajectory for each iteration. Further, with many novel technologies in consideration, comparing design-related climate sensitivities becomes

complicated due to different architectures. Due to these limitations, the existing methodological framework becomes unfeasible, when applied during the design stage, even with rapid climate assessment models such as AirClim. In this research, we propose the first reduced-order functions to estimate the climate impact, called Climate Functions for Engine Design (hereon, CFED), which evaluate the impact during the engine cycle design stage, making them suitable for feasibility and optimization studies.

First, we discuss the methodology towards the CFED development in Sec. 2. The basis of developing the CFED equations is a sensitivity analysis presented in Sec. 3 wherein we vary the fuel burn, emissions and altitude to understand the impact of each of these on an appropriate climate metric. Then, based on the individual species' sensitivities, we derive the individual CFED equations per species (Sec. 3.2.2-3.2.5). We analyze the CFED performance sensitivities due to variation in emissions and cruise altitude against the results from the detailed simulation approach (Sec. 4.1) to assess their applicability. We also evaluate CFED performance considering a set of randomly selected input emissions at different altitudes to verify that the CFED approach provides the expected results (Sec. 4.2). Finally, we discuss the key takeaways from this research as well as recommendations for future work.

2 Methods

In this section we describe the method to estimate the sensitivities of the climate impact with respect to engine emissions and fleet fuel burn that eventually lead to the CFED equations. We start with an overview of the method in Sec. 2.1. Thereafter, we discuss the different elements of the method in the subsequent subsections. This includes the baseline emission inventory, the simulation space, the climate evaluation in OpenAirClim and the air traffic growth scenario.

2.1 Overview

There exists a unidirectional relationship between engine design and climate impact, i.e., a given engine design drives its performance and emissions, which leads to climate impact. In principle, the impact of a given unit of emissions is independent of its source for given atmospheric conditions. Therefore, instead of engine design parameters, the CFED equations are based on fuel burn and emissions at a given altitude as the inputs. The methodology for the CFED development is shown in Fig. 1.

The performance in terms of fuel burn and emissions is captured in the emission inventory, serving as an input for climate assessment. The baseline emission inventory is developed using an in-house model framework (Kroon (2022); Jahjah (2025)). For existing aircraft, the model estimates the aircraft performance from the Base of Aircraft Data (BADA v3.15) performance tables for a given operational network of flights (Nuic et al., 2010). The NO_x emissions are calculated using the Boeing Fuel Flow Method (BFFM2) (DuBois and Paynter, 2006), and the nvPM emissions are calculated using the Mission Emissions Estimation Methodology (MEEM) (Ahrens et al., 2023). The loop is subject to variation in fleet fuel burn ($W_{\text{fuel, fleet}}$ in $\text{kg}(\text{fuel})$), emission index of NO_x (EINO_x in $\text{g}(\text{NO}_2) \text{ kg}(\text{fuel})^{-1}$), emission index of non-volatile particulate matter (nvPM) number ($\text{EInvPM}_{\text{num}}$ in $\# \text{ kg}(\text{fuel})^{-1}$) and the cruise altitude (in feet). The variation in the fleet fuel burn ($W_{\text{fuel, fleet}}$) and emissions ($W_{\text{emissions, fleet}}$) is accounted for by scaling the baseline inventory via appropriate scaling factors one at a time.

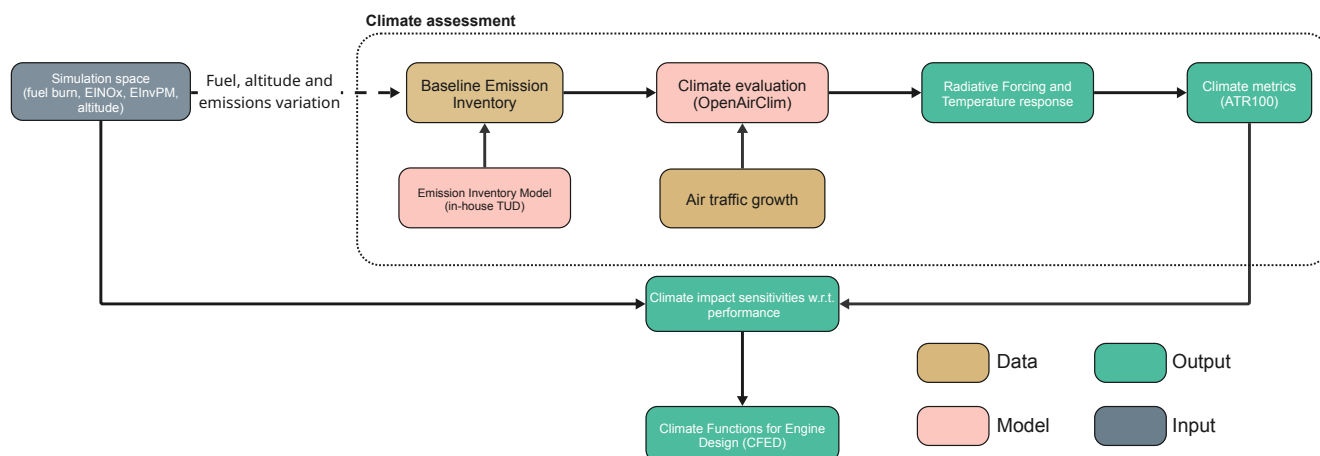


Figure 1. The methodology implemented for CFED development. For each change in fuel burn and emissions applied on the baseline inventory at different altitudes, the climate assessment is carried out, resulting in species ATR_{100} sensitivity due to the change in altitude, fuel burn and emissions.

For each variation, the changes in the climate metric ATR_{100} are calculated for the aviation-relevant species, i.e., CO_2 , H_2O , O_3 , CH_4 , Primary-Mode Ozone (PMO), Stratospheric Water Vapor (SWV), and contrails (for an overview on aviation's climate effects see e.g. Lee et al., 2021). Note that we denote contrail-cirrus and line-shaped contrails, which precede contrail-cirrus, as contrail induced cloudiness (CiC). The climate response is generated in OpenAirClim v0.16, the open-source version of AirClim (Völk et al., 2023).

2.2 Baseline Emission Inventory

The baseline emission inventory consists of an aircraft fleet in 2050 operated by a future geared turbofan engine with a lean combustor, designed for medium-range missions (F-GTF). The fuel is 100% Sustainable Aviation Fuel (SAF), with a Lower Heating Value (LHV) of $44.1 \text{ MJ kg(fuel)}^{-1}$ (Märkl et al., 2024). The design mission range is 4200 NM and the design capacity is 200 passengers. The cruise altitude is 10.67 km (FL350) at a Mach number of 0.78 (Lin et al., 2026).

To model future fleet performance, first the flight network is simulated with a reference aircraft, the A321neo (A321N). Thereafter, to derive the performance of the F-GTF configuration, at each mission way-point, we apply Performance Improvement Factors (PIFs). The PIFs capture technological improvements in fuel burn, and reduction in $EINO_{x,cruise}$ and $EInvPM_{num,cruise}$ relative to the reference A321N, given in Table 1. Although they are obtained for the design mission and cruise emissions, in this research, we assume that the PIFs are valid across other missions and operating conditions.

For the reference, we consider the A321N equipped with the rich-burn Pratt & Whitney PW1133G-JM operating on the standard Jet-A1 ($LHV = 43 \text{ MJ kg(fuel)}^{-1}$) fuel, the standard specification in BADA v3.15 (Nuic et al., 2010). For the F-GTF,



Parameter	Units	A321N (reference)	F-GTF (baseline)	PIF
Design mission block energy per PAX per NM	[MJ/PAX/NM]	1.27	1.06	16.4%
$EINO_{x,cruise}$	[g kg(fuel) ⁻¹]	14.3	7.77	45.68%
$EInvPM_{num,cruise}$	[# kg(fuel) ⁻¹]	1.36×10^{15}	1×10^{11}	>99.99%

Table 1. Performance Improvement Factors (PIFs), relative to the reference A321N, implemented to obtain the emissions for the F-GTF configuration for the baseline emission inventory. The PIFs are calculated for the design mission, and applied on all other operating conditions.

a 16.4% improvement in the energy consumption per passenger per NM over the reference is considered (Lin et al., 2026), leading to a reduction of 18.43% in fleet fuel burn, upon accounting for the LHV difference. The reference $EINO_{x,cruise}$ and $EInvPM_{num,cruise}$ were calculated employing the BFFM2 (DuBois and Paynter, 2006) and the MEEM methods (Ahrens et al., 2023) respectively. For cruise at 10.67 km (FL350) and Mach number 0.78, the $EINO_{x,cruise}$ was calculated to be 14.3 g(NO₂) kg(fuel)⁻¹ for the A321N. For the F-GTF configuration, the Lean Direct Injection (LDI)-staged combustion was assumed, leading to an $EINO_{x,cruise}$ of 7.77 g(NO₂) kg(fuel)⁻¹ (Antoine and Kroo, 2005), resulting in a reduction of 45.68% in $EINO_{x,cruise}$. Using the MEEM methodology, the A321N $EInvPM_{num,cruise}$ was calculated to be 1.36×10^{15} # kg(fuel)⁻¹. For the F-GTF configuration, an $EInvPM_{num,cruise}$ of 1×10^{11} # kg(fuel)⁻¹ is assumed at all altitudes. Currently, this emission index is the lower limit in the lean-burn regime of the aerosol and contrail microphysics model which predicts contrail ice emission index for a given $EInvPM_{num}$ (Yu et al. (2024); Voigt et al. (2026); Kärcher and Yu (2009)).

