D2.3 - State of the art review of aviation climate impact assessment

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Abstract

This document represents the output of CLAIM Task 2.1: state-of-the-art aviation climate impact assessment methodologies. The deliverable aims to analyze the relevant climate impact methodologies for assessing the relationship between non-CO_2 and CO_2 climate impacts and support the identification of knowledge gaps, barriers and needs for research in view of the climate impact assessment, to orient the technology research streams for future green and zero-emission aircraft. A review of EU-funded actions and research projects has been performed, with focus on climate impact assessment methodologies due to aviation activity, as well as other national and international actions and literature works. Several critical insights have been drawn about how aviation contributes to climate change and the potential pathways to mitigate these impacts. While significant progress has been made in modelling tools and operational strategies, achieving a sustainable aviation sector will demand the integration of expertise from atmospheric, engineering, economics, and social sciences. Achieving net-zero or significantly reduced emissions will require sustained innovation, investment, and cooperation across the aviation ecosystem. Future efforts should prioritize addressing the highlighted gaps, fostering international collaboration, and ensuring that climate mitigation becomes an integral part of aviation's operational and strategic goals.

Keywords

Clean Aviation, CLAIM, Climate Change, Impact Assessment, Methodologies, State of the art.

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Information Table

Contract Number	**101140632**
Project Title	Clean Aviation Support for Impact Monitoring
Topic	HORIZON-JU-CLEAN-AVIATION-2023-02-CSA-01
Type of Action	HORIZON JU Coordination and Support Actions
Project Start Date	2024-01-01
Duration	18 Months
Project Coordinator	Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR)
Deliverable Number	D2.3
Deliverable Title	State of the art review of aviation climate impact assessment
Version	1.0
Status	Final
Responsible Partner	CIRA
Deliverable Type	Report
Contractual Date of Delivery	2025-04-30
Actual Date of Delivery	2025-06-16
Dissemination Level	PU

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Document history

Version	Date	Status	Author	Description
0.5	2025-04-04	Draft	EB	First draft version
0.9	2025-05-16	Final Draft	EB	Final draft release
1.0	2025-06-16	Final	EB	Final release

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Table of Acronyms and Abbreviations

Acronym/Abbreviation	Description / Meaning
ACACIA	Advancing the Science for Aviation and Climate
aCCFD	algorithmic Climate Cost Function
AHEAD	Advanced Hybrid Engines for Aircraft Development
AEM	Advanced Emission Model
ATM	Air Traffic Management
ATM4E	Air Traffic Management for Environment
ATR	Average Temperature Response
BECOM	Better Contrail Mitigation
CAST	Climate and Aviation Sustainable Trajectories
CCF	Climate Cost Function
CATS	Climate compatible Air Transport System
CFAD	Climate Functions for Aircraft Design
CIRA	Italian Aerospace Research Center
CLIMOP	Climate assessment of innovative mitigation strategies towards operational improvements in aviation
DLR	German Aerospace Center
ECATS	Environmentally Compatible Air Transport System
ECF	Environmental Cost Function
EU	European Union
ERF	Effective Radiative Forcing
ETS	Emissions Trading System
GCM	General Circulation Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLOWOPT	Global-Warming-Optimized Aircraft Design
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
ICT	Information and Communications Technologies
ISO	Intermediate Stop Operations
LAQ	Local Air Quality
MDO	Multidisciplinary Design Optimisation
LNG	Liquid Natural Gas
ML	Machine Learning
NWP	Numerical Weather Prediction
OI	Operational Improvement
PMO	Primary Mode Ozone
REACT4C	Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate
PTL	Power to Liquid
RF	Radiative Forcing
RPK	Revenue Passenger Kilometers
SAAM	System for traffic Assignment and Analysis at a Macroscopic level

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SAF	Sustainable Aviation Fuels
SESAR	Single European Sky Advanced Research
SOTA	State of the Art
UNEP	United Nations Environment Programme
WMO	World Meteorological Organization

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1. Introduction

1.1 Scope of the document

The deliverable aims to analyze the relevant climate impact methodologies for assessing the relationship between non-CO_2 and CO_2 climate impacts and support the identification of knowledge gaps, barriers and needs for research in view of the climate impact assessment, to orient more appropriately the technology research streams for future green and zero-emission aircraft. The methodology is based on a dedicated taxonomy that considers a dataset of projects, to rank their proposed approaches according to their relevance to the climate impact assessment topic.

This final SOTA evaluation contributes to the development of an analysis of the relevant climate impact methodologies for assessing the relationship between non-CO_2 and CO_2 climate impacts and support the identification of knowledge gaps, barriers, and needs for research in view of the climate impact assessment, to orient more appropriately the technology research streams for future green and zero-emission aircraft. By analyzing EU-funded initiatives and other significant projects, several critical insights have been drawn about how aviation contributes to climate change and the potential pathways to mitigate these impacts.

1.2 Summary

This document represents the output of Task 2.1: State-of-the-art aviation climate impact assessment methodologies (Lead: CIRA). A review of previous and ongoing EU-funded actions and research projects (ATM4E, REACT4C, ACACIA, BECOM, CLIMOP, GLOWOPT, etc.) has been performed, with focus on climate impact assessment methodologies due to aviation activity, as well as other national and international actions (HyPERION, CIRRUS-H2, CIRRUS-HL, etc.). Relevant literature works were also analyzed.

This document is organized as follows: Section 1.3 contains a general introduction about the several ways in which aviation affects the climate. Section 2 contains an in-depth analysis of relevant projects and a synthetic overview of the methodologies addressed by them, whereas Section 3 contains a short description of other projects, including national/international actions and ongoing EU-funded research projects. Section 4 presents an analysis of relevant literature works. Discussion and conclusions are reported in Section 5.

1.3 Climate impacts of aviation

Flight emissions modify the atmospheric concentrations of the components, altering the Earth radiative balance and causing climate change due to their chemical-physical interactive behaviours and their persistence over time through the atmospheric column. The impact amount depends on the time and place where it happens, since it also depends on the background conditions (e.g., weather conditions). The climate impacts of aviation are related to the effects of CO_2, NO_x -induced O_3, water vapour and contrails [1]. Moreover, NO_x impacts have several chemical feedbacks, while particulates are also important [2].

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Long-term effects of climate change have an impact on various aspects of the environment, ecosystems, and human societies, including:

- Rising Sea Levels
- Increased global temperatures, resulting in more frequent and severe heat waves
- Changing Precipitation Patterns
- Biodiversity Loss
- Agricultural Challenges
- Health Risks
- Extreme events
- Human losses and social-economic emergencies
- Migration and Displacement:
- Loss of Historical and Cultural Site.

At a basic level, the climate impact of CO_2 is strongly related to the total amount of CO_2 released during the transport and industrial activities including the flights, but at a more rigorous level the radiative forcing calculation is non-linear [3]. The impact is independent of the emission location, since CO_2 is a long-lived gas. For constant flight level and fuel burn, the climate impact of CO_2 is related to a first approximation to the air-distance travelled, even if the flight distance and the fuel use are not linearly related [4]. It is given by the product of the route time (calculated taking into account the winds at flight level) and true airspeed, which is generally assumed to be constant. Therefore, the route time is used as a simple proxy for the climate impact of CO_2. The climate impact is therefore greater for longer flights, w

hich require more fuel and therefore produce greater amounts of CO_2 in one trend of the traffic flows that shows in 2024 a +8% of increment vs 2023 for the non-intra-Europe routes from the European Aviation Overview 2024 (Source: EUROCONTROL).

The climate impact of NOx-induced O_3 is dependent on emission latitude and altitude ([5],[6]), at a constant cruise altitude of 250 hPa: specifically, the impact is largest at the equator and decreases towards the poles ([5],[7]). A simplified climate impact proxy is therefore a function of the route latitude. It is worth noting that the climate effect of NO_x-induced ozone increases is significantly compensated by an accompanying decrease in methane (plus a methane-induced decrease in ozone), so the net climate impact of NO_x changes is not easy to compute.

The climate impact of water vapor emissions is more relevant if the emissions are made directly into the stratosphere [8], where they have a longer lifetime. Therefore, the total route time that the aircraft would be in the stratosphere could be considered a simplified climate impact proxy. However, while it offers a practical approximation, more detailed analyses are necessary to capture the full spectrum of atmospheric and climatic effects of aviation.

The climate impact from contrails (formed as a result of mixing hot moist exhaust air with cooler ambient air) is a complex interplay of their formation conditions, persistence, and radiative properties, with the Schmidt-Appleman criterion often used to predict their occurrence.

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2. Detailed analysis of relevant projects

2.1 REACT4C

REACT4C (Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate - https://www.react4c.eu/) is a project coordinated by DLR (Sigrun Matthes, Germany) and funded by the European Commission within the 7th Framework Programme. It was carried out from January 2010 to April 2014, with the participation of eight partners. This project investigated a concept to identify alternative routes characterized by a minimal climate impact, based on a weather-dependent route optimization [9]. The main objectives were:

1. to evaluate the feasibility of adopting flight routes leading to reduced fuel consumption and emissions, thus reducing the environmental impact;
2. to estimate the overall global effect of such ATM measures in terms of climate change.

The novelty elements in REACT4C are represented by a modelling chain for optimisation of aircraft trajectories with respect to their climate impact, which is dependent on actual weather conditions. Specifically, the modelling concept of REACT4C is based on the calculation of climate cost functions (CCFs), which are a measure for the climate impact of a local emission and represent the interface between climate-chemistry modelling on the one hand and flight planning of aircraft trajectories on the other hand [10]. The name CCF was later modified in a sense that it stands for climate change functions, in order to make clearer, that the unit of these functions is a metric for climate change, e.g. temperature change, or warming potential, and not necessarily economic costs (comment from the coordinator of REACT4C, Sigrun Matthes). REACT4C focused on the North Atlantic region, as for long-haul flights less constraints due to airspace structure were anticipated for flight trajectories and more chances to enable re-routing expected, also with auxiliary new air transport systems, satellite communications and onboard devices able to support the pilots and minimize their effort automatically. Furthermore, this study area is characterized by synoptical-scale archetypical weather patterns, which enable the creation of a set of representative weather situations, as the one produced by Irvine et al., (2013) [11] through a weather classification performed considering specific air traffic routes.

In the framework of REACT4C, the climate cost functions (CCFs) have been calculated with the chemistry–climate model EMAC (ECHAM/MESSy Atmospheric Chemistry; [12]), which additionally includes two important sub-models: ATTILA, a Lagrangian transport scheme [13] and AIRTRAC, which calculates contributions from additional emissions to concentrations based on ATTILA. The determination of the CCFs starts with the calculation of the contributions of additional emissions to atmospheric concentrations (nitrogen oxides, ozone, methane, contrails, water vapour, carbon dioxide) and contrail properties. To this aim the EMAC model is used, which has a grid with resolution of approximately 2.8° longitude×2.8° latitude. On this grid a time-region grid, covering the area where the optimisation is performed, is overlayed. For each time-region grid point, predefined emissions are released and partitioned on 50 air parcel trajectories, which are randomly distributed in the EMAC grid box in which the time-region grid point is located. A Lagrangian transport scheme has been adopted since it allows the inclusion of a multitude of cost function calculations in a single EMAC simulation. Each air parcel trajectory is characterised by its position at any time and includes an arbitrary number of properties P (e.g., the contribution of the emissions to specific

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chemical species NO_x, H_2O, contrail coverage etc). The Lagrangian approach is based on detailed modelling of the background processes within EMAC and an additional, simplified, simulation of the contributions from emissions taking place in the respective time regions. For each air parcel trajectory, the contribution of the pulse emission to the atmospheric composition is calculated by the sub-model AIRTRAC that solves a simplified set of chemical equations on the air parcel trajectories and the emissions are partitioned into background emissions and additional emissions. This approach has the advantage of being numerically efficient, since many time regions are calculated in parallel, even if the calculations are less detailed than the representation of the background processes simulated by EMAC. The approach further calculates the contribution of an emission in the time region and separates it from compensating effects through changes in contribution from other sectors caused by non-linear processes, e.g. chemical saturation effects. Considering that the overall objective is to minimise the contribution of air traffic to climate change, this approach is better, since it does not lead to misinterpretations of the results due to compensation effects.

This approach leads to a 4D distribution of trace gasses and contrails for which radiation flux changes and radiative forcing are calculated for the individual species. They are then used to calculate different climate metrics, on the basis of the different climate aspects to be considered. Separate cost functions are calculated for each disturbance: CO_2, NO_x (via O_3 and CH_4), H_2O, and contrails are considered. CCFs are represented by maps in which the colour-coded values represent, for every time region and every species, the climate impact referring to the original emission location. This means that if emissions are released at a time region where CCFs show a high sensitivity, these emissions cause a high global climate impact, whereas emissions released at locations with low CCF values cause low or even negative global climate impact (cooling). An example of CCF is shown in Figure 1, calculated for contrails and relative to the metric F-ATR20, i.e., 20-year mean near-surface temperature change induced by an aircraft flying.