Demand forecasts and fleet developments were simulated to derive a future air traffic scenario as part of the HORIZON Europe project, MINIMAL (Schaumeier et al., 2024). The F-GTF configuration services part of the global aviation demand by executing approximately 8.1 M flights in 2050. The route network is shown in Fig. 2 with a typical mix of different flight distances covering the globe. Out of the 8.1 M flights in 2050, 5.5 M flights (68%) are short-haul flights (<1000 NM). However, the total fleet fuel burn and consequently, the total emissions are dominated by the long-haul flights (≥1000 NM). The fleet fuel burn and flown distance due to long-haul flights are approximately 68% and 74% respectively of the corresponding global values. The NO_x and nvPM number emissions due to long-haul flights are 65% and 66% respectively. This shows that despite more number of flights across short-haul routes, the traffic on the long-haul routes characterizes the global emissions.

Combining the fleet network with trajectory calculation using the PIFs the baseline emission inventory in 2050 is calculated, for which the results are shown in Table 2. The emissions of CO₂ and H₂O are based on constant emission indices of $EICO_2 = 3.11$ kg kg(fuel)⁻¹ and $EIH_2O = 1.37$ kg kg(fuel)⁻¹ respectively for the SAF-powered fleet (Märkl et al., 2024).

2.3 Simulation Space

To obtain a large set of emission inventories corresponding to possible emission cases, the baseline inventory (Sec. 2.2) is scaled across all flight waypoints on the basis of $EINO_{x,cruise}$, $EInvPM_{num,cruise}$ and the fleet fuel burn at the different cruise

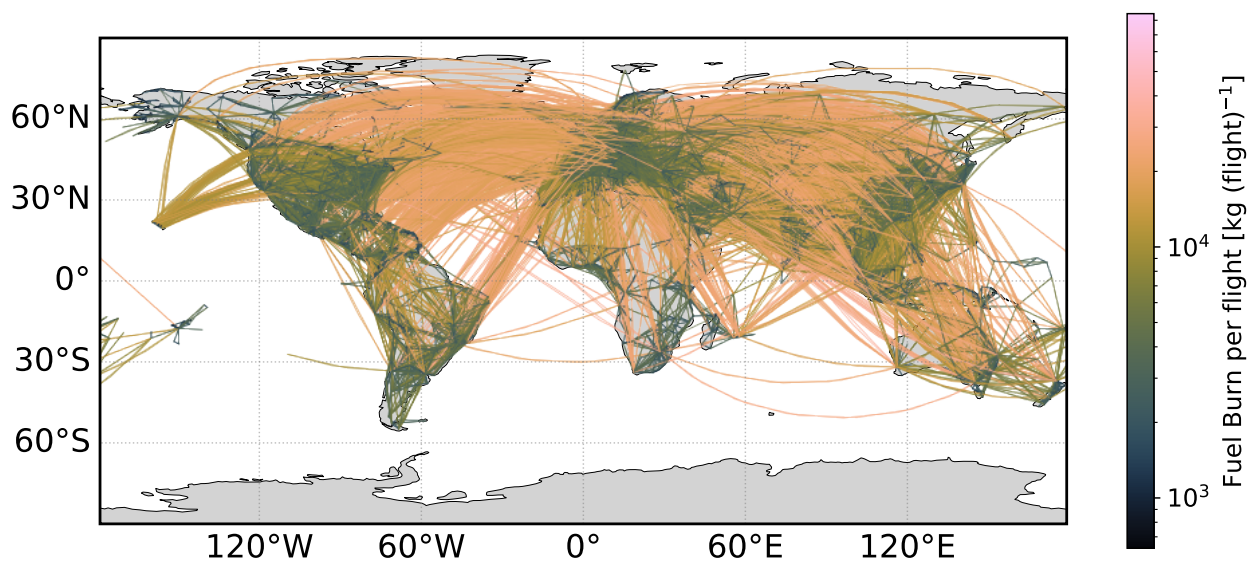


Figure 2. Global distribution of the annual fuel burn per flight in 2050 across the routes flown by the future (F-GTF) configuration.

Parameter	Global	Short haul (<1000 NM)	Long haul (≥1000 NM)
No. of flights [million]	8.1	5.5	2.6
Fuel burn [Tg]	53.32	17.28	36.04
CO ₂ [Tg]*	165.84	53.75	112.09
H ₂ O [Tg]	73.05	23.68	49.38
NO _x [Tg]	0.445	0.156	0.289
nvPM [#]	5.56×10^{21}	1.88×10^{21}	3.68×10^{21}
Total flown distance [billion km]	18.55	4.82	13.73
Global mean EINO _x [g(NO ₂) kg(fuel) ⁻¹]	8.35	9.03	8.02
Global mean EInvPM _{num} [# kg(fuel) ⁻¹]	1.04×10^{11}	1.09×10^{11}	1.02×10^{11}

Table 2. Global fuel burn and emissions statistics for the F-GTF configuration at 10.67 km (FL350), Mach number 0.78. *Note that we do not consider life-cycle CO₂ emissions explicitly, as this is not a requirement for CFED development, and can be directly specified as a CFED input (Sec. 3.2.2).

altitudes. These scaling factors are applied one at a time and are given in Table 3. The obtained scaled emission inventories form the basis of the climate sensitivity assessment needed for the CFED development, shown in Figure 1.



Factor	Scaling Factor Range	Resolution	Parameter Range	No. of points
$W_{\text{fuel, fleet}}$	[0.75, 1.6]	0.5	[39.9, 85.2] Tg	18
$\text{EINO}_{\text{x, cruise}}$	[0.75, 11]	0.25	[5.82, 85.5] $\text{g}(\text{NO}_2) \text{ kg}(\text{fuel})^{-1}$	42
$\text{EInvPM}_{\text{num, cruise}}$	[1, 10^5]	-	[10^{11} , 10^{16}] $\# \text{ kg}(\text{fuel})^{-1}$	20
Flight level	-	10	[260, 360]	11

Table 3. The simulation space used for CFED development. For $\text{EInvPM}_{\text{num}}$, the points are considered distributed equally across the scaling factor range on a logarithmic scale.

For the fleet fuel burn scaling, we apply a lower and upper limit of -75% and +60% relative to the baseline respectively, along with a very large range for $\text{EINO}_{\text{x, cruise}}$. This enables a large simulation space, accommodating a range of possible cycle-combustor options, for instance, CCE architectures with high $\text{EINO}_{\text{x, cruise}}$ without NO_x mitigation techniques (Johansson et al. (2026); Kaiser et al. (2016)). The $\text{EInvPM}_{\text{num, cruise}}$ is varied across five different orders of magnitude from 10^{11} to 10^{16} , accounting for both rich-burn and lean-burn regimes. In this research, a configuration corresponding to $\text{EInvPM}_{\text{num, cruise}} < 1 \times 10^{14} \# \text{ kg}(\text{fuel})^{-1}$ is considered in the lean-burn regime. For the cruise altitude, we consider a range of FL260 to FL360 in steps of 10 flight levels (7.92 km-10.97 km), while maintaining a constant Mach number of 0.78.

2.4 Climate evaluation in OpenAirClim

The climate impact is estimated using OpenAirClim v0.16 (OAC) (Völk et al., 2023). In OAC, the CO_2 response and the temperature change response is based on Etminan et al. (2016) and Boucher and Reddy (2008). The contrail assessment methodology is based on similar principles as the research of Dahlmann et al. (2016), with an updated design-dependent Schmidt-Appelman Criterion (SAC) calculation (Megill and Grewe, 2025) and a fully revised CiC coverage, optical depth and RF calculation (Megill, 2026) that considers optical depth changes due to nvPM number emission (Bock and Burkhardt, 2019). Details regarding the required inputs for updated CiC calculations are given in Appendix B. OAC also considers the radiative changes due to NO_x emissions leading to ozone increases and methane depletion, based on the approach in AirClim (Grewe and Stenke, 2008). In addition, their effect on stratospheric water vapor (SWV) concentration changes (Harmsen (2026); Pletzer (2024)) is included. The relationship between the steady-state near-surface temperature response, ΔT_{spec} and the initial RF imbalance caused due to a species follows a linear relationship (Lee et al., 2010):

$$\Delta T_{\text{spec}} \approx \lambda_{\text{spec}} \cdot R_{\text{spec}} \quad (1)$$

where λ_{spec} is the climate sensitivity parameter in $\text{K}(\text{Wm}^{-2})^{-1}$, calculated as:

$$\lambda_{\text{spec}} = r_{\text{spec}} \cdot \lambda_{\text{CO}_2} \quad (2)$$

where r_{spec} is the species efficacy and λ_{CO_2} is the climate sensitivity parameter of CO_2 . The transient behavior of the temperature change is simulated based on Boucher and Reddy (2008). In this research, the following values of species efficacy (r_{spec})



190 and climate sensitivity parameter (λ_{spec}) are considered as given shown in Table 4, taken from de F. Forster and Shine (1999) for SWV and Ponater et al. (2006) for all others.

Parameter	CO ₂	H ₂ O	O ₃	CH ₄	CiC	PMO	SWV
τ_{spec}	1	1.14	1.37	1.14	0.59	1.37	1
λ_{spec}	0.73	0.83	1	0.86	0.43	1	0.73

Table 4. Climate sensitivity parameters and efficacies implemented for CFED development.

For meaningful comparison across the variation in emissions and altitude, a suitable climate metric is required. The work of Megill et al. (2024) demonstrates that the Average Temperature Response (ATR) is the most suitable for assessing aviation climate effects. For each species, the ATR_{100} is calculated as (Dahlmann et al., 2016):

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$$\text{ATR}_{100,\text{spec}} = \frac{1}{100} \int_0^{100} \Delta T_{\text{spec}}(t) dt \quad (3)$$

2.5 Air Traffic Growth and Background Atmospheric Scenario

To evaluate the climate impact, a key input is the air traffic growth scenario, in addition to the emission inventory. The growth rate can be both at a regional and/or a global level, as well as involve past and/or future traffic, depending on the objective. Here, we consider the global air traffic growth rate. The time period starts from 2040, when the configuration enters the market, 200 to 2139, the end year for the calculation of $\text{ATR}_{100,\text{spec}}$. From 2040 to 2050, an updated growth rate adjusted to the Business-as-usual (BAU) scenario is considered, based on simulations accounting for demand forecasts and the global fleet development, carried out during the MINIMAL project (Schaumeier et al., 2024). Beyond 2050, the BAU scenario from Grewe et al. (2021), until 2100 is considered. The growth rate beyond 2100 is assumed to be identical to the growth rate in 2100. The fuel burn trend due to the air traffic growth is shown in Figure 3. Until 2050, the mean global fuel burn growth rate is 1.63%, after which 205 it slows down to 0.48%. To estimate the response of CO₂ and CH₄ in a given year, the IPCC SSP2-4.5 scenario (Meinshausen et al., 2019) is considered for the temporal trend of the atmospheric concentration of these species.

3 Results: Sensitivities as a basis for the climate functions for engine design

This section elaborates on the key results of this research. First, we discuss the variation in the fuel burn and the emissions due to the cruise altitude variation at the emission inventory level, followed by the variation in the resultant $\text{ATR}_{100,\text{spec}}$. Then, for 210 each species, the sensitivities of $\text{ATR}_{100,\text{spec}}$ is analyzed with respect to changes in the fuel burn and emissions due to the fuel burn and emission scaling factors as described in Sec. 2.3, resulting in the CFED equations obtained for each of them.

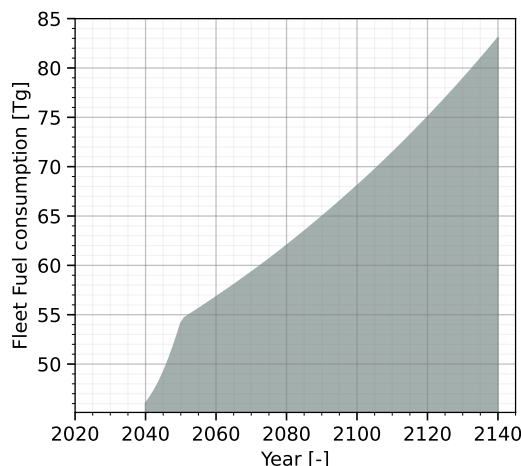


Figure 3. Background fleet fuel consumption scenario considered for CFED development.

3.1 Fuel burn and emission sensitivities with altitude

For the range of the altitude variation given in Table 3 and a subsonic Mach number of 0.78, the fuel burn increases for lower altitudes due to higher cruise thrust setting compared to the baseline case of FL350 (10.67 km), shown in Fig. 4 (a). With a
 215 higher cruise thrust at lower altitudes, the $EINO_{x,cruise}$ increases due to a higher combustion temperature, leading to an overall increase in the global mean $EINO_x$, as seen in Fig. 4 (b). As a result of increase in fuel burn and $EINO_x$, the total fleet NO_x emissions increase as well, seen in Fig. 4 (c).

In contrast, the $nvPM_{num}$ trends are not straightforward. With decreasing altitude, the increasing thrust initially leads to a rapid increase in the $EInvPM_{num,cruise}$. The global mean $EInvPM_{num,cruise}$ peaks at an altitude of 9.75 km shown in Fig. 4
 220 (d) and then starts reducing. This behavior can be explained by the nature of the $EInvPM_{num}$ formation in the baseline engine due to the impact of varying cruise altitude. The median cruise $EInvPM_{num}$ and the median cruise thrust setting referenced at the ICAO Landing and Take-off (LTO) cycle conditions, as well as the $nvPM$ formation during the LTO cycle, is shown in Fig. 5 across all flights and mission phases. Like the BFFM2 for NO_x emission estimations, the MEEM method relies on the ICAO LTO emission measurements for in-flight $nvPM$ estimation as well (Ahrens et al., 2023). With decreasing altitude, the
 225 cruise thrust setting in Fig. 5 (a) starts increasing from a value of about 52.7% of the maximum thrust at 10.97 km (FL360), to a value of about 69.6% at 7.92 km (FL260). This leads to an initial increase of $EInvPM_{num}$ until 57.5% of the maximum thrust, the setting corresponding to the maximum $EInvPM_{num}$ in the MEEM $nvPM$ estimation model's 5-point method (Ahrens et al., 2023), as seen in Fig. 5 (b), resulting in the peak $EInvPM_{num}$ at 9.75 km (FL320) in Fig. 4 (d). Below this altitude, the $EInvPM_{num}$ starts reducing with increasing thrust setting, following the LTO cycle trend. This leads to the relatively stable
 230 trend of the total $nvPM_{num}$ below 9.75 km (FL320) in Fig. 4 (e), as the fuel burn increases with lowering altitudes. While the $EInvPM_{num}$ is the highest at 9.75 km (FL320), the maximum total $nvPM_{num}$ emissions occur at 8.53 km (FL280). Note

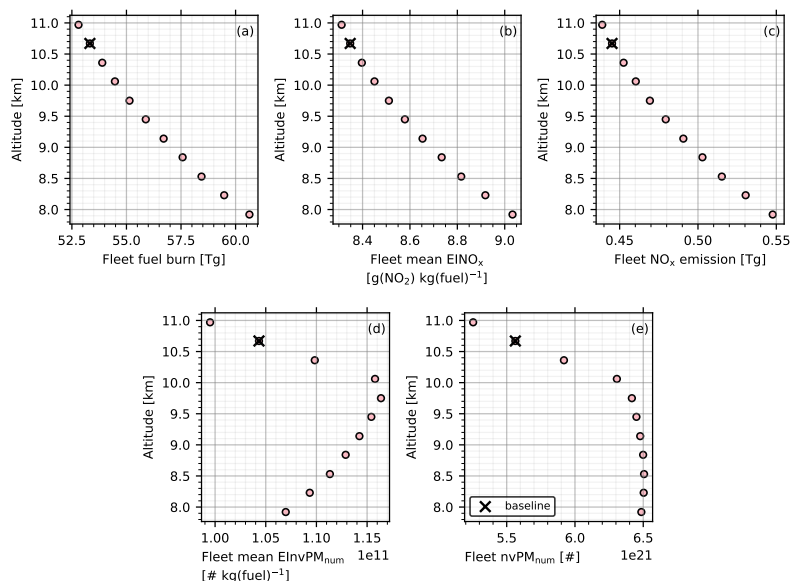


Figure 4. The variation in (a) fleet fuel burn, (b) fleet mean EINO_x , (c) fleet NO_x emissions, (d) fleet mean $\text{EInvPM}_{\text{num}}$, and (e) fleet nvPM number emissions as a function of altitude.

that the trends shown in Fig. 5 are a result of the reference PW1133G-JM engine scaled to the lean-burn regime after applying the PIFs given in Table 1. For an actual lean-burn engine, e.g., LEAP with TAPS configuration, the ICAO LTO cycle trend of nvPM emissions will be different.