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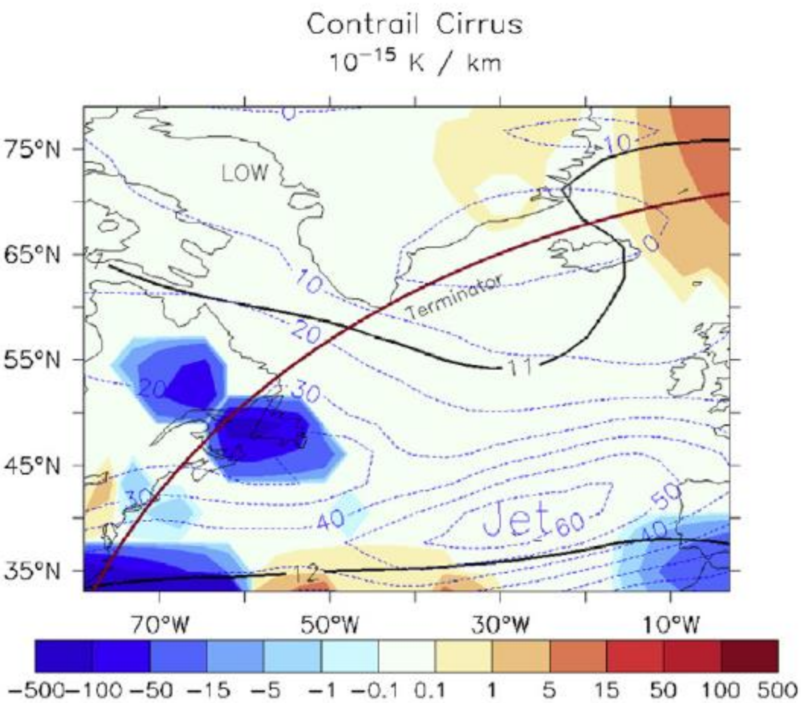

Figure 1. Climate cost functions for the metric F-ATR20 at 200 hPa and 12 UTC, calculated for contrails (Aircraft induced cloudiness) and expressed in [10^{-15}K/km]. The meteorological situation is overlaid. From Grewe et al. (2014) [16].

CCFs are then used by a flight planning tool to obtain aircraft trajectories and respective emissions. The simulation of the flow of air traffic is performed with the System for traffic Assignment and Analysis at a Macroscopic level (SAAM; [14]). From any traffic demand (airport origins and destinations, aircraft types and departure times), a set of full 4-D aircraft trajectories is generated and for each of them the calculation of the emissions is performed by using the advanced emission model (AEM). It has been developed to estimate the mass of fuel burnt, and emissions produced by a specific aircraft-engine configuration for a specific 4-D aircraft trajectory [15]. In this way the emissions along each flight route are calculated and the multiplication of the calculated emissions with the climate cost function leads to the total climate impact of the individual flight routes. Based on these data, an optimal air traffic flow is determined. The best choice of these 4-D aircraft trajectories is made using optimisation with an objective function minimising a mathematical cost that can be based on either economical values or on the climate impact.

The results from REACT4C indicate that a large potential exists to reduce the contribution of air traffic to climate change by rerouting, however a trade-off exists between climate impact reductions and cost increase. Grewe et al. (2014) [16] analysed air traffic re-routing options which avoid climate sensitive regions and focused on a specific one-day case study: a winter day for trans-Atlantic flights. They considered different objectives for the optimization: economic costs, short-term climate impacts (F-ATR20 and P-AGWP20) and long-term climate impacts (P-AGWP100). The results, shown in Figure 2 taken from [16], are separated for

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westbound (blue) and eastbound (red) flights, since the impact of meteorology on routing, largely differs depending on the flight direction, as tail and head winds play a large role. Air traffic routing with the minimum cost is considered as the reference point and the economic costs and climate changes from traffic changes are analysed in relation to it. The economic best flights are in the lower right corner of the plot, whereas flights with the minimum climate impact are in the upper left corner. The climate optimised air traffic leads to a maximum reduction of the climate impact in the range of around 25% and 60% associated with an increase in economic costs around 15%. A clear difference between eastbound and westbound flights is evident, as eastbound routes benefit from the tail winds of the jet stream. Grewe et al. (2014) [16] concluded that the best solution is that with the largest climate reductions at lowest cost increase. For the specific case study they analysed, small changes in flight trajectories already significantly reduce their climate impact: a 25% decrease in the climate impact can be achieved at a 0.5% cost increase.

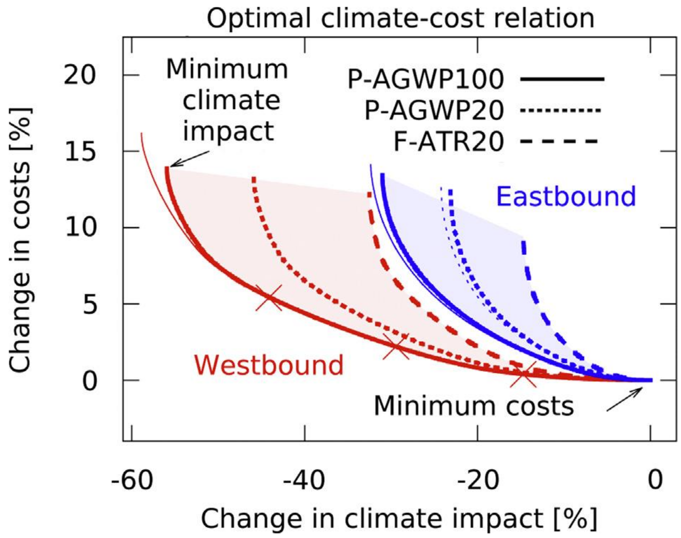

Figure 2. Relation of economic costs changes and climate impact changes for the one-day trans-Atlantic air traffic. From Grewe et al. (2014) [16].

Furthermore, distinct weather-related differences have been found in CCFs, indicating a clear dependence from the actual weather situation. Matthes et al. (2012) [9] showed an illustrative example, reported in Figure 3, of how a unit NO_x emission, emitted from two distinct locations within the same weather pattern, leads to very different temporal evolution of the NO_x concentration change, the contribution to ozone and the induced radiative imbalance. Large differences of O_3 radiative forcing, of one order of magnitude, can be found between these two emission locations A and B. These differences are mainly caused by different prevailing local transport characteristics at the respective emission location. In the case of emission location B, the emitted species are transported to lower altitudes and towards the tropics, whereas in the case of emission location A the emitted species remain at high altitudes and latitudes. This results in different lifetimes of NO_x, different local ozone production efficiency, and different specific radiative impact. This example demonstrates the importance of the emission location and of the meteorological conditions during emission.

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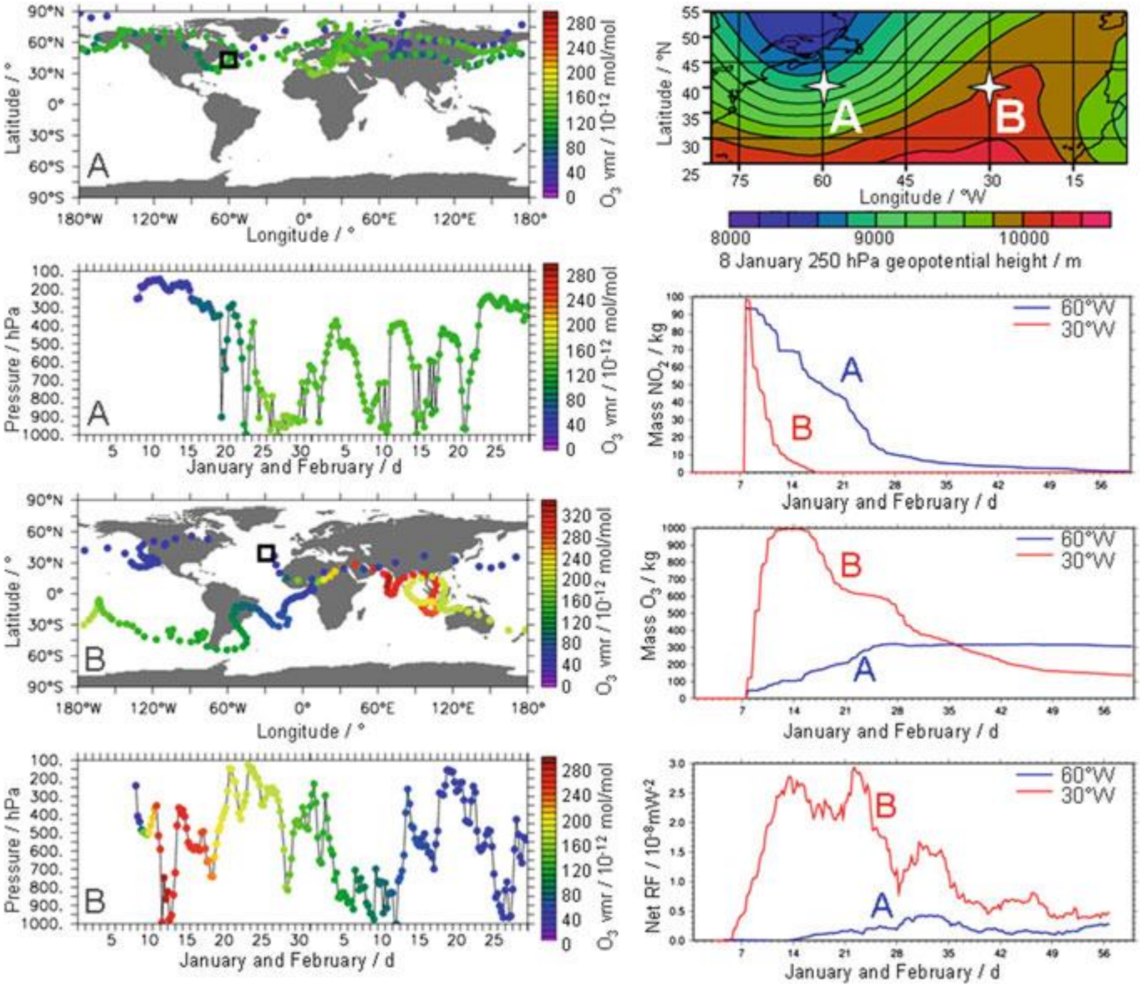

Figure 3. Temporal development of perturbations following aviation NO_x emissions at two different emission locations A and B (stars) for a particular weather pattern over the North Atlantic as indicated by the geopotential height (upper right). The trajectory pathways and altitudes for both emission locations A and B are shown on the left, where the color indicates the ozone mixing ratio. The time series of the NO_x perturbation, ozone perturbation and induced net O3 radiative forcing (10^{-8} mW/m^2) for the two emission locations are shown on the right. From Matthes et al. (2012) [9].

A summary for all weather simulations is given in Grewe et al. (2017) [17], where a climate-optimized routing strategy is simulated for all trans-Atlantic flights on different winter and summer days representative of typical weather patterns over North Atlantic. For all days considered, they found multiple feasible combinations of flight routes with smaller climate impact than the scenario which minimizes economic cost. Grewe et al. (2017) [17] also presented a research roadmap for climate-optimized routing, illustrating the steps to overcome the challenges of implementing operationally such a system. Figure 4 reports the roadmap they formulated considering several aspects such as atmospheric science, ATM-science, economical science and pilot project.

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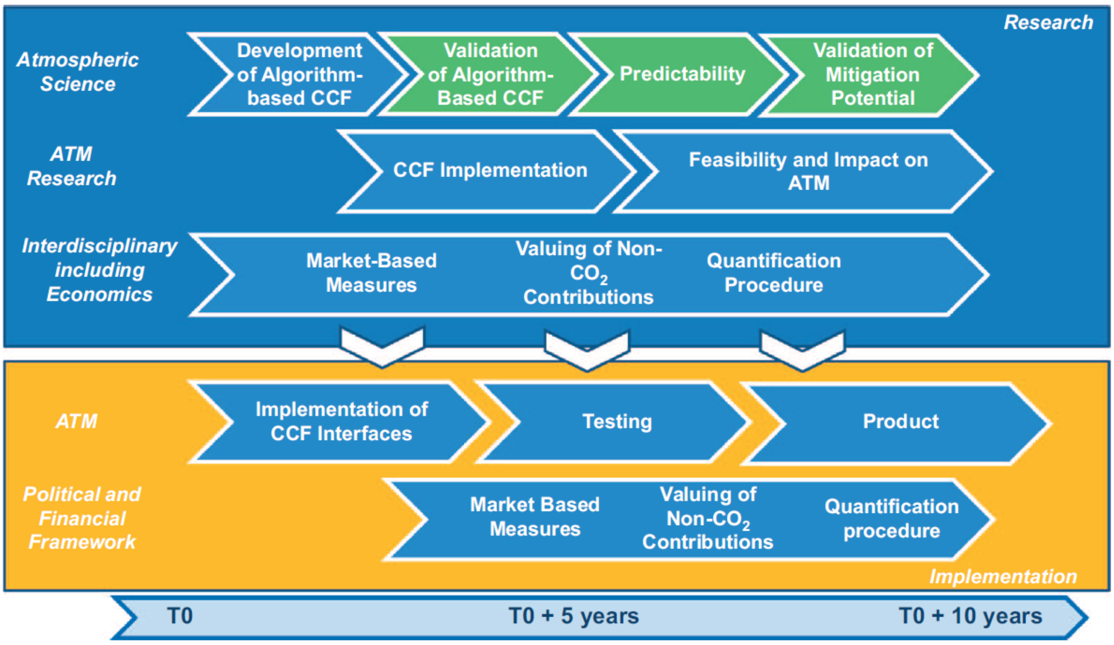

Figure 4. Road map for implementing climate-optimized routing. Research and implementation activities are indicated in the blue and orange box, respectively. Validation activities are marked in green. From Grewe et al. (2017) [17].