235 3.2 Climatological sensitivities of emissions

With the fleet-level fuel burn and emissions sensitivities analyzed as a function of altitude, in this subsection, we describe the climate response results in terms of ATR_{100} . First, we discuss the $\text{ATR}_{100,\text{spec}}$ values corresponding to the variations shown in Fig. 4. Thereafter, we analyze the sensitivities of these $\text{ATR}_{100,\text{spec}}$ values due to the fuel burn and emission scaling variations as described in Table 3.

240 3.2.1 $\text{ATR}_{100,\text{spec}}$ sensitivity as a function of altitude

Fig. 6 shows the variation of the $\text{ATR}_{100,\text{spec}}$ as a function of altitude. Some key insights can be identified. As the altitude increases, the CO_2 response starts to reduce as the fleet-level fuel burn reduces, as shown in Fig. 4 (a). This trend is independent of location of altitude, as CO_2 is a well-mixed greenhouse gas (WMGHG). In contrast, the H_2O response increases with altitude, despite reducing fuel burn and consequently, reduced H_2O emissions. At 7.92 km (FL260), the contribution of $\text{ATR}_{100,\text{H}_2\text{O}}$ is 0.08 mK (0.69%), which rises to 0.7 mK (4.2%) at 10.97 km (FL360). Unlike CO_2 , the climate response of H_2O emissions is altitude and latitude dependent (Grewe and Stenke, 2008; Dahlmann et al., 2023). At higher altitudes, the

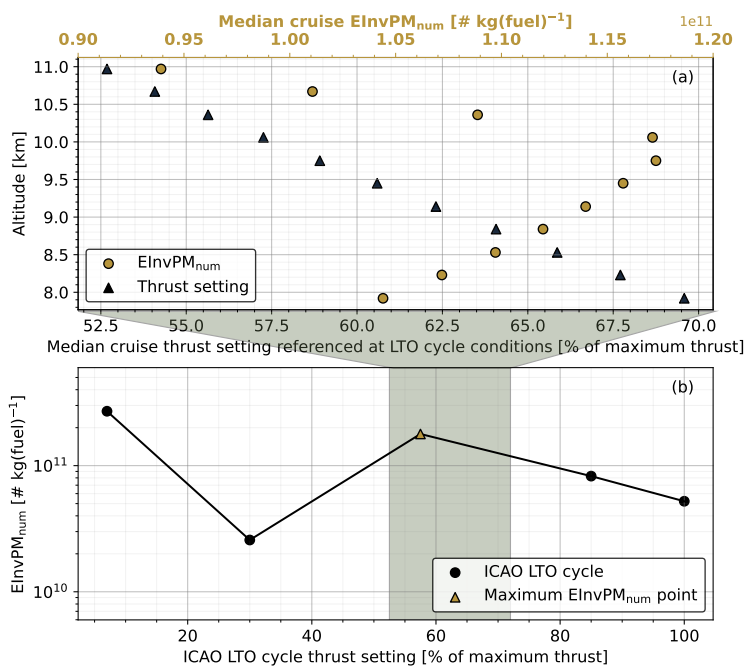


Figure 5. The nvPM formation at the fleet level for the baseline engine as a function of altitude, after applying the $EInvPM_{num}$ PIF from Table 1. (a) The variation in the median cruise thrust setting and the median $EInvPM_{num,cruise}$ for all flights. (b) The trend of $EInvPM_{num}$ with the thrust setting during the ICAO LTO cycle, the reference for nvPM calculation.

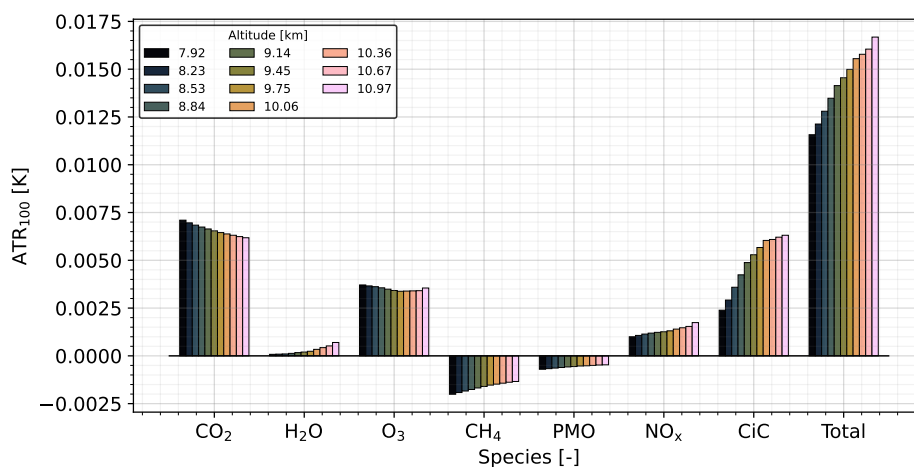


Figure 6. Variation of ATR_{100} for different species as a function of altitude. The NO_x response is the sum of O₃, CH₄ and PMO responses. No SWV impact was calculated. The total response is the sum of CO₂, H₂O, NO_x and the CiC response.

tropospheric water vapor lifetime is high (Pletzer and Grewe (2024); Frömming et al. (2021); Dahlmann et al. (2023)), leading to more accumulation of H₂O emissions, and hence, more warming. The NO_x response is the sum of O₃, CH₄ and PMO responses. With reducing NO_x emissions as the altitude increases as seen in Fig. 4 (c), the tropospheric O₃ enhancement initially reduces. However, at altitudes higher than 9.75 km (FL320), the response starts increasing again, despite lowering NO_x emissions, due to the longer lifetime of O₃ at higher altitudes. (Grewe and Stenke (2008); Dahlmann et al. (2016); Dahlmann et al. (2023)). In line with reduced NO_x emissions with altitude, the lower rate of CH₄ destruction leads to a lower cooling effect. Similar trend can be observed for the PMO response, which is coupled with the CH₄ response (Dahlmann et al., 2016). The dependency of CH₄ and PMO responses on the altitude is lower than the O₃ response (Dahlmann et al., 2023). Overall, despite reducing NO_x emissions with increasing altitude, the combined O₃, CH₄ and PMO responses lead to an increasing total NO_x response with altitude, showcasing the high altitudinal sensitivity of the NO_x response. For the CiC response, an increasing trend with altitude is observed. For the altitude variation implemented in this research, the potential persistent contrail formation increases with altitude (Megill and Grewe (2025); Megill (2026)), leading to a higher CiC response with altitude. However, the rate of response increase is slower at higher altitudes. This follows the trend of the vertically integrated and latitude area-weighted RF_{CiC} distribution (Fig. C1 (a), Appendix), resulting from the traffic distribution shown in Fig. 2. With an altitude increase until 10.06 km (FL330), the RF_{CiC} increases across all longitudes. However, at longitudes greater than 150° in either direction, further increase in altitude leads to a reduction in the RF_{CiC}. As a result, the mean RF_{CiC}, while rising rapidly initially with altitude, tends to rise more slowly at altitudes greater than 10.06 km (FL330). The mean RF_{CiC} is the underlying RF for ATR₁₀₀ calculations. Overall, despite reductions in fuel consumption with altitude, the total impact in terms of ATR₁₀₀ tends to increase, showcasing the trade-off between fuel consumption and climate impact.

In the next subsections, we discuss the response sensitivities of the different species according to the fuel burn and emission variations as described in Table 3, leading to the CFED equations. To decouple fleet sizing effects, the ATR₁₀₀ is normalized with the total fuel burn for all the species except CiC, which is normalized w.r.t. the total flown distance by the fleet. As no variation in distance is considered, the total flown distance remains constant throughout the research, as given in Table 2.

3.2.2 CO₂ response sensitivity

The ATR_{100,CO₂} response is independent of altitude or geographical location, purely a function of the total CO₂ emitted in the atmosphere. Across the variation in the fleet fuel burn as defined in Table 3, the following CO₂ CFED is obtained:

$$\text{ATR}_{100,\text{CO}_2}/\text{fuel} = 3.76 \times 10^{-14} \cdot \text{EICO}_2 \quad (4)$$

where ATR_{100,CO₂}/fuel is the fuel-normalized ATR_{100,CO₂} in K kg(fuel)⁻¹ and EICO₂ is the CO₂ emission index in kg kg(fuel)⁻¹. Comparing the coefficient with existing literature, in the work of Dahlmann et al. (2025), a value of 1.083×10^{-13} K kg(fuel)⁻¹ for the BAU scenario is reported for the period 2025-2124 for CO₂. Considering a default EICO₂ of 3.16 kg kg(fuel)⁻¹ in Eqn. 4 yields a value of 1.18×10^{-13} K kg(fuel)⁻¹, the difference being 9% relative to Dahlmann et al. (2025). Keeping in mind differences due to the emission scenario, the coefficient value obtained in Eqn. 4 shows good agreement.