Frömming et al. (2021) [18] extended previous studies and presented the entire ensemble of REACT4C CCFs for eight representative weather situations in the North Atlantic region for winter and summer. The main objective was to derive systematic relationships between the emission location, the prevailing weather situation during emission, and the resulting aviation climate impact. They found an enhanced significance of the position of emission release in relation to high-pressure systems, to the jet stream, to the altitude of the tropopause, and to time of day and polar night. Specifically, their main findings are summarized in the following.

- Regarding chemical effects of aviation NO_x emissions, the emission region and transport pathways of emissions within the first week(s) after emission is relevant.
- The climate impact of H_2O emissions is largely controlled by the distance to the tropopause, with emissions released close to the tropopause or even in the lowermost stratosphere, causing the strongest climate impact.
- The main factor for contrail cirrus climate impact is the diurnal variation of insolation in combination with the lifetime of contrails and it has the potential to change the sign of contrail climate impact (warming or cooling). More detailed and smaller scale structures of contrail formation areas cannot be resolved with the present model resolution. A higher spatial and temporal resolution of time regions and of the underlying atmospheric conditions would be favourable for future studies on contrail CCFs.

Common features of the non-CO_2 CCFs, found in [18], facilitate the development of more generalized algorithmic climate cost functions (aCCFs). Predicting the sign and magnitude of individual CCFs for the actual weather situation is necessary if they are intended to be used for climate-optimal flight planning. However, due to excessive use of computing time, it is not

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possible to calculate CCFs in detail for any actual situation. Therefore, a procedure would be necessary to bypass detailed simulations and obtain more generic climate change functions, so-called algorithmic climate change functions (aCCFs), developed in the *ATM4E project* [19]. The first aCCFs are described in van Manen and Grewe (2019) [20] and Yin et al. (2023) [21]. These algorithms facilitate the prediction of CCFs by means of instantaneous meteorological data from weather forecasts without the necessity of computationally extensive recalculation of CCFs by means of chemistry–climate model simulations. A number of assumptions and simplifications were necessary for such an approach. These aCCFs would facilitate weather-related climate-optimized planning of flight trajectories for any weather situation.

2.2 ATM4E & FlyATM4E

The European project ATM4E (SESAR2020, Exploratory Research - https://www.atm4e.eu/) was coordinated by DLR (Sigrun Matthes, Germany). It was carried out from May 2016 to April 2018, with the participation of 6 partners. The project investigated a concept for the environmental evaluation of air traffic operations, with the main aim of optimizing the ATM in the European air space, considering impacts on climate, air quality and noise, following up on initial ideas developed in REACT4C. Beyond a feasibility study to optimize single aircraft trajectories in realistic weather conditions, different air traffic scenarios were analysed, to understand the impact of environmentally optimized flights on changes in air traffic flows, creating challenges for ATM. The main aim of the project was split into four objectives:

1) To define a multidimensional function (Environmental Change Function, ECF) that includes effects on climate, air quality and noise. Previous studies highlighted that trajectory modification, in order to avoid specific regions, could contribute to the reduction of climate impact on aviation. A first attempt of trajectory optimization considering the climate impact was conducted in the frame of the project REACT4C (Sec. 3.1), which allowed the development of trajectories aimed to minimize both the costs and the climate impact. This process was performed by using suitable CCFs. In ATM4E a step forward was done, combining the cost optimization and climate impact with an environmental optimization near the airports, including noise and air quality. To this aim, ECFs were introduced as functions of space and time, to be used for the quantification of the whole environmental impact, establishing a relationship between pollutant emissions and ATM. An ECF informs whether the environmental impact of an emission in this region is strong or weak.

2) To plan flight trajectories aimed to mitigate the environmental impact, under different meteorological situations. This second objective was to plan flight trajectories able to mitigate the environmental impact considering characteristic meteorological situations, based on different air traffic management assumptions and optimization strategies and to investigate to what extent the resulting changes in traffic flows lead to particular challenges for ATM when such optimization is performed. A multi-phase concept for the integration of climate, Local Air Quality (LAQ) and noise was designed and implemented, considering three consecutive flight phases (take-off, cruise, and landing). Finally, the optimization campaign has been initiated and, for the first time, the entire traffic of a characteristic winter day has been environmentally optimized in four dimensions with different ATM and optimization strategies. It was the first time that algorithmic CCFs (aCCFs) have been explored in such a wide-ranging optimization.

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Specifically, such aCCF are derived from CCFs, by identifying a parametric relationship between meteorological key variables and estimated climate effects. This relationship is used in order to provide a quantitative estimate of the individual non- CO_2 effects (contrail cirrus, NO_x -induced effects on ozone and methane, water vapour) and the meteorology at time and location of emission. Relying on this aCCF concept, indicated a mitigation potential of more than 20% climate impact for a 1 % fuel penalty for the case study performed.

3) To evaluate environmentally-optimized routes in a future atmosphere in a comprehensive climate-chemistry modelling allowing a proof of concept of climate-optimization with daily route analysis. This third objective was the evaluation of the algorithmic ECFs and the potential to reduce environmental impacts by using ECFs. In other words, it was explored to what extent climate optimized trajectories (identified using the ECF concept) resulted in an overall climate impact mitigation. A one-year simulation of air traffic, with associated emissions and chemical and radiative impact, has been performed. It was shown that using ECFs for identifying climate optimal routes, leads to a reduction of overall climate impact of aviation missions.

4) To develop a roadmap including recommendations and an implementation strategy for the environmental optimization of aircraft trajectories in close collaboration with aviation stakeholders. A roadmap was developed with recommendations and an implementation strategy for the environmental optimization of aircraft trajectories in close collaboration with aviation stakeholders. This roadmap presents the steps required for the definition of a climate-optimized routing in Europe. It became clear that benefits for the environment need to be represented in performance indicators to demonstrate these benefits in a quantitative way, in order to create an incentive for environmentally optimized trajectories. Second, next steps need to investigate robustness of identified routing options, and quantifying the associated uncertainties, and translate this to a concept for measuring and providing this information.

The feasibility of climate-optimized aircraft trajectories and the associated workflow was further explored in the European project FlyATM4E (SESAR2020, Exploratory Research) coordinated by DLR (Sigrun Matthes, Germany). The overall objective of the project FlyATM4E was to develop a concept to identify climate-optimised aircraft trajectories in which Air Traffic Management (ATM) can help to provide a robust and eco-efficient reduction in aviation’s climate impact and estimate mitigation potential considering CO_2 and non-CO_2 emissions. A systematic analysis of the spatially and temporally resolved climate impact of aviation’s emissions was performed by using algorithmic climate change functions for a set of non-CO_2 impacts with a particular focus on identifying sources of uncertainties. Flight trajectory optimization and planning tools were used to explore possibilities in including uncertainties when performing climate-optimized trajectories. The project results highlight that the mitigation potential of flight trajectory optimization shows a large spatial and temporal variability due to the variability of the underlying atmospheric conditions.

FlyATM4E contributed to solutions targeting on identifying climate optimized trajectories which provide alternative aircraft trajectories which have a lower climate effect by avoiding those regions of the atmosphere where aviation emissions have a large climate effect, e.g. by forming warming contrails. The project was working towards two solutions. Sol-FlyATM4E-01 is an enabler solution which uses temperature, relative humidity, outgoing longwave radiation and geopotential in order to calculate climate effects of aviation emissions at a given location and time. The solution Sol-FlyATM4E-02 describes the necessary extension of aircraft

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trajectory planning processes to implement a well-informed and robust multi-objective flight planning with the goal to consider the total climate impact (CO_2 and non-CO_2 effects). The algorithmic climate change functions as defined per Sol-FlyATM4E-01 serve as an enabler for this solution.

Yin et al. (2023) [21] developed aCCF 1.0 as part of the chemistry-climate model EMAC to evaluate aviation emissions' climate impacts across the Northern Hemisphere. The model estimates 20-year average temperature responses (ATR20) for emissions like CO_2, NO_x, H_2O, and contrail cirrus. Then, in order to demonstrate the usage of the aCCF 1.0 in aircraft trajectory optimization considering non- CO_2climate effects, the O3 aCCF was used to calculate the Radiative Forcing due to aviation NO_x -induced O3 by combining aCCF with the air traffic simulation submodel AirTraf. It was found that climate-optimized trajectories could reduce the total ATR20 of about 50%, with the largest contribution from reduction in contrail cirrus (89% decrease). On the other side, compared to cost-optimized trajectories, climate-optimized routes increased fuel consumption and NO_x emissions, but achieved substantial reductions in radiative forcing from non-CO_2 effects (Figure 5).

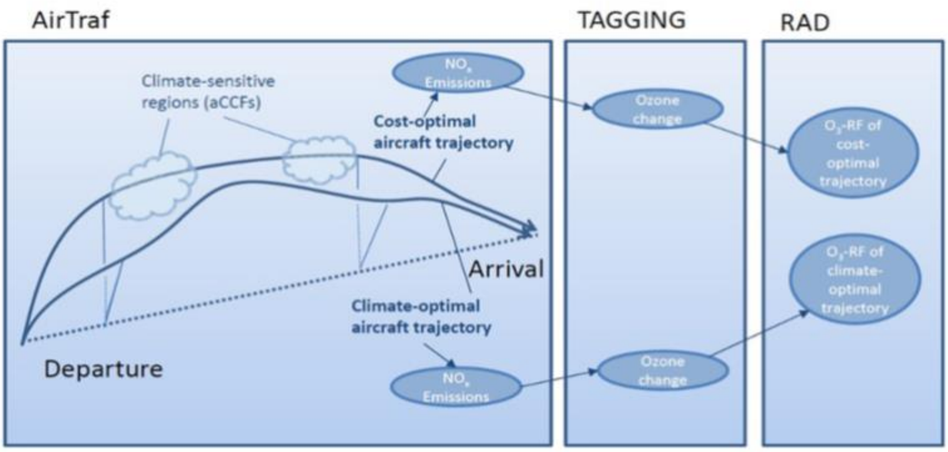

Figure 5. Test strategy for verifying the O3- NO_x aCCFs: Radiative forcing calculations for ozone changes caused by online air traffic NO_x emissions for cost- and climate optimized flight trajectories. From Yin et al. (2023) [21]. In the companion paper by Dietmuller et al. [22], a Python library for computing individual and merged non- CO_2 algorithmic climate change functions (CLIMaCCF V1.0) was presented.

These SESAR candidate solutions for climate-optimized aircraft trajectories have been further explored since, e.g. in SESAR industrial research projects, like the VLD project ALBATROSS (coordinated by Airbus). Furthermore, a series of follow-up research projects are currently exploring the topic of climate-optimized trajectories, represented by the consideration of ECHO areas, e.g. in two SESAR industrial research projects: CICONIA (coordinated by Airbus, France) and CONCERTO (coordinated by Thales, France), and a SESAR exploratory research project F4EClim (coordinated by DLR, Sigrun Matthes, Germany), starting in September 2024.

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2.3 GLOWOPT

GLOWOPT (Global-Warming-Optimized Aircraft Design - http://www.glowopt.eu/) is a project funded by Clean Sky 2 and coordinated by Technische Universität Hamburg (TUHH) from 2019 to 2022. With respect to previous projects (e.g., REACT4C and ATM4E), GLOWOPT is based on a different climate mitigation approach: it aimed at the optimization of aircraft design and not of aircraft operations (e.g., through flight routes). The high-level objective of GLOWOPT was to perform an aircraft design optimization minimizing the climate impact: to this aim, the concept of climate change functions, introduced in REACT4C, was transferred to the optimization of aircraft design.

Usually in aircraft design studies, fuel burn, maximum take-off mass or direct operating cost are used as cost functions. However, more than 50% of the climate impact from aviation is stemming from non- CO_2 effects. Hence it is essential to find a way to include these non- CO_2 effects in the aircraft design optimization process. In the framework of GLOWOPT, Climate Functions for Aircraft Design (CFAD) were developed, which provided a detailed representation of the climate impact associated with emissions generated by variables such as different cruise altitudes, aircraft speed, climb angles and flight trajectory. Subsequently, CFAD were integrated into an existing Multidisciplinary Design Optimisation (MDO) framework to optimise the design of the reference aircraft with minimal climate impact, incorporating input parameters such as fuel consumption and emission indices for various climate factors.

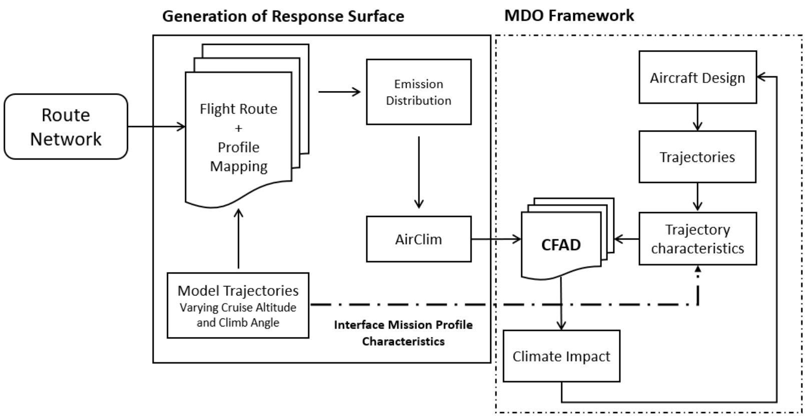

Figure 6. Development methodology of CFAD and integration with MDO framework. From Radhakrishnan et al. (2022) [25].