280 3.2.3 H₂O response sensitivity

Fig. 7 shows the variation of the fuel-normalized ATR_{100,H_2O} , i.e., $ATR_{100,H_2O}/\text{fuel}$ with altitude, found to be following a cubic equation, given in Eq. 5,

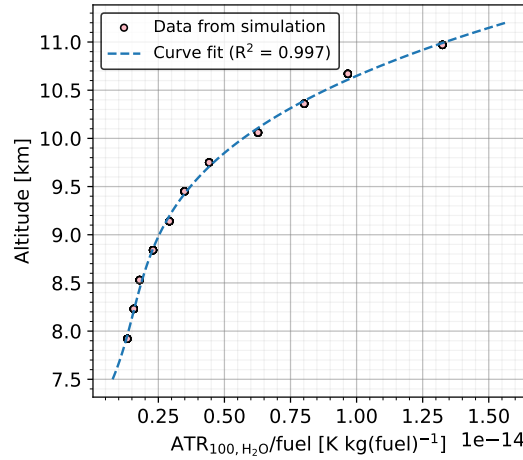


Figure 7. The variation of $ATR_{100,H_2O}/\text{fuel}$ across altitudes. A cubic fit across the data was found best describing the relationship.

$$ATR_{100,H_2O}/\text{fuel} = [(3 \times 10^{-16} \cdot h^3) - (7.37 \times 10^{-15} \cdot h^2) + (6.10 \times 10^{-14} \cdot h) - 1.69 \times 10^{-13}] \cdot EI_{H_2O} \quad (5)$$

where $ATR_{100,H_2O}/\text{fuel}$ is the fuel-normalized ATR_{100,H_2O} in $K \text{ kg(fuel)}^{-1}$, and h is the altitude in km. EI_{H_2O} is the
 285 emission index of H_2O in kg kg(fuel)^{-1} .

3.2.4 NO_x response sensitivity

Next, the dependence of fuel-normalized ATR_{100,NO_x} , i.e., $ATR_{100,NO_x}/\text{fuel}$, on cruise $EINO_x$ and the cruise altitude is shown in Fig. 8 (a). At each flight level, the response increases linearly with the $EINO_x$, where the sensitivity of this increase is a function of altitude. A small scatter in $ATR_{100,NO_x}/\text{fuel}$ was observed at different altitudes for each $EINO_x$. This indicated
 290 a second-degree dependence of ATR_{100,NO_x} on the fuel burn, as no other parameter has been varied. However, the dependence was found to be negligible, as linearity describes the relationship sufficiently well across the scatter mean, with the R^2 being greater than 0.99 at each altitude. Therefore, the structure of the CFED at each altitude is,

$$ATR_{100,NO_x}/\text{fuel} = m_{alt,NO_x} \cdot EINO_{x,cruise} + c_{alt,NO_x} \quad (6)$$

where m_{alt,NO_x} is the slope in $K \text{ g(NO}_2)^{-1}$ and c_{alt,NO_x} is the intercept in $K \text{ kg(fuel)}^{-1}$ of the different linear fits in Fig. 8
 295 (a). The dependency of m_{alt,NO_x} and c_{alt,NO_x} on the altitude was analyzed, and shown in Figs. 8 (b) and (c), respectively. Both the slope and the intercept variation were found to be following a quadratic equation ($R^2 > 0.99$). Hence,

$$m_{alt,NO_x} = a_{0,NO_x} \cdot h^2 + a_{1,NO_x} \cdot h + a_{2,NO_x} \quad (7)$$

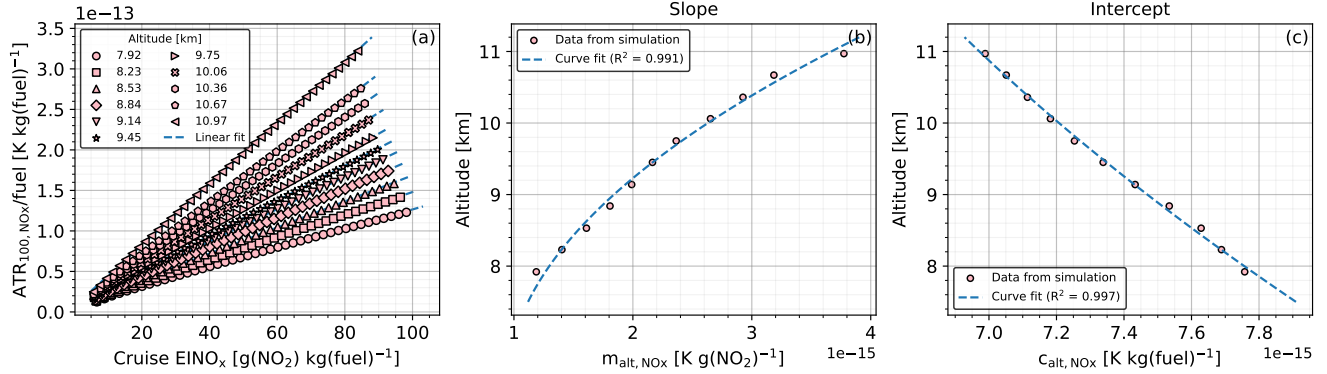


Figure 8. (a) The variation of $ATR_{100,NO_x}/fuel$ as a function of variation in altitude and $EINO_{x,cruise}$. For each altitude, a linear fit was found best describing the relationship. (b) The variation of the slope of the linear fit as a function of altitude. (c) The variation of the intercept of the linear fit as a function of altitude. For both the parameters, a quadratic fit was found best describing the relationship.

$$C_{alt,NO_x} = b_{0,NO_x} \cdot h^2 + b_{1,NO_x} \cdot h + b_{2,NO_x} \quad (8)$$

where h is the altitude in km, a_{i,NO_x} and b_{i,NO_x} ($i = 0, 1, 2$) are the constants of the quadratic fit for the slope and the intercept curves respectively. Combining Eqs. 6, 7 and 8, the NO_x CFED is obtained as:

$$ATR_{100,NO_x}/fuel = [(1.24 \times 10^{-16} \cdot h^2) + (-1.56 \times 10^{-15} \cdot h) + 5.84 \times 10^{-15}] \cdot EINO_x + (1.28 \times 10^{-17} \cdot h^2) + (-5.05 \times 10^{-16} \cdot h) + 1.10 \times 10^{-14} \quad (9)$$

3.2.5 Contrail-induced cirrus response sensitivity

The CiC response has a complex dependence on nvPM emissions and ambient conditions (Voigt et al., 2026). Figure 9 (a) shows the trend of the distance-normalized $ATR_{100,CiC}$ with varying $EInvPM_{num,cruise}$. Note the horizontal logarithmic axis. With increasing altitude, the ambient conditions become favorable for contrail formation with lower atmospheric temperature. The peak contrail formation and subsequently, the CiC impact takes place around the tropopause (Grewe and Stenke, 2008), where conditions are cold and humid enough for contrail ice crystal formation.

The analysis is carried out separately for the rich-burn and the lean-burn regimes. In Fig. 9 (b), the rich-burn regime shows an increasing CiC impact with $EInvPM_{num,cruise}$. Increasing nvPM emissions lead to more ice-crystal formation leading to a higher contrail and consequently, contrail-cirrus formation. For a given altitude, the rich-burn $ATR_{100,CiC}/km$ was found to follow the inverse tangential equation structure given in Eq. 10, following Grewe et al. (2021),

$$ATR_{100,CiC,rich}/km = a_{CiC,rich} \cdot \tan^{-1}(b_{CiC,rich} \cdot EInvPM_{num,norm}^{CCiC,rich}) \quad (10)$$

where $a_{CiC,rich}$, $b_{CiC,rich}$ and $c_{CiC,rich}$ are the altitude-dependent coefficients. $EInvPM_{num,norm}$ is the cruise $EInvPM_{num}$ normalized with a reference $EInvPM_{num}$ of $1.5 \times 10^{15} \# kg(fuel)^{-1}$ (Völk et al., 2023). Only $a_{CiC,rich}$ was found to show