Figure 6 shows the schematic representation of the CFAD development and integration with the MDO process. For the CFAD development, emission inventories are calculated for various mission profile parameters, e.g., cruise altitude, climb angle, descent angle etc., which determine the location of the emissions released and are influenced by the aircraft design parameters. For the calculation of the CFAD the climate-chemistry response model AirClim ([5], [23]) was used. This model is especially designed to evaluate the climate impact of aviation. Therefore, the contribution of CO_2, NO_x -induced O3, NO_x -induced CH_4 and PMO, H_2O, and contrails is analysed. AirClim combines pre-calculated atmospheric data and an emission inventory to calculate the Radiative Forcing and, based on that, the temperature

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change. The chosen climate metric for the temperature response is the Average Temperature Response with a time horizon of 100 years (ATR100).

GLOWOPT directly addressed the specific issue of minimization of global warming by performing an aircraft design optimization based on CFAD that leads to a design solution with substantially lower climate impact compared to a reference design while considering the operating regime of the relevant market segment. The total ATR100 change is the sum of the contributions due to CO_2, H_2O, and NO_x emissions and the formation of contrails. GLOWOPT showed that the total climate impact could be significantly reduced compared to a reference generic long-range widebody aircraft by flying lower and slower in combination with a lower engine pressure ratio, and by adapting the aircraft design and propulsion to these operating conditions. Low altitude cruise reduces the contrails' impact and reduced engine overall pressure ratio reduces the NO_x impact. On the other hand, the climate impact due to CO_2 increases, because the CO_2 emissions are directly related to the fuel burn.

However, the outcome of flying slower considerably increased the flight time and the direct operating cost of the climate optimized aircraft also increased when operated on the entire network compared to the reference aircraft. Achieving maximum climate mitigation potential is linked with cost increase. Therefore, a careful consideration of the trade-off between crucial performance parameters (cost and time) and climate mitigation is necessary. Proesmans and Vos, (2022) [24] carried out optimizations for three objectives: climate impact, fleetwide fuel mass and operating costs by varying several aircraft design variables. The results, shown in Figure 7, indicate that none of the three objectives leads to the same solution. Although the fuel- and cost-optimized aircraft are rather similar, they appear to be conflicting with the global warming objective. A general recommendation for aircraft design studies is to consider trade-off analysis and multi-objective cost function in conjunction with CFAD [25].

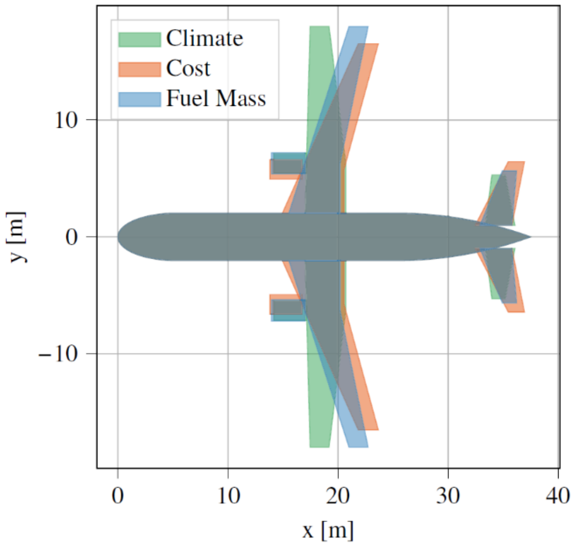

Figure 7. Top-view comparison of aircraft optimized for three different objectives. From Proesmans and Vos, (2022) [24].

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2.4 ACACIA

ACACIA (Advancing the Science for Aviation and Climate - https://www.acacia-project.eu/) is a Horizon 2020 Research and Innovation Action coordinated by the DLR (Sigrun Matthes, Germany) that started in January 2020 and ended in February 2024. ACACIA improved scientific understanding on non-CO_2 effects of aviation and produced scientific results available for the assessments carried out by the Intergovernmental Panel on Climate Change (IPCC) and for scientific papers relevant to the 2022 UNEP/WMO report.

It is well known that the Aviation community aims to reduce the climate impact caused by CO_2 and non-CO_2 emissions. In fact, non- CO_2 emissions may impact climate in the same way as aviation's CO_2. However, the impact of the non- CO_2 effects (e.g. ozone and methane from NO_x emissions, contrails, indirect aerosol effects) currently is associated with much larger uncertainties. In this context, the four objectives of ACACIA for scientifically based and internationally harmonised policies and regulations for a more climate-friendly aviation system were:

1. to improve the scientific understanding of those impacts that have the largest uncertainty, in particular, the indirect effect of aviation soot and aerosol on clouds.
2. to identify needs for international measurement campaigns to constrain numerical models and theories with data and formulate several design options for such campaigns.
3. to put all aviation effects on a common scale that will allow providing an updated climate impact assessment.
4. to provide the knowledge basis and strategic guidance for future implementation of mitigation options, giving robust recommendations for no-regret strategies for achieving reduced climate impact of aviation.

In fact, ACACIA has put together research across different scales from the laboratory experiments to global models, and it proceeded from fundamental physics and chemistry to the provision of recommendations for policy, regulatory bodies, and other stakeholders in the aviation business.

Moreover, ACACIA provided a significant contribution to the literature available for writing the reports in the 7th cycle of the IPCC. Skowron et al. [26] highlighted the importance of background concentrations when estimating aviation climate impact of NO_x. They investigated how further efforts leading to greater fuel efficiency (and therefore lower CO_2 emissions) may be preferable to reducing NO_x emissions in terms of aviation’s climate impacts. In [27], the results from a multi-model sensitivity study were presented. In particular, it was shown that flying at lower altitudes leads to a reduction of radiative forcing of non- CO_2 effects along with slightly increased CO_2 emissions and impacts, when cruise speed is not modified.

Furthermore, ACACIA outlined the first steps to extend the current Lagrangian modelling scheme ([28],[29]) that was already successfully applied to the study of gas-phase emissions, by developing a tagging approach for aerosols. Aviation’s contribution to anthropogenic global warming is estimated in the range 3.5 – 5%, without considering the contribution from aerosol interactions with liquid clouds (indirect effects), given their high degree of uncertainty, but of course a more accurate and complete assessment is only possible if aerosol effects are considered. Once that the Lagrangian aerosol scheme is verified and ready, climate change

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functions that contemplate aerosol-cloud interactions may be produced for the first time. Such an advancement would improve climate-friendly aircraft routing by providing a more complete and therefore accurate mitigation policy.

2.5 CLIMOP

The project ClimOP (Climate assessment of innovative mitigation strategies towards operational improvements in aviation - https://www.climop-h2020.eu/) was aimed to analyse those aspects of aviation operations that can be implemented to reduce the climate impact of the aeronautic industry, taking non- CO_2 effects into account. The project started in December 2020 and ended in June 2023. ClimOp Consortium was coordinated by Deep Blue and included representatives from the aviation industry (IATA, SEA), academic and research institutes (NLR, DLR, TU-Delft, ITU) and SMEs (DBL, AMIGO). Harmonised mitigation strategies to foster the implementation of operational improvements were proposed. To this end, the ClimOp consortium built on its knowledge and expertise covering the whole spectrum from aviation operations research to atmospheric science and consulting to airline and airport operations.

The main objectives of ClimOP were the following:

1. To determine alternative innovative Operational Improvements (OI) to reduce climate impact taking CO_2 and non- CO_2 effects into account.
2. To quantify the climate impact of the alternative sets of OI.
3. To evaluate the stakeholder impact of these alternative sets of OI.
4. To develop a series of harmonized mitigation strategies for each alternative set of OI.
5. To provide recommendations for target stakeholders on supporting measures to implement the alternative sets of OI.

The strategy adopted can be summarized through the following steps:

1. Identification of stakeholders that are potentially involved in the implementation of OI in the aviation industry (e.g. airlines, airports) and related needs.
2. Definition of a list of impact indicators and of a methodology that can be adopted to quantify the impact of the OI sets on climate.
3. Definition of a list of the OI considered, definition of a realistic time horizon on which these improvements can be implemented in daily aviation operations.
4. Quantification of the climate and economic impact on the aviation stakeholders of the alternative sets of OI, by adopting appropriate modelling tools.
5. Development of harmonized mitigation strategies for the alternative sets of OI and definition of the methodology to validate such strategies.
6. Identification of influencing target stakeholders (from aviation and from the political and economic framework) and definition of recommendations for them, in terms of policy actions and supporting measures.

The selected operational improvements (OIs) are expected to bring long and medium-term benefits, since they require no technological innovations or new regulations. For example, single-engine taxiing, E-taxi, hybrid taxi or converting the entire land fleet to electric. These mitigation actions cover ground operations, but most of the selected Operational

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Improvements are aimed at reducing emissions during Terminal Manoeuvring Area, Network and in-flight operations.

2.6 BECOM

The EU-funded BeCoM project (Better Contrail Mitigation - https://becom-project.eu/) aims to better understand how contrails affect the climate. Contrails are white streaks left behind by planes flying overhead, which give a relevant contribution to the climate impact from aviation. The project started in June 2022 and is currently in progress (it will end in May 2026) under the coordination of the Technische Universiteit Delft. The project aims to provide a contribution to the mitigation of the climate impact of non- CO_2 aviation emissions and to the prediction of the precise location and time of contrail formation. Observations and measurements, as well as modeling and predictions through advanced numerical methods and Artificial Intelligence, are some of the multi-level approaches to deal with contrails. Recommendations for strategies to tackle the climate impact caused by aviation are also drawn up. Aviation contributes to about 5% of the total anthropogenic climate change when including non- CO_2 effects, e.g. contrail formation and the impact of NO_x emissions on ozone and methane. Among various non- CO_2 effects, the contrail-cirrus radiative forcing is the most effective (~2/3) even if affected by large uncertainties. The most critical affecting factor is the large weather-induced variability of the radiative impact of individual contrails, so this is the quantity that BeCoM will predict better since the knowledge of the individual radiative forcing is the basis for avoidance of just those contrails that contribute most to the overall climate impact. Once this is standard, it will be possible to formulate adequate mitigation measures and develop policy-driven implementation schemes. BeCoM will address the uncertainties related to the forecasting of persistent contrails and their weather-dependent individual radiative effects. BeCoM focuses on: 1) obtaining a larger and higher resolution database of relative humidity and ice supersaturation at cruise levels for assimilation into numerical weather prediction (NWP) models; 2) providing more adequate representation of ice clouds in their supersaturated environment in the NWP models; and 3) validation of the predictions to determine and reduce the remaining uncertainties of contrail forecasts. To facilitate the assimilation and validation process, BeCoM will develop a novel hybrid artificial intelligence algorithm. Based on the contrail prediction, BeCoM will develop a policy framework for effective contrail avoidance through a trajectory optimization approach. BeCoM will enable a better understanding of contrail's climate impact and formulate recommendations on how to implement strategies to enable air traffic management to reduce aviation's climate impact. The BeCoM consortium builds on its knowledge and expertise covering a wide spectrum from atmospheric science and climate research to aviation operations research and policy developments will also be drawn up.

The improved persistent contrail skills in BeCoM will be implemented in the Earth-System model EMAC/Contrail, which is further coupled with the air traffic simulator (EMAC/AirTraf) to optimize flight trajectory over a long period of, e.g., one year, concerning the contrail avoidance, the consequent climate impact, and the cost. The challenge is correctly implementing the new contrail prediction approach into the existing contrail model, which will be resolved via close communications and collaborations between WP2 and WP4. In addition, they apply the non- CO_2 -based measures from WP5 to the EMAC/AirTraf to perform a similar

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procedure as the above. Accordingly, they evaluate the changes in climate impact reductions between a free-run (i.e., no regulatory measures) and regulated trajectory optimization.

For accounting for non- CO_2 effects, an algorithmic concept characterizing weather-dependent climate charges of aircraft emissions at a given location and time (algorithmic 4-D cost functions for climate change) is developed. This includes the elaboration of (1) a monetarization logic that quantifies the amount of emission certificates to be surrendered or respectively the level of emission charge/tax to be paid per climate impact of CO_2, H_2O, NO_x, and contrail-cirrus, as well as (2) a workflow for accounting existing non- CO_2 uncertainties. To achieve robust climate-sensitive flight planning, parametric analysis of algorithmic cost functions for climate change is conducted.

2.7 Synthetic overview of the methodologies

A synthesis of the methodologies adopted in the projects discussed in the previous sections, along with the main results achieved, is presented in Table 1.

Table 1. Methodologies and main results achieved in the frame of the projects analyzed.