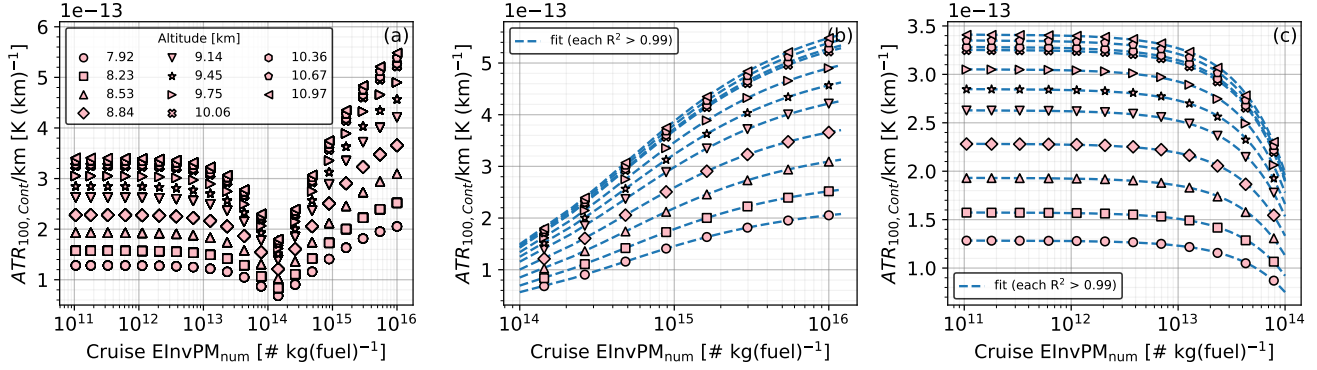


Figure 9. (a) The variation of $ATR_{100,CiC}/km$ as a function of $EInvPM_{num,cruise}$ and altitude. (b) The variation shown only for the rich-burn regime ($EInvPM_{num,cruise} > 10^{14} \# kg(fuel)^{-1}$). An inverse tangential function was found best describing the variation. (c) The variation for only the lean-burn regime ($EInvPM_{num,cruise} < 10^{14} \# kg(fuel)^{-1}$). A linear fit was found as best describing the relationship.

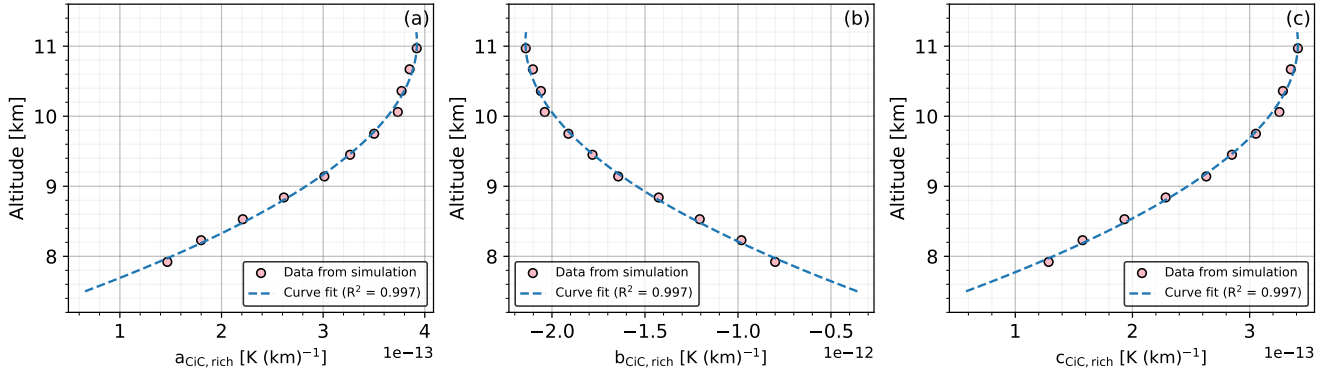


Figure 10. (a) Variation of $a_{CiC,rich}$ as a function of altitude. (b) Variation of $a_{CiC,lean}$ with altitude. (c) Variation of $b_{CiC,lean}$ with altitude.

significant variation with altitude, with $b_{CiC,rich}$ and $c_{CiC,rich}$ remaining relatively constant, having a Relative Standard Deviation (RSD) of 0.3% and 0.06% respectively across altitude. Hence, the mean values of $b_{CiC,rich}=1.93$ and $c_{CiC,rich}=0.58$ are taken. The altitudinal variation of $a_{CiC,rich}$ is shown Fig. 10 (a), with a quadratic fit describing the variation. Thus, the following rich-burn CiC CFED is obtained:

$$320 \quad ATR_{100,CiC,rich}/km = [(-2.58 \times 10^{-14} \cdot h^2) + (5.71 \times 10^{-13} \cdot h) - 2.76 \times 10^{-12}] \cdot \tan^{-1}(1.93 \cdot EInvPM_{num,norm.}^{0.58}) \quad (11)$$

where h is the cruise altitude in km. The lean-burn regime behavior is shown in Fig. 9 (c). A recent measurement campaign showed significant contrail formation in the lean-burn regime for a SAF-powered configuration, where the exhaust plume is nvPM-poor (Voigt et al., 2026). The main contributor towards ice-crystal formation in the nvPM-poor regime are the volatile

aerosol particles. For a given altitude, the CiC response in this case was found to follow a linear equation,

$$\text{ATR}_{100,\text{CiC},\text{lean}}/\text{km} = a_{\text{CiC},\text{lean}} \cdot \text{EInvPM}_{\text{num},\text{norm.}} + b_{\text{CiC},\text{lean}} \quad (12)$$

where $a_{\text{CiC},\text{lean}}$ and $b_{\text{CiC},\text{lean}}$ are the altitude-dependent slope and intercept respectively. In contrast to the rich-burn case, both were found to show significant variation with altitude, as shown in Figs. 10 (b) and (c) respectively. For either of them, a quadratic relationship was fitted, leading to the following lean-burn CiC CFED:

$$\begin{aligned} \text{ATR}_{100,\text{CiC},\text{lean}}/\text{km} = & [(1.41 \times 10^{-13} \cdot h^2) - (3.11 \times 10^{-12} \cdot h) + 1.51 \times 10^{-11}] \cdot \text{EInvPM}_{\text{num},\text{norm.}} + \\ & [(-2.26 \times 10^{-14} \cdot h^2) + (4.99 \times 10^{-13} \cdot h) - 2.41 \times 10^{-12}] \end{aligned} \quad (13)$$

330 4 CFED Performance Evaluation

In this section, we evaluate the performance of the CFED equations, derived in Eqns. 4, 5, 9, 11 and 13. First, we assess the CFED performance towards capturing the relevant normalized ATR_{100} sensitivities with respect to emission and cruise altitude variation comprising the simulation space from Table 2.3, as shown in Figs. 7, 8 (a), 9 (b) and 9 (c). Thereafter, we analyze the out-of-sample CFED performance on 100 randomly selected scaling factor combinations of fuel burn, EINO_x and

335 $\text{EInvPM}_{\text{num}}$ at each altitude.

4.1 Normalized species ATR_{100} sensitivities

Figure 11 shows the comparison of the CFED predictions against the full modeling output along with the relative error in the CFED prediction. For H_2O as shown in Fig. 11 (a), the CFED predictions match well with the $\text{ATR}_{100,\text{H}_2\text{O}}/\text{fuel}$ trends obtained from the full model simulation. The relative error as given in Fig. 11 (b) is within $\pm 5\%$. For $\text{ATR}_{100,\text{NO}_x}/\text{fuel}$, the overall altitude-dependent linearity of the metric with $\text{EINO}_{x,\text{cruise}}$ is captured by the CFED, as given in Eqn. 9. Interestingly, the relative error in Fig. 11 (d) is found to increase rapidly at $\text{ATR}_{100,\text{NO}_x}/\text{fuel}$ values below $0.4 \text{ K kg(fuel)}^{-1}$. This is mainly due to the SWV response, which is absent below a total SWV mass of 1.6 Tg , i.e., at low $\text{EINO}_{x,\text{cruise}}$ due to a lower CH_4 destruction (Pletzer, 2024). As the NO_x CFED is derived as a result of curve fitting across a range of $\text{EINO}_{x,\text{cruise}}$, the SWV effect is distributed across all $\text{EINO}_{x,\text{cruise}}$ values, resulting in the sharp increase. However, such low $\text{ATR}_{100,\text{NO}_x}/\text{fuel}$ would correspond to extremely low $\text{EINO}_{x,\text{cruise}}$ values around $6 \text{ g(NO}_2) \text{ kg(fuel)}^{-1}$, as seen in Fig. 11 (c). For higher $\text{ATR}_{100,\text{NO}_x}/\text{fuel}$ values, the relative error lies within $\pm 5\%$. The CFED rich-burn CiC predictions and the relative error are shown in Figs. 11 (e) and (f) respectively. For altitudes greater than or equal 8.84 km (FL290), the relative error is found to be within $\pm 2\%$. At the lower end of the altitude variation, i.e., 7.92 km (FL260), the CFED $\text{ATR}_{100,\text{CiC},\text{rich}}/\text{km}$ prediction error rises to as high as around -6% . Similarly, for the lean-burn predictions, the relative error across all altitudes higher than 7.92 km (FL260) lies within -2% to $+4\%$, as seen in Fig. 11 (h). The Mean Absolute Error (MAE) for H_2O , NO_x , rich-burn CiC and lean-burn CiC CFED predictions are 3.12% , 3.17% , 1.75% and 1.75% respectively. Overall, across species, the CFED equations capture the normalized species ATR_{100} sensitivities with respect to emission and altitude variation with a mean error of 2.71% .