Projects	Aim	Main results
REACT4C	Definition of a concept to identify alternative routes characterized by a minimal climate impact. Modelling concept based on the calculation of climate cost functions (CCFs), which are a measure for the climate impact of a local emission.	A large potential exists to reduce the contribution of air traffic to climate change by rerouting. A trade-off exists between climate impact reductions and cost increase. A clear dependence from the actual weather situation was found.
ATM4E / FlyATM4E	Optimization of the ATM in the European air space, considering impacts on climate, air quality and noise. Environment Change Functions (ECFs) were introduced as function of space and time, to be used for the quantification of the whole environmental impact, establishing a relationship between pollutant emissions and F-ATR (Average temperature response).	A roadmap was developed with recommendations and an implementation strategy for the environmental optimization of aircraft trajectories in close collaboration with aviation stakeholders. Benefits for the environment need to be represented in performance indicators to demonstrate the effectiveness in a quantitative way.
GLOWOPT	Optimization of aircraft design and not of aircraft operations.	GLOWOPT showed that the total climate impact could be significantly reduced (compared to

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	The concept of CCF (introduced in REACT4C) is transferred to the optimization of aircraft design: Climate Functions for Aircraft Design (CFAD). CFAD were integrated into an existing Multidisciplinary Design Optimization (MDO) framework to optimize the design of the reference aircraft with minimal climate impact.	a reference generic long-range widebody aircraft) by flying lower and slower in combination with a lower engine pressure ratio, and by adapting the aircraft design and propulsion to these operating conditions. A future recommendation for aircraft design studies is to consider trade-off analysis and multi-objective cost function in conjunction with CFAD.
ACACIA	To improve the scientific understanding of those impacts that have the largest uncertainty (i.e. non- CO_2), by combining atmospheric observations, with state-of-the art atmospheric modelling, comprising lab-studies, evaluating multi-model simulation experiments, and quantifying remaining uncertainties. To provide a significant contribution to the literature available for writing the IPCC reports.	Novel concepts have been defined on how to deal with uncertainties, in order to provide confidence intervals. Importance of background concentrations when estimating aviation climate impact of NO_x. An effort leading to greater fuel efficiency (lower CO_2 emissions) may be preferable to reducing NO_x emissions. Flying at lower altitudes leads to a reduction of radiative forcing of non-CO_2 effects.
CLIMOP	To define operational improvement (OI) aimed to reduce the climate impact of the aeronautic industry, taking non- CO_2 effects into account. Definition of a list of impact indicators and of a methodology that can be adopted to quantify the impact of the OI sets on climate. Definition of a list of the OI considered, definition of a realistic time horizon on which these improvements can be implemented.	Quantification of the climate and economic impact on the aviation stakeholders of the alternative sets of OI, by adopting appropriate modelling tools. Recommendations for target stakeholders.

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BECOM	To better understand how contrails affect the climate. To provide a contribution to the mitigation of the climate impact of non- CO_2 emissions and to the prediction of the precise location and time of contrail formation. Quantification of the large weather-induced variability of the radiative impact of individual contrails. Observations, advanced numerical methods and Artificial Intelligence.	The improved contrail skills in BeCoM are implemented in the Earth-System model EMAC/Contrail, which is further coupled with the air traffic simulator (EMAC/AirTraf) Work In progress.

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3. Short description of other projects

This section contains a short description of other projects related to the climate impact of aviation, including both national (funded by single Government) and international actions. Some projects are still ongoing (e.g. E-CONTRAIL, CICONIA), for this reason final conclusions are not yet available.

HyPERION - *Hydrogen for environmentally responsible aviation propulsion* (https://www.airbus.com/en/newsroom/press-releases/2023-06-successful-hyperion-pilot-project-paves-the-way-for-civil-aviation)

In December 2020, Safran, Airbus, and Ariane Group came together in a joint research project called HyPERION, with the support of the French Government's Investments for the Future Program (PIA). The goal of HyPERION (the project's name is the French acronym for hydrogen for environmentally responsible aviation propulsion) was to explore safe and efficient technical hydrogen propulsion solutions which could offer an alternative to fossil fuel for commercial aviation by 2035.

CIRRUS-H2

In partnership with Airbus, Safran and Dassault, ONERA is managing the CIRRUS H2 project also financed by the DGAC (2021- 2023). The purpose of the project is to analyse the formation and properties of condensation trails generated by the combustion of hydrogen. The project also aims to explore experimental approaches for in-situ data acquisition used to validate numerical studies.

CIRRUS-HL - *Research campaign on ice clouds in high latitudes* (https://cirrus-hl.de/)

The CIRRUS-HL campaign is a joint atmospheric research project by German research centres and universities. The experiment deploys the research aircraft HALO together with satellites and models to gain new insights into nucleation, properties, and climate impact of ice clouds in high latitudes, hence in a region of the world with strongest anthropogenic increase in surface temperatures. Aviation effects on clouds and contrail impact on climate will be studied in flight above Central Europe and the North Atlantic flight corridor.

ClimAviation (https://climaviation.fr/en/)

ClimAviation, a fusion of the words Climate and Aviation, is an ambitious research action to understand and quantify the climate impacts of aviation. ClimAviation is funded over the period 2021-2026 by the French Civil Aviation Authority (DGAC) as part of the French National Recovery and Resilience Plan and NextGenerationEU. This scientific research project brings together some thirty researchers from the Institute Pierre-Simon Laplace (IPSL) – represented in particular by its stakeholders Sorbonne University and the French National Centre for Scientific Research (CNRS) – and from the French Aerospace Lab (ONERA).

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CATS - *Climate-compatible Air Transport System*

Within the project "Climate compatible Air Transport System" (CATS, 2008–2012) DLR developed a comprehensive simulation and assessment approach with the goal to identify the operational and technological potential measures to reduce the climate impact of the actual and future air traffic. In previous literature studies, it was shown the potential to reduce the climate impact of air traffic through global operations of a representative twin engine long-range aircraft at lower cruise altitudes and speeds. As part of the CATS project, the increase in mitigation potential given by the combination of aircraft design and operational changes was analysed. Based on the analysis of operational changes, the reference aircraft is optimized for cruising conditions with reduced climate impact. Both aircraft, the reference and the redesigned configuration, are assessed on a global route network with varying cruise conditions relative to typical current flight profiles. Optimal cruising conditions are derived from the Pareto diagram for each route and for the global network. The resulting fleet's mitigation potential allows for a cost-benefit analysis, trading off reduced climate impact for increased cash operating costs.

AEROPLANE - Advancing mEasures to Reduce aviatiOn imPact on cLimate and enhAnce resilieNce to climate-changE

AEROPLANE is an exploratory research project coordinated by Deep Blue and funded by the European Commission within the Horizon Europe Programme. It is started in 2023 and will end in 2026, with the participation of four partners. The project objective is to develop innovative solutions for aviation industry, responding to the pressing need to reduce the impact of aviation on climate and, at the same time, to enhance its resilience to ongoing changes. Therefore, the project has a mission to create an innovative integrated toolkit for aviation, focusing on:

1) Quantifying and reducing aviation's climate impact addressing both CO_2 and non- CO_2 effects. This service aims to measure the impact of flight trajectories and help users, like airlines and air traffic controllers, to consider alternative, less impactful routes.
2) Enhancing resilience to extreme weather. This service focuses on how extreme temperatures can affect take-off performance and noise pollution.

CICONIA - Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment

The SESAR JU CICONIA (Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment) project is ongoing and is a project that starts on 01/07/2023 and ends on 30/06/2026, it is part of the aviation research and innovation framework and aims to assess and reduce the climate effects of air operations through new operational concepts. SESAR (Single European Sky ATM Research) is an initiative that aims to modernise the air traffic management system in Europe, improving efficiency and reducing the environmental impact of aeronautical activities. CICONIA focuses on analysing the needs and impacts of innovations that can contribute to a reduction in CO_2 emissions and other pollutants from air transport. This may include the development of new technologies, the reorganisation of flight routes, the optimisation of operations and the integration of climate-related factors in the decision-making process.

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The SESAR JU CICONIA project develops a methodology based on innovative operational concepts to reduce the climate impact of aviation, considering not only CO_2 emissions but also atmospheric effects. This innovative approach uses operational concepts that consider weather forecasts and operational choices to optimize flight paths and minimize emissions. The project's strengths include the use of real-time weather data and the improvement of flight paths to minimize climate impacts. However, its weaknesses concern the complexity of its large-scale implementation and the technological limitations in adapting existing systems.

The project involves a variety of stakeholders, including government bodies, flight operators, aircraft manufacturers and researchers, with the aim of promoting more sustainable practices in the aviation sector.

Therefore, the SESAR JU CICONIA project is an initiative aimed at developing and evaluating new operational concepts in the aviation sector, with the primary objective of reducing the environmental impact and climate change associated with air operations.

E-CONTRAIL - Artificial Neural Networks for the Prediction of Contrails and Aviation Induced Cloudiness

E-CONTRAIL is a research project coordinated by UNIVERSIDAD CARLOS III DE MADRID and funded by the European Commission within the Horizon Europe Programme. It is started in 2023 and will end in November 2025, with the participation of three partners. The project's objective is to conduct a detailed investigation into contrails and aviation-induced cloudiness, utilizing state-of-the-art satellite imagery to examine their potential impact on the environment. Furthermore, the project aims to quantify the radiative forcing of ice clouds and to use deep learning architectures to generate AI models capable of predicting the radiative forcing of contrails based on data-archive numerical weather forecasts and historical traffic. The final goal is to provide aviation stakeholders with an early and accurate prediction of those volumes of airspace with the conditions for large climate impact due to contrails and aviation-induced cloudiness.

CONCERTO - dynamicC cOllaboration to geNeralize eCo-friEndly tRajecTOries

CONCERTO is a research project coordinated by THALES LAS FRANCE SAS and funded by the European Commission within the Horizon Europe Programme. It is started in 2023 and will end in 2026, with the participation of 21 partners. The project aims to develop innovative processes and tools that reduce CO_2 emissions and manage non- CO_2 climate impacts, integrating with existing systems. The overall goal is for the aviation industry to embrace a climate-conscious future, adopting more eco-friendly trajectories and thus achieving higher climate impact reduction without requiring major changes on legacy ATM and airlines systems.

REFMAP - Reducing Environmental Footprint through transformative Multi-scale Aviation Planning

REFMAP is a research project coordinated by KUNGLIGA TEKNISKA HOEGSKOLAN and funded by the European Commission within the Horizon Europe Programme. It is started in 2023 and will end in 2026, with the participation of 10 partners. The project's aim is to measure the environmental impact of air mobility for airliners and unmanned aircraft systems across

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multiple scales, by optimizing individual trajectories and the flow traffic of multiple vehicles to minimize their impact on a wide range of communities. REFMAP will examine the impact that environmental data availability for every type and route of air vehicle will have on aviation business models. This will be achieved via the development of an analytics platform processing environmental and weather data such as wind, noise, CO_2 and non- CO_2 emissions. This platform will rely on a number of technical solutions, including numerical simulation, predictive models, and deep-learning methods.

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4. ANALYSIS OF RELEVANT LITERATURE WORKS

Apart from international projects, considerable work in the field of climate impact of aviation has been carried out by several research groups in the world. For this reason, an analysis of relevant literature works has been performed, to have a comprehensive overview of the state of art on this topic.

4.1 Assessing the impact of aviation on climate (Marais et al., 2008)

In the work by Marais et al. (2008) [30], the authors presented a flexible, simplified, probabilistic framework to estimate the marginal climate impacts of new aviation activities. First, the current and future emissions inventories both for aviation and for all anthropogenic sources were estimated. Then the potential change in globally averaged surface temperature was determined using impulse response functions derived from carbon-cycle and coupled atmosphere and ocean general circulation models (GCMs). Next, several different indicators are calculated, i.e., change in global average surface temperature, percentage impact on gross domestic product (GDP), and net present value of future impacts of climate change.

The CO_2 impact on the climate system was modeled using linearized impulse response functions, derived from carbon-cycle and GCMs, considering that this impact is nonlinear, since additional units of CO_2 cause less radiative forcing (RF). In particular, a logarithmic relationship between RF and CO_2 concentration can be assumed:

$$RF(t) = \log_2 \frac{X_{present} - X(t)}{X_{1750}}$$

In which X is the atmospheric concentration of CO_2, which is assumed equal to 278 ppm in 1750. Then, the average temperature change is calculated as follows:

$$\Delta T(t) = \int_{t_0}^{t} RF(t) \times G_T dt$$

where G_T is the carbon cycle impulse response function, which can be defined in several ways, but in the present work has been designed in a simple way, by using a simple energy balance model that relates climate sensitivity to the temperature response.

For the short-lived effects (lifetimes less than one year including effects of NO_x on ozone, contrails and aviation induced cirrus, water, sulfates and soot) the radiative forcing was assumed only active in the year of the emissions in order to determine the temperature change associated with each effect as for CO_2.

Then, a method to assess the economic impact of changes in surface temperature has been proposed, based on two different damage function formulations. The first one assumes that damage (expressed in %GDP) is proportional to temperature change, while the second one uses a second order expression:

$$D(t) = a_1 \Delta T_{1900}(t) + a_2 \Delta T_{1900}(t)^2$$

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The simplicity of this method allows us to explicitly describe the influence of uncertainties in modeling aviation emissions effects on the expected marginal future costs of aviation impacts.

4.2 Analysing the opportunities and challenges for mitigating the climate impact of aviation: A narrative review (Lai et al., 2021)

Lai et al. 2021 [31] analysed the opportunities and challenges of mitigation measures adopted to reduce the climate impact of aviation and focuses on Sweden. The authors adopted a comprehensive and multidisciplinary approach, considering the aviation industry as a socio-technical system. They considered literature beyond the traditional fields of science, engineering and economics, including research from humanities and social sciences and offering new perspectives that are relevant for the transitions needed at multiple levels to reduce aviation's climate impact.

They identified three factors for limiting the climate impact of air travel, described in the following.

1) **Travel volume**, i.e., passenger kilometres travelled per inhabitant per year.
   The reduction of travel volume, i.e., the reduction of the number of people travelling, is an indirect attempt to reduce aviation's environmental impact by reducing travel demand. One common rule aimed at minimising travel volume is aviation ticket taxes; in Europe, several countries have implemented this tax, but to date there is limited evidence that this mitigation measure translates to decreased aviation emissions. Moreover, aviation ticket taxes have also been criticised for failing to encourage innovation within the industry itself.
   Another important aspect in the reduction of the need for travel is the possibility for people to perform activities virtually instead of physically, a sort of "virtual mobility" possible thanks to improvements to information and communications technologies (ICT); the COVID-19 pandemic has highlighted the value of ICT. However, ICT is less likely to reduce personal travel, whose demand has continued to rise.
   Finally, it is worth considering the psychological and socio-cultural dynamics of general climate change discourse. In this framework, Sweden is the birthplace of the so-called "flight shame" movement: 14% of Swedes have said they stopped flying because of the climate and the knowledge of the climate impact of aviation plays the biggest role for individuals choosing to stop flying.