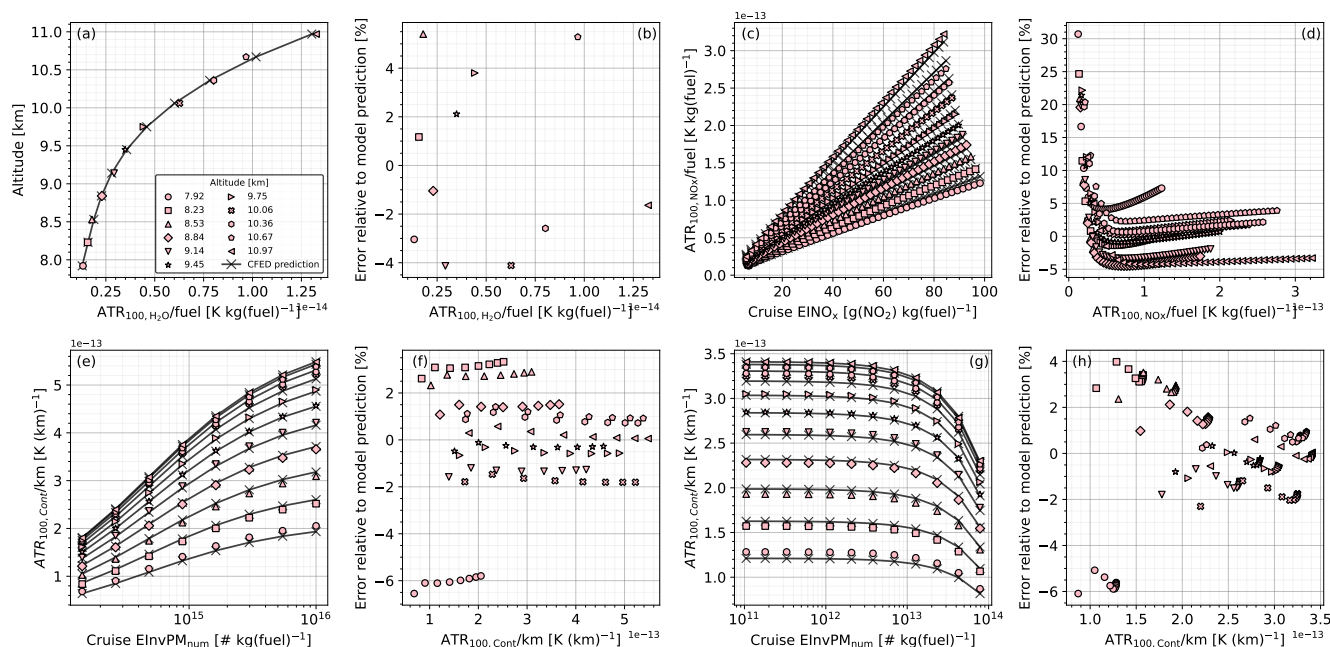


Figure 11. Sensitivity of relevant normalized species ATR_{100} vs emissions and altitude compared for CFED equations against the full modeling output. (a) $ATR_{100,H_2O}/fuel$ as a function of altitude, (b) the relative error for CFED $ATR_{100,H_2O}/fuel$ prediction, (c) $ATR_{100,NO_x}/fuel$ as a function of altitude and $EINO_{x,cruise}$, (d) the relative error for CFED $ATR_{100,NO_x}/fuel$ prediction, (e) $ATR_{100,CiC}/km$ as a function of altitude and rich-burn $EInvPM_{num,cruise}$, (f) the relative error for rich-burn CFED $ATR_{100,CiC}/km$ prediction, (g) $ATR_{100,CiC}/km$ as a function of altitude and lean-burn $EInvPM_{num,cruise}$, (h) the relative error for lean-burn CFED $ATR_{100,CiC}/km$ prediction.

4.2 Out-of-sample CFED performance

Fig. 12 shows the distribution of the randomly selected out-of-sample CFED evaluation points, which lie within the ranges of the simulation space given in Table 3. The CFED performance at each scaling factor combination was compared with the output from the full methodological framework shown in Fig. 1. For CO_2 , both the model as well as the CFED result in a constant value of $ATR_{100,CO_2}/fuel$ of about $1.17 \times 10^{-13} K kg(fuel)^{-1}$. For other species, the CFED performance evaluated against the model output is shown in Fig. 13 for each altitude. For H_2O in Fig. 13 (a), both the model as well as the CFED evaluations result in a single value at each altitude, given that H_2O response is a function of the total H_2O emissions at a given altitude, which depend on the total fuel burn. A high R^2 of 0.997 is obtained, indicating very good H_2O CFED performance. The NO_x response comparison is given in Fig. 13 (b). Overall, the prediction matches well with the methodological output across all altitudes, resulting in a high R^2 of 0.995. Next, the CiC CFED performance evaluated against the model output is shown in Fig. 13 (c) and (d) for the rich-burn and the lean-burn regimes respectively. Both CiC CFED equations show no unusual behavior and are close to modeling prediction, resulting in R^2 values upwards of 0.99 respectively.

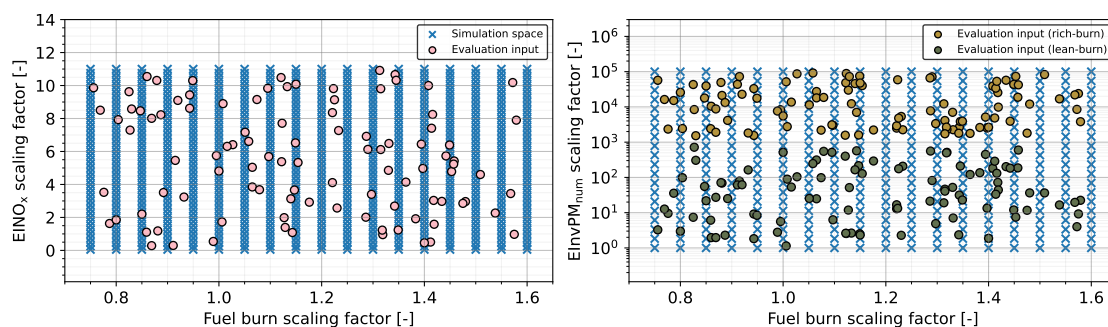


Figure 12. Distribution of the samples selected for CFED performance evaluation plotted against the points from the simulation space (Table 3) applied at each altitude. (a) The fuel burn and EINO_x scaling factors. (b) The fuel burn and EInvPM_{num} scaling factors. Separate sample sets for the lean and the rich-burn regimes are chosen.

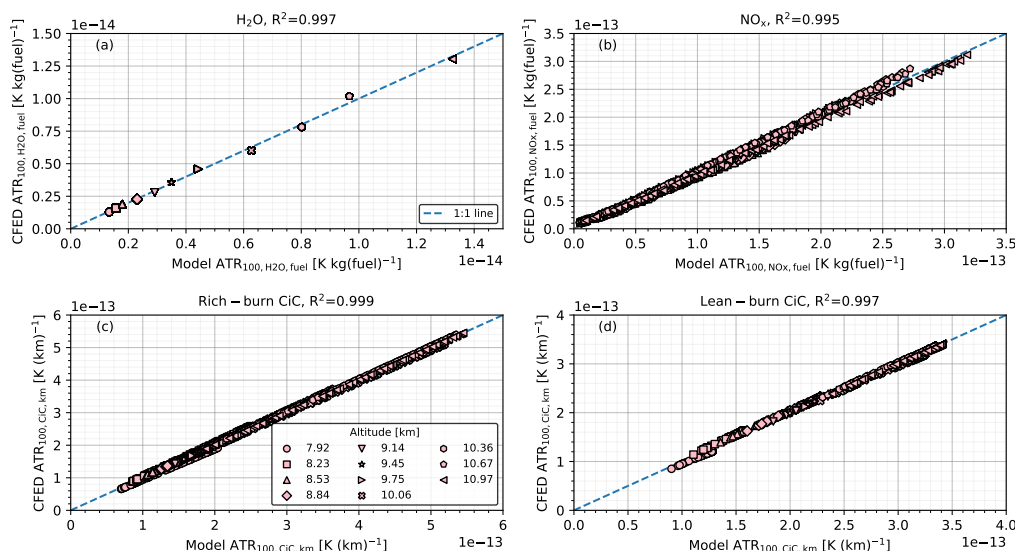


Figure 13. Performance of the (a) H₂O, (b) NO_x (c) rich-burn CiC and (d) lean-burn CiC CFED equations measured against the output from the full methodological implementation shown in Fig. 1.