2) **Energy intensity**, i.e., energy unit per passenger kilometre.
   Another way to reduce the climate impact of aviation is to limit the energy intensity required by aircraft, i.e., to improve aviation's fuel efficiency. ICAO have instigated a vast range of options to improve energy intensity through airline operations modification, fleet modernization, new aircraft introduction, and payload capacity expansion. However, the high price associated to these improvement options may not be financially sustainable or technically feasible for airlines with limited budgets. On the contrary, airlines with stronger financial capabilities have more opportunities to renew their aircraft fleet, which is the most efficient way to improve energy intensity.
   Another initiative of the Swedish government was to propose differentiated take-off and landing fees, i.e., individual flights performed by different aircraft types are charged

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at a different rate based on their climate impact and fuel mix. Less energy efficient aircraft would be subject to higher take-off and landing fees, indirectly serving as an incentive for airline to renew their fleet with higher energy efficiency aircraft.

3) **Emission intensity**, i.e., the emissions per unit of energy used.
Several international initiatives are devoted to the reduction of aviation emission intensity, defined as emission per unit energy consumed during aircraft operation.
The two most famous international projects that aim to limit the increase in greenhouse gas emissions are the EU Emissions Trading System (ETS) and the ICAO Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). ETS operates by the cap-and-trade principle where aviation's annual CO_2 emissions are restricted through emission allowances allocated to airlines. CORSIA aims to achieve global carbon neutral growth through offsetting the increase in total CO_2 emissions from international flights based on 2019 level. However, the effectiveness of both schemes is questioned, and their global contributions are unlikely to reduce aviation emissions significantly. In particular, ETS is criticised for handing out too many free allowances to the aviation industry, while the offsetting emissions as a collective unit under the CORSIA scheme may not motivate the individual polluters to implement any abatement options. Lastly, neither of the two schemes account for non-CO_2 emissions.
Another way to abate aircraft emissions is to focus on innovative technologies: alternative fuels and propulsion systems.
Sustainable aviation fuels (SAF), including advanced biofuels and electrofuels, are identified as the immediate solution to reduce emissions. Advanced biofuels may be derived from biomass, but the sustainability of future large-scale SAF production is under scrutiny and the non-CO_2 effect of biofuels is still not widely understood. Electrofuels, or power-to-liquid fuels (PtL), are produced from green hydrogen and non-fossil CO_2, be it biogenic or directly captured from the air. A potential large-scale demand for electrofuels would imply a strong increase in electricity generation, furthermore, the use of captured biogenic carbon may be viewed as illogical by consumers and policymakers as the re-release of CO_2 during fuel combustion contradicts the very purpose of the carbon removal technology. Furthermore, the non-CO_2 effects of electrofuels are relatively unexplored and its total climate impact remains uncertain.
Hydrogen fuels and electric propulsion systems are suggested to be the future for carbon-free aviation. Hydrogen production and utilisation is not new per se, but industrial actors are emphasising the need for new policies and regulations to ensure a functional hydrogen economy. Unlike SAF, use of hydrogen fuels requires changes in aircraft and engine designs as well as the development of accompanying infrastructure for hydrogen processing, with high production costs. Similarly turboelectric, hybrid electric or all-electric aircraft will also involve new designs of aircraft power and propulsion systems. The use of electric aircraft would also entail an update of the current power supply network and development of necessary charging infrastructure. Concerning electric aviation, the focus of ongoing research and projects is generally limited to the technical design of aircraft, whilst subjects like battery handling have received little attention. Likewise, little exploration of consumer perspectives and awareness of these innovations has been performed: without knowledge and trust, it would be difficult to evoke consumers' acceptance or willingness to pay. Furthermore, low climate impact could only be attained if electric

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aircraft are charged with renewable electricity, implying a potential burden shifting of environmental impact from the aviation industry to the energy sector.

Several measures are in place that aim to reduce the climate impact of the aviation industry, ranging from regulations to technology alternatives to fossil-based jet fuel. Understanding the needs of aviation to reduce its climate impact requires a multidisciplinary perspective, going beyond the technical aspects to include the socio-economic and political dimensions of these potential transitions. For example, Lai et al. 2022 [31] find that market creation is a major challenge, as most consumers of air travel today have limited willingness to pay for more expensive, but more sustainable flight technologies and fuels.

4.3 Simulation and evaluation of sustainable climate trajectories for aviation (Planes et al., 2021)

The work by Planes et al. (2021) [32] examined the environmental impacts of aviation, especially its contribution to climate change, and explored different methods to align the aviation sector with the goals of the Paris Climate Agreement. In fact, the aviation industry was responsible for 2.6% of global CO_2 emissions in 2019 and also contributes to climate change through non- CO_2 impacts. Both impacts can be measured by means of the Effective Radiative Forcing (ERF). It has been estimated that aviation could contribute for about 22% of global climate change impacts by 2050 due to projected growth and technological limitations. For this reason, in order to mitigate this prospective, this work has introduced the simulation tool CAST (Climate and Aviation Sustainable Trajectories), developed to model and evaluate sustainable trajectories for aviation using a carbon budget framework. CAST integrates technological, operational and fuel-based solutions to assess the alignment of aviation's climate strategies with the Paris Agreement's (1.5°C and 2°C) targets.

Regarding the Aviation Climate Modeling, the framework is based on an adapted Kaya equation, which decomposes CO_2 emissions into four components:

- Revenue Passenger Kilometers (RPK), reflecting air traffic levels. It represents the level of air traffic, coupling the number of passengers and the distance flown.
- Aircraft load factor, representing occupancy efficiency of aircraft.
- Energy intensity per seat, expressing the efficiency improvements in fuel consumption.
- Carbon intensity of fuel.

Figure 8 shows the evolution of Kaya equation parameters for aviation since 1991. The simulation tool CAST uses historical data and scientific projections to model aviation levers of action (traffic growth, energy efficiency, fuel decarbonization), while non- CO_2 effects are integrated via ERF metrics, emphasizing strategies for mitigation. The analysis distributes a share of the global carbon budget to aviation, typically 2.6% for CO_2 and 3.5% for ERF, based on current sectoral contributions. Future scenarios adjust these shares to evaluate trade-offs between aviation and oter industries.

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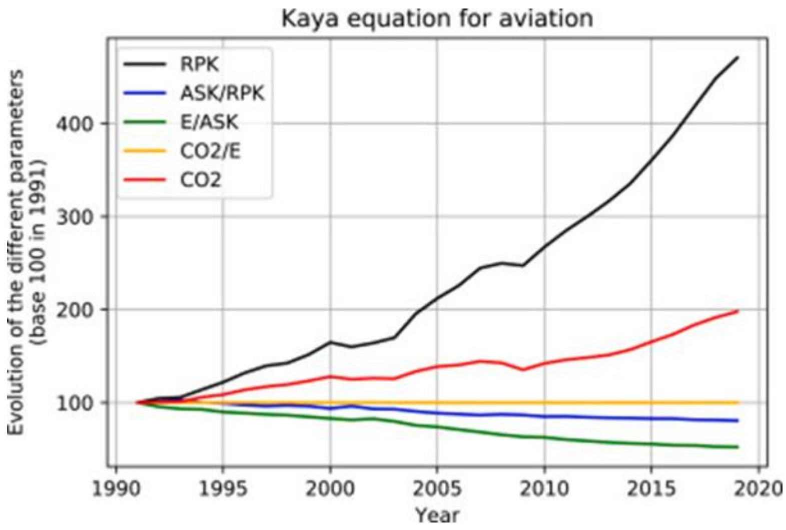

Figure 8: Evolution of Kaya equation parameters for aviation since 1991. From Planes et al. (2021) [32].

The authors found that, without intervention, aviation's CO_2 emissions will significantly exceed its allocated carbon budget under both 1.5°C and 2°C trajectories, requiring an urgent action to limit growth and decarbonize operations. Different scenarios have been analyzed:

- Trend Scenario: Assumes modest efficiency improvements (1% annually) and no significant operational or fuel changes. This results in unsustainable emissions under any growth scenario.
- Low-Carbon Energy Scenario: Incorporates a 35% fleet-wide decarbonization by 2050 (e.g., biofuels or hydrogen). This aligns with a 2°C trajectory but still exceeds the 1.5°C budget without reducing traffic growth.
- Technology-Based Scenario: Implements optimistic assumptions for energy efficiency (1.5% annual improvement) and a 70% decarbonized fleet. Compatible with 2°C goals even with moderate traffic growth but incompatible with 1.5°C limits without drastic traffic reductions.

Then, the paper highlights the importance of integrating non- CO_2 mitigation strategies, advancing low-carbon fuels, and adopting ambitious efficiency targets. Economic measures, like carbon offset schemes (e.g., CORSIA), provide transitional support but fall short of achieving long-term sustainability.

In conclusion, the CAST tool demonstrates that achieving the Paris Agreement targets will require a combination of technological innovation, policy interventions, and behavioral changes within the aviation industry. Future updates to CAST will incorporate resource availability for alternative fuels and detailed modeling of fleet renewal and emerging technologies. It was recommended to accelerate the development of alternative fuels and high-efficiency aircraft, to optimize flight paths and ground operations to reduce fuel consumption and to align growth rates with sustainable trajectories by implementing demand management policies.

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4.4 Evaluating the climate impact of aviation emission scenarios towards the Paris agreement including COVID-19 effects (Grewe et al., 2021)

This article [33] examines the environmental challenges associated with aviation and the measures proposed to mitigate the impact on global warming, providing an in-depth analysis of various technologies and strategies aimed at reducing GHG emissions and improving fuel efficiency within the aviation sector. These measures are contextualized within global environmental goals, particularly the Paris Agreement, which aims to limit global temperature rise to below 2°C above pre-industrial levels.

The study underscores that aviation accounts for a significant portion of global greenhouse gas emissions. Its non-CO_2 effects, such as contrail formation and NO_x emissions, are also significant contributors to atmospheric warming. Emerging technologies are reviewed, such as alternative fuels (e.g., sustainable aviation fuel, hydrogen), electric propulsion systems, and advanced aircraft designs, evaluating their potential to reduce emissions but also highlighting the limitations and scalability challenges associated with each solution. Operational improvements, such as optimizing flight paths and improving air traffic management systems, are identified as critical but insufficient in isolation to meet climate targets. A main conclusion of the paper is that, even with the integration of all currently discussed technologies and measures, the ECATS projection (Figure 9) shows that aviation would still cause a temperature increase exceeding 5% of the limits set by the Paris Agreement. This finding highlights the urgent need for more radical innovations and systemic changes in the aviation industry. Finally, the paper promotes intensified research and development, robust policy frameworks, and international collaboration to address the gap between current technological advancements and the ambitious climate goals.

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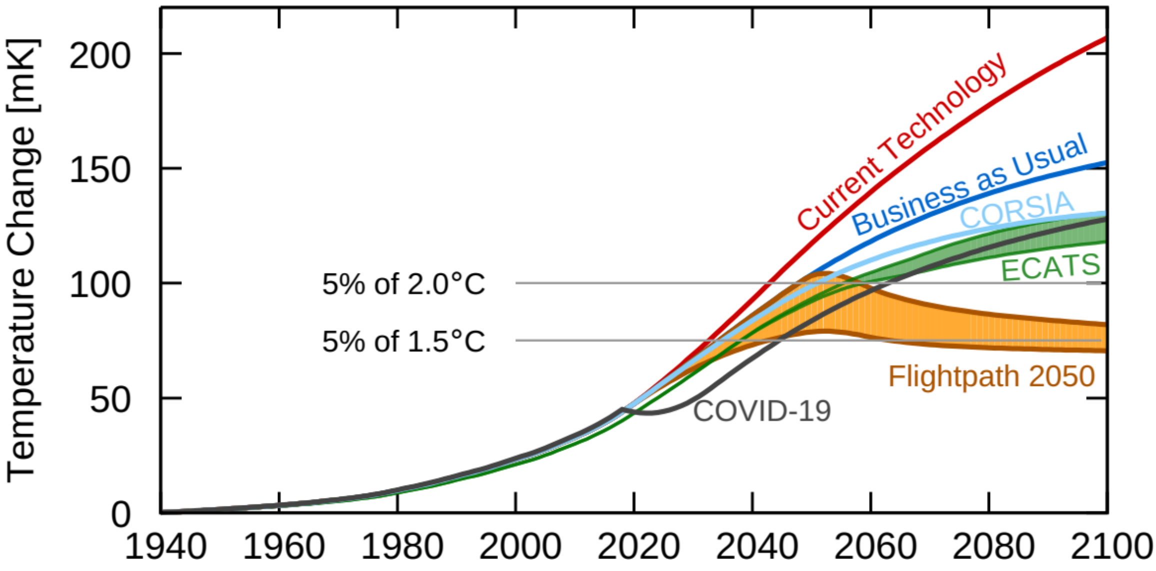

Figure 9. Near-surface temperature change of five scenarios including CO_2 and non- CO_2 -effects. From Grewe et al. 2021 [33].

4.5 Climate-Optimised Intermediate Stop Operations: Mitigation Potential and Differences from Fuel-Optimised Configuration (Zengerling et al., 2022)

Aviation's contribution to anthropogenic radiative forcing is estimated at around 3.5%, and therefore significantly contributes to climate change [1]. In contrast to technological improvements, operational approaches require shorter implementation times and are able to realise mitigation potentials faster [34]. The objective of the study by Zengerling et al (2022) [35] is to assess the climate mitigation potential of Intermediate Stop Operations (ISO). For this purpose, adjustments to the concept aiming for fuel efficiency are twofold:

1) The intermediate stop airport is not selected according to fuel-optimal criteria,but based on minimal climate impact.
2) Cruise flight levels are reduced and step climbs are avoided if this reduces the climate impact.

Regarding point 1, the non- CO_2 effects (such as the effects induced by water vapour (H_2O), nitrogen oxides (NO_x), and contrail cirrus) do not only depend on the fuel consumption, but also on emission location, time, and meteorological boundary conditions ([1],[2],[36]). Hence, a sole focus on fuel efficiency and resulting reduction in CO_2 emissions does not necessarily reduce the total climate impact. While regarding point 2, shorter stage lengths allow to reduce the amount of fuel, which reduces the aircraft mass. A reduction in fuel consumption through reduced aircraft weight leads to higher flight altitudes if maximum fuel efficiency is targeted ([37],[38]). Thus, engine emissions are generally released at higher altitudes, which can result

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in an increase in the climate impact caused by non- CO_2 effects, such as NO_x and contrails ([27],[39]).

The contribution of Zengerling et al (2022) [35] to the current state of research, firstly provides a methodology to characterise climate-optimised ISO, including selection of intermediate refuelling airport and flight altitudes that significantly contribute to a reduction in the climate impact. Secondly, they assess the climate mitigation potential of implementing ISO on long-haul flights departing from or landing in Europe. They estimate the mitigation potential of the climate-optimised ISO concept in terms of Average Temperature Response over 100 years (ATR100) reduction of up to 40% for long-haul flights compared to the non-stop reference case. Figure 10 illustrates changes in ATR100 caused by the implementation of climate-optimised ISO. The authors confirm that the resulting increase in ATR100 caused by additional CO_2 emissions proportional to the rise in fuel consumption is overcompensated by the reduction in the impact of all non- CO_2 effects. This is caused by changed emission locations both horizontally and vertically.

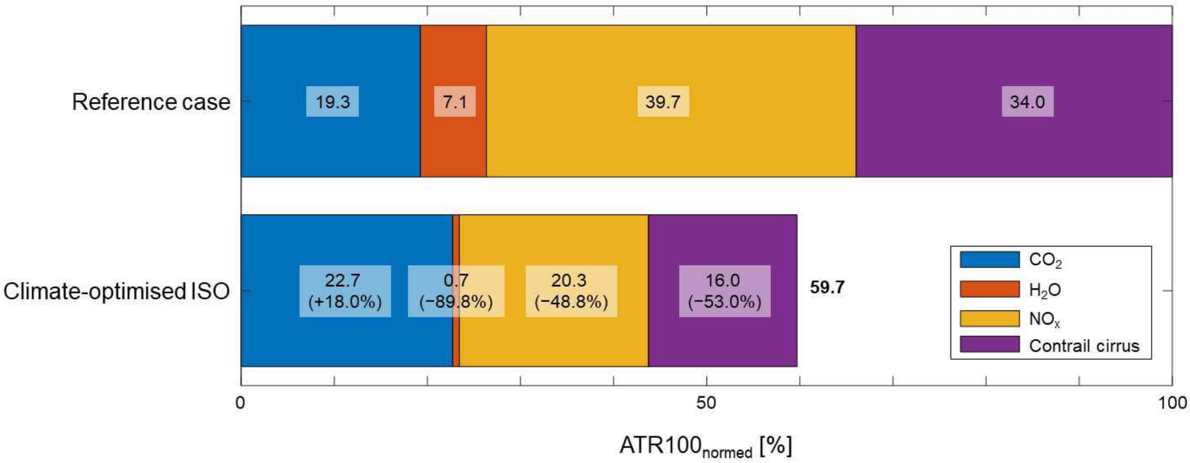

Figure 10. Change in ATR100 per emission species for climate-optimised ISO compared to the non-stop reference case. From Zengerling et al (2022) [35].

Thirdly, they compare the results from the climate-optimised ISO set-up with its fuel-optimised counterpart. They find that the climate-optimised ISO routes are on average conducted at lower latitudes and altitudes, as seen in Figure 11 where the zonal and vertical distributions of CO_2 emissions are shown for both cases.

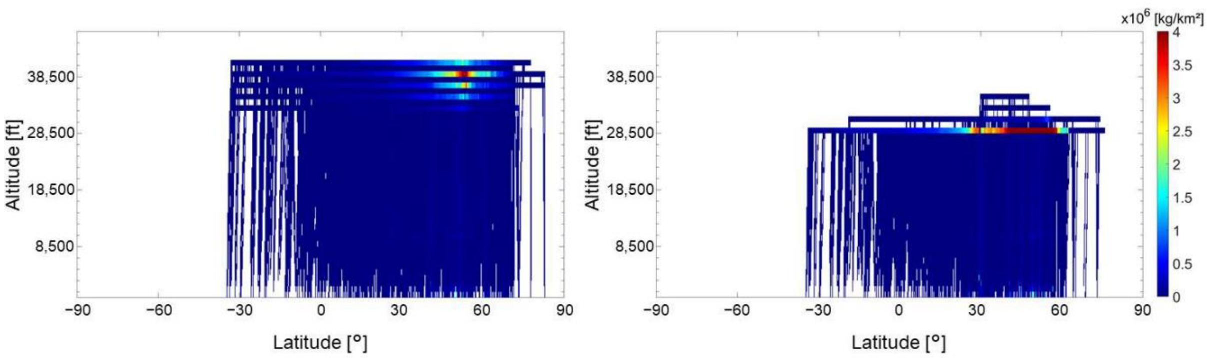

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Figure 11. Zonal and vertical distribution of CO_2 emissions with fuel-optimised ISO (left) and climateoptimised ISO (right). From Zengerling et al (2022) [35].

Furthermore, climate-optimised ISO severely impacts non-climate parameters, such as fuel burn and flight time so that stakeholder interests are affected in course of implementation. Finally, they suggest that to address this issue, eco-efficient operation set-ups can be derived that reduce fuel consumption and ATR at the same time.

4.6 Assessing the climate impact of the AHEAD multi-fuel blended wing body (Grewe et al., 2017).

Grewe et al. (2017) [40] investigate the climate impact of a future aircraft design, a multi fuel blended wing body (MF-BWB), conceptually designed within the EU-project AHEAD (Advanced Hybrid Engines for Aircraft Development) and shown in Figure 12. The proposed innovative AHEAD hybrid engine uses two combustion chambers with two types of fuels in series in order to reduce emissions. In a first combustion chamber liquid hydrogen (LH2) or liquid natural gas (LNG) is burnt to reduce the CO_2 emissions. A part of the emerging exhaust is inserted into the second combustor chamber, which is fuelled with bio kerosene and burnt flameless in a water vapour rich and low oxygen environment reducing NO_x emissions. From the conceptual point a decrease in emissions is obvious, but it is crucial to consider the impact on climate via non-CO_2 effects.

Figure 12. Drawing of the AHEAD MF-BWB. From Grewe et al 2017 [40].

The authors investigated the contribution of the AHEAD technology to a reduction of the long-term temperature change in comparison to a future conventional technology, for a 100-year time period. They defined a reference aircraft with approximately the same size and range and they considered a change of the whole fleet. They also evaluated the case of a future fleet (B787-FUT) of the reference aircraft with enhancements in fuel efficiency of 10% and a reduction in CO_2 emissions of 25%, considering an entry into service for the AHEAD aircraft in 2050. The climate impact assessment of AHEAD new aircraft requires some considerations with respect to contrail processes, while the other effects arising from CO_2, H_2O, and NO_x emissions are analysed with the AirClim chemistry-climate response model.

As the proposed aircraft has very different characteristics compared to conventional technologies, the parameters for the contrail formation criterion (Schmidt-Appleman criterion) have been re-calculated based on the use of two different fuels. This analysis showed that contrail formation from AHEAD aircrafts potentially already occurs at higher temperature and then lower altitudes than for conventional aircraft. The contrail geometry and microphysical properties for the new and a reference aircraft have been investigated by means of Large-

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Eddy-Simulations (LES), showing that the shape and geometry of the contrails is not significantly affected. Then, the Climate Model ECHAM4/5-CCMod which includes a contrail-cirrus parameterisation has been used to study the effect of contrail-cirrus on climate. The emissions of a complete AHEAD fleet have been considered in the model. This analysis shows an increase in contrail-cirrus radiative forcing compared to conventional technologies, if the number of emitted particles is equal to conventional technologies. However, there are strong indications that the AHEAD engines would have a substantial reduction in the emission of soot particles and this leads to a substantial reduction in the contrail-cirrus radiative forcing caused by the lower optical thickness and a shorter lifetime of the AHEAD contrail-cirrus compared to conventional technologies.

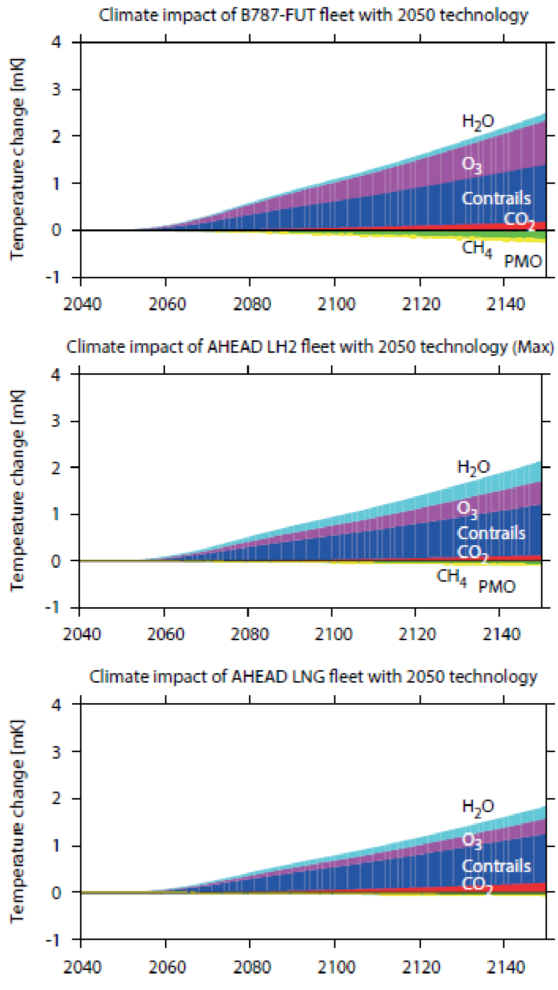

Figure 13. Temperature change [mK] induced by the B787- FUT (top), AHEAD-LH2-Max (mid), and AHEAD-LNG (bottom) fleet. Individual contributions are marked in color: H2: light blue, O_3: magenta, contrail-cirrus: blue, CO_2: red, CH_4: green, and PMO: yellow. From Grewe et al 2017 [40].

Results from this simulation are then used in a climate-chemistry response model (AirClim) to estimate the overall climate impact of a fleet of AHEAD aircraft. Figure 13 shows the temporal evolution of the temperature change for the reference configuration B787-FUT (top) as well

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as the AHEAD fleets (LH2 and LNG). Ozone changes and contrail-cirrus contribute most to the induced temperature increase for the B787-FUT, whereas contrails, water vapour, and ozone changes are important for the AHEAD technologies. The results show that the AHEAD-LNG version significantly reduces the climate warming (about 20 to 25%) in comparison to conventional technologies (LH2 version has a lower reduction potential).

Grewe et al. (2017) [40] stress the importance of frequent iteration between engine design, aircraft design and climate impact analysis during the development phase of new and climate compatible aircraft.

4.7 Eco-efficiency in aviation (Grewe and Linke, 2017)

Grewe and Linke 2017 [41] aim to compare different mitigation options with respect to their eco-efficiency, defined as the ratio of climate impact changes to cost increases, i.e., an indication of the overall potential to reduce the climate impact from aviation as well as the related costs.

The authors provide a review of several approaches aimed to reduce the climate impact of aviation, considering findings from both research project and literature works. Figure 14 reports a summary scheme of the reviewed approaches, further described in the following.

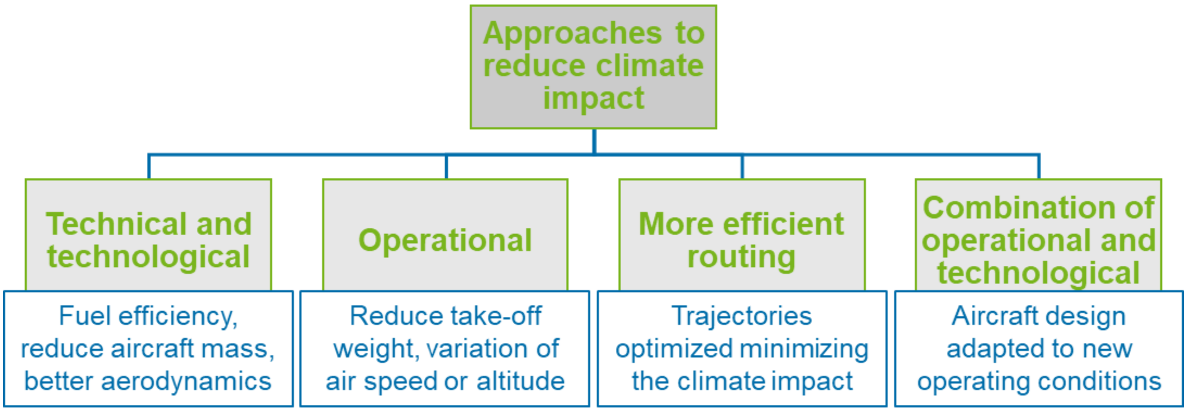

Figure 14. Summary scheme of the approaches to reduce the climate impact of aviation reviewed in Grewe and Linke 2017 [41].