5 Discussion

The CFED equations are derived and given in Eqns. 4, 5, 9, 11 and 13 for the different species. The reduced-order analytical functions enable design stage climate assessment of aircraft engines, allowing for feasibility studies such as design-climate tradeoff analysis or engine optimization for minimum climate impact. These functions are an attempt towards addressing the research gap of climate assessment during the engine design stage, accounting for the iterative nature of designing an aircraft



engine, as well as the computationally expensive step of generating emission inventories. Normalizing with fuel burn allows the application of these functions for any fleet size, as long as the relevant emission indices are known at a given altitude. The function predictions are in line with the current understanding of the climate impact caused due to aviation, as seen in Sec. 4. Upon closer look, a natural implication of the emission scaling on the engine side leading to scaling of the input emissions on the climate side becomes evident. For a given technology, CFED equations can also be utilized for scenario sensitivity studies, as long as the combination of relevant emissions trends is confined within the simulation space.

However, some limitations need to be highlighted. The development of CFED equations is based on the intrinsic assumption of equivalent change in emissions across all operating conditions, design and off-design, due to change in the emissions resulting from engine design variation. As an implication, the CFED prediction for an advanced design with available detailed performance profile may deviate from the prediction from the climate assessment loop shown in Fig. 1. The nvPM emission sensitivity across altitudes is based on the dynamics of the reference PW1133G-JM engine. With the potential of the MEEM methodology becoming robust in the future predicting nvPM emissions during cruise (Ahrens et al., 2025), the contrail-cirrus lean-burn regime behavior is likely to be updated, based on emission sensitivity behavior (Voigt et al. (2026); Yu et al. (2024)).

A few key areas for future research remain. Currently, the CFED equations have been developed for ATR₁₀₀ for a SAF-powered fleet for short-to-medium range applications. (Note that we have not considered life-cycle CO₂ emissions, explicitly, as those are heavily depending on the carbon source and the production. However, it can be easily considered by adapting EICO₂ in Eqn. 4.) A natural next step is analyzing the sensitivity of the functions with respect to changing metric and time horizon, and with a different fuel, e.g., H₂. The CFED equations are based on responses corresponding to a global route network for a sub-fleet of the global air transport fleet in the future. Regional sensitivity of the responses remain to be seen. In addition, each step during the impact assessment carries an uncertainty due to various reasons. The integration of uncertainties with the current CFED equations is an area of focus in the future.

6 Conclusions

This research presents novel reduced-order Climate Functions for Engine Design (CFED) aimed at climate assessment of aircraft engines during the cycle design stage, by utilizing cruise emissions and altitude as inputs. The equations developed for each aviation-relevant species, enable prospective users to assess the impact of aircraft engines during the design stage for a global fleet network. These functions eliminate the need of applying the full methodological framework required for climate assessment during the iterative design stage, which involves the creation of emission inventories, saving significant computational costs. The CFED equations are able to reproduce normalized ATR₁₀₀ sensitivity trends with emission and altitude variation with a mean error of 2.71% across all species. Comparing the performance of these functions with the output of the full methodological framework for randomly selected emission scaling combinations resulted in very good agreement, with R² values greater than 0.99 achieved for the different species. In practice, the functions can be applied for any engine architecture operating at typical subsonic cruise altitudes, since they only consider the cruise emissions indices of CO₂, H₂O, NO_x and nvPM as the inputs. With growing demand and the contribution of aviation towards anthropogenic warming possibly



increasing in the future, propulsion systems are central in achieving key climatological goals. As such, fulfilling the future
405 demand sustainably will require climate optimized engines, where the CFED equations presented in this research can play a
key role.

Code and data availability. The CFED model is available at: <https://github.com/harjotsingh21/CFED>

Appendix A: Conversion from flight level to altitude in km

The conversion from flight FL to altitude in km is given as below:

$$410 \quad \text{alt}[\text{km}] = \text{FL} \times 0.03048 \quad (\text{A1})$$

The altitude in km is rounded off to two decimal places.

Appendix B: Aircraft/engine dependent parameters for contrail calculation in OpenAirClim v0.16

The Schmidt-Appelman criterion (SAC) for calculating mixing line slope for contrail formation is dependent on aircraft/engine related parameters (Schumann, 1996), as shown in Eqn. B1:

$$415 \quad G = \frac{c_p p_a}{\epsilon} \frac{EI_{\text{H}_2\text{O}}}{(1 - \eta)Q} \quad (\text{B1})$$

where G is the mixing line slope in Pa (K)^{-1} , $c_p = 1004 \text{ J (kg K)}^{-1}$ is the isobaric heat capacity of air, p_a is the ambient pressure in Pa, ϵ is the molar mass ratio of H_2O and air, $EI_{\text{H}_2\text{O}}$ is the emission index of H_2O in kg (kg fuel)^{-1} , η is the overall propulsion efficiency, and Q is the fuel LHV in J (kg)^{-1} . OAC v0.16 considers the SAC mixing line slope calculation at a reference level of 250 hPa, i.e., G_{250} (Megill and Grewe (2025); Megill (2026)). We assume an overall efficiency of 0.402
420 (Johansson et al., 2026). Combined with the $EI_{\text{H}_2\text{O}}$ and LHV values as given in Sec. 2.2, we obtain a G_{250} value of 2.10 Pa (K)^{-1} .

OAC v0.16 also requires aircraft wingspan to account for wake vortex corrections (Megill and Grewe (2025); Megill (2026)). We consider a wingspan of 37 m for the aircraft (Lessis et al., 2025).

Appendix C: CiC Radiative Forcing

425 Due to the traffic distribution as shown in Fig. 2, the resultant RF_{CiC} distribution as a function of altitude, vertically integrated and area-weighted over latitude, is shown in Fig.C1 (a). The mean of the distributions is shown in Fig. C1 (b), showcasing stagnating RF behavior with altitude, as shown in Fig. 6.

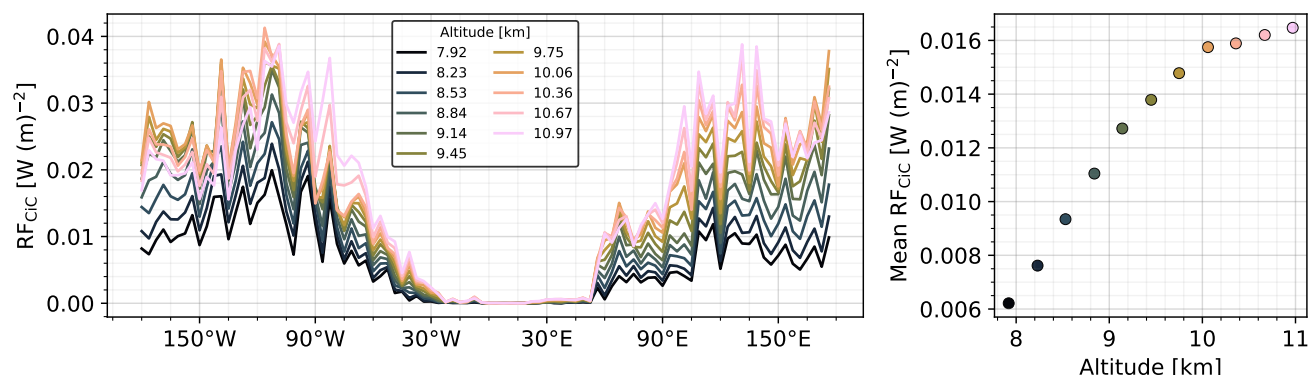


Figure C1. (a) Latitude area-weighted and altitude-integrated RF_{CiC} distribution over longitude as a function of altitude variation. The altitude integration assumes random overlap between layers (Dahlmann et al. (2016); Megill (2026)). Note that wingspan correction is not taken into account. (b) Mean of the RF_{CiC} as a function of altitude variation as implemented in this research.

Author contributions. HSS and FY conceptualized the research idea. HSS carried out the formal analysis, data curation and validation. FY acquired research funding. HSS and FY developed the methodology. FY, AGR and VG provided supervision. HSS prepared the manuscript with contributions from all co-authors.

Competing interests. At least one of the (co-)authors is a member of the editorial board of Journal of Environmentally Compatible Air Transport System (JECATS).

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