1) **Technical and technological measures.**

   They include improvements in fuel efficiency, e.g. by increasing engine efficiencies, by reducing the aircraft structural mass and by improving aerodynamics. For example, the EU-project AHEAD proposed new combustor technologies for the reduction of emissions.

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2) Operational measures.

They include:

- reduction of take-off weight, avoiding unnecessary weight. For example, reducing the fuel quantity at take-off and refuelling the aircraft during the mission, through air-to-air refuelling (concept not immediately feasible) or through “Intermediate Stop Operations” (ISO).
- variation of air speed: a reduction of the speed, down to a minimum fuel consumption, results in lower release of engine exhaust gases, such as CO_2 and NO_x.
- variation of altitude: lowering the cruise altitude leads to a reduction in the global coverage of contrails (results from TRADEOFF project) and to a reduction of the 100-year Average Temperature Response, but with an increase in direct operating cost (CATS project).

3) More efficient routing

Definition of trajectories optimized minimizing the climate impact, this strategy was examined in the project REACT4C. An essential prerequisite for this approach is a continuously adapted flight planning process which requires accurate meteorological data and data link technologies to provide data to the aircraft.

4) Combination of operational and technological measures

In order to augment the benefit coming from new operating conditions (e.g. lower cruise altitude or lower speed) the idea is to adapt the aircraft design accordingly.

Numerous options to reduce aviation’s climate impact exist, but they are characterized by different frameworks and their direct comparison is not trivial, due to several aspect in which they may differ, such as:

1. climate impact reduction potential,
2. change in operating costs,
3. eco-efficiency: relation between climate impact reduction and change in operating costs,
4. earliest date of implementation, and
5. additional costs, such as investments in re-design or extra infrastructure.

To overcome this issue, the authors propose multi-dimensional diagrams, which can serve as a basis for decision-making, as they clearly outline the different aspects of individual mitigation options. An example diagram is reported in Figure 15, which includes all the five abovementioned aspects and compare results from several projects. The net's area is indicative of the quality of a mitigation option because the most promising value is always at the end point of each axis.

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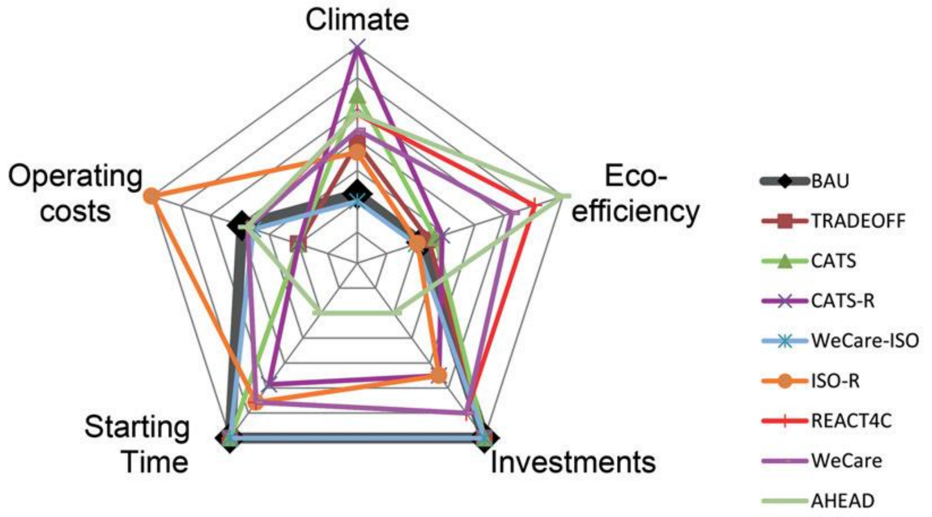

Figure 15: Multi-dimensional presentation of different mitigation options. From Grewe and Linke 2017 [41].

4.8 Climate assessment of single flights: Deduction of route specific equivalent CO_2 emissions (Dahlmann et al., 2023)

One of the anthropogenic emission sectors, where non- CO_2 effects play an important part, is aviation. Hence, for a quantitative estimate of total aviation climate impact, assessments need to comprise both CO_2 and non- CO_2 effects (e.g., water vapor, nitrogen dioxide, and contrails), instead of calculating and providing only CO_2 impacts. As often such comprehensive information is not available for all aircraft movements, a simplified calculation method is required to calculate non- CO_2 impacts. In Dahlmann et al (2023) [4], they introduce a simple calculation method which allows quantifying climate assessment relying on mission parameters, involving distance and geographic flight region. Therefore, the objectives of the study by Dahlmann et al (2023) [4] can be summarized as follows:

1. Present dependence of CO_2 and non- CO_2 climate effects on specific emission parameters.
2. Introduce a simple calculation method using mission parameters (mission length and geographic flight region) to calculate non-CO2 effects.

Regarding point 1, while a calculation of CO_2 effects relies directly on fuel consumption, for non- CO_2 detailed information on aircraft trajectory, engine emissions, and ambient atmospheric conditions are required. While regarding point 2, achieving this goal allows the total climate impact of aviation emissions to be calculated for individual flight missions. As, for different types of aircraft, NO_x emissions per fuel consumption as well as the probability of producing contrails or flight profiles may change. The contribution of Dahlmann et al (2023) [4] to the current state of research is a systematic analysis of simulated climate impact from more than 1000 city pairs with an Airbus A330-200 aircraft (Figure 16) depending on the flight

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distance and flight region to derive simplified but still realistic representation of the non- CO_2 climate effects is presented.

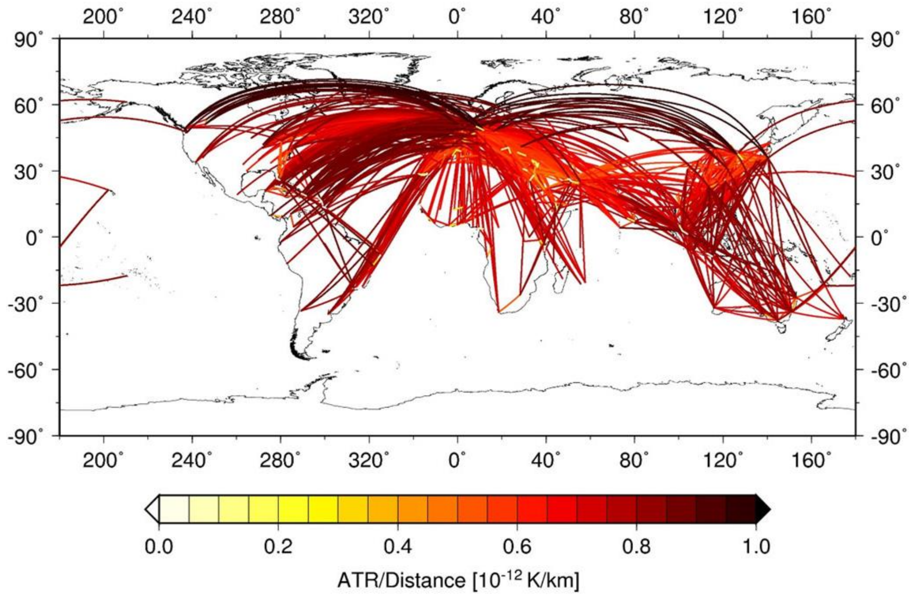

Figure 16: Specific climate impact in terms of ATR100 per km for all analyzed global route network with all flights operated by an Airbus A330-200 aircraft in 2006. From Dahlmann, Koch et al. (2016) [42].

Three types of mathematical formulas for the CO_2 and non- CO_2 climate impact of aviation are presented in Dahlmann et al (2023) [4]. The climate impact is given as CO_2 equivalent factor (climate impact of an emission of 1 kg of a species relative to that of 1 kg CO_2 emission) using ATR100 as climate metric. The values represent annual and global mean values. The first is very simple constant factor, the second includes a distance dependency and the third additionally includes a latitude dependency. Therefore, they aim at stepwise capturing some main sensitivities of the non- CO_2 impacts by using easily available information like flight distance and geographical latitude.

From the application of the new mathematical formulas proposed in this work [4] the authors deduce that for assessing non- CO_2 effects from aviation than individual aircraft missions, that are able to represent geographic, in particular, latitudinal dependence of non- CO_2, represent the climate impact of non- CO_2 effects much better than other formulas that are composed of simple constant CO_2 multiplier. Indeed, the mean square error decrease from 1.18 for a constant factor down to 0.24 for distance dependent factors and can be reduced even further to 0.19 for a distance and latitude dependent factor. Specifically, the introduced formulas allow to provide a more realistic quantitative estimate of the total climate impact of aircraft missions and the use of latitude-dependent factors, in addition to mission duration and fuel consumption, increases the accuracy of the climate.

Nevertheless, as the authors themselves point out, the formulas introduced have limitations as they are derived from one single aircraft type of A330-200 aircraft. Using different aircraft

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types and different emission compositions would further increase the accuracy, but also the complexity of the calculations and the need for further information, which often are not available. The climate impact here is analysed on a climatological base. It is assumed that the aircraft flies the whole year in a lot of different weather situations. The obtained results are valid on an annual mean basis, while one single flight under specific weather conditions can have completely different climate impact, compared to the impact of the annual mean basis. Like the different aircraft types, the inclusion of such information would increase on the one hand side the accuracy, but on the other hand increase the amount of information and increase the complexity of the calculation [43].

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5. Discussion and Conclusions

The review presented in this document analysed the diverse methodologies and related findings and implications of various projects and literature works that address the climate impact of aviation. By analyzing EU-funded initiatives and other significant national and international projects, several critical insights have been drawn about how aviation contributes to climate change and the potential pathways to mitigate these impacts.

As regards the modelling and metrics development, projects like REACT4C and ATM4E have pioneered the development of climate cost functions (CCFs) and environment change functions (ECFs), enabling better integration of climate considerations into aviation operations. These functions provide actionable metrics for evaluating the trade-offs between economic costs and climate impacts. Projects like GLOWOPT and AHEAD have underscored the importance of integrating climate considerations into aircraft design. The development of Climate Functions for Aircraft Design (CFAD) and hybrid engines demonstrated how innovations can significantly reduce non- CO_2 effects and overall climate impact. In this view, initiatives like ACACIA and BeCoM have advanced the understanding of non- CO_2 effects (including contrails and NO_x -induced ozone changes). These efforts have identified the need for refined atmospheric models and better integration of these effects into policy and operational frameworks. Projects such as CLIMOP and CICONIA emphasize the importance of engaging stakeholders to ensure practical implementation of mitigation strategies. The inclusion of performance indicators and the development of policy-driven frameworks are critical for the promotion of sustainable aviation practices.

Operational changes, such as the Intermediate Stop Operations (ISO) studied by Zengerling et al. (2022) [35], show significant potential for reducing climate impacts, with reductions in Average Temperature Response (ATR100) of up to 40%. However, these improvements often involve trade-offs, such as increased fuel burn or extended flight times.

Despite these advancements, several challenges and gaps still persist:

- The variability and complexity of non- CO_2 emissions, such as contrail radiative forcing, require further research and improved predictive models.
- Many mitigation strategies involve increased costs or operational complexity, necessitating robust cost-benefit analyses.
- Adoption of circular fuel supply for air transport with hydrothermal Liquification (HTL) Biofuels.
- Characterization of the mechanisms involved in the biodiesel productions e.g. from waste oil.
- The transition to low-carbon fuels, hydrogen or electric propulsion is characterized by technical, economic, and infrastructural challenges.

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- The international harmonization of policies, in particular for emissions trading and offset mechanisms, remains a relevant obstacle.

In conclusion, the pathways to mitigating aviation's climate impact are becoming clearer through initiatives like those reviewed in this document. The review confirms that the climate impact of aviation is a complex issue, requiring a combination of technological, operational, and policy-driven solutions. While significant progress has been made in modelling tools and operational strategies, achieving a sustainable aviation sector will demand the integration of expertise from atmospheric science, engineering, economics, and social sciences. Moreover, the collaboration among airlines, regulators, manufacturers, and researchers is critical for developing and implementing practical and effective solutions. Achieving net-zero or significantly reduced emissions will require sustained innovation, investment, and cooperation across the aviation ecosystem. Future efforts should prioritize addressing the highlighted gaps, fostering international collaboration, and ensuring that climate mitigation becomes an integral part of aviation's operational and strategic goals.

Innovative approaches, such as those based on Machine Learning (ML), can help models to predict GHG, the impact of mitigation policies, and the efficiency of airline operations. Specifically, Linear Regression models can be used to foresee GHG emissions according to flight data, Multivariate Regression to consider the simultaneous influence of several factors (such as type of aircraft, weather conditions, routes), Random Forest to model the non-linear complexity of emissions based on multiple characteristics. These models can be continuously updated with new data to improve their prediction capability over the time, and tacking into account the opportunities provided by new optimised operations and innovative technologies with a special focus on the potential benefits collectable by disruptive propulsion systems and highly integrated architectural aircraft concepts

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