EXPLORATORY RESEARCH

sesar JOINT UNDERTAKING

Report on recommendations on regarding the implementation of robust and climate impact reducing ATM operations

Deliverable ID:	D4.3
Dissemination Level:	PU
Project Acronym:	FlyATM4E
Grant:	891317
Call:	H2020-SESAR-2019-2
Topic:	SESAR-ER4_05-2019 - Environment and Meteorology for ATM
Consortium Coordinator:	DLR
Edition date:	31 August 2022
Edition:	00.02.00
Template Edition:	02.00.05

EUROPEAN PARTNERSHIP

Co-funded by the European Union

Authoring & Approval

Authors of the document

Name / Beneficiary	Position / Title	Date
UC3M	WP4 leader	23/08/2022

Reviewers internal to the project

Name / Beneficiary	Position / Title	Date
DLR	Coordinator	31/08/2022
TUD	WP3 leader	31/08/2022
UC3M	WP4 leader	31/08/2022
TUHH	WP2 leader	31/08/2022

Reviewers external to the project

Name / Beneficiary	Position / Title	Date

Approved for submission to the SJU By - Representatives of all beneficiaries involved in the project

Name / Beneficiary	Position / Title	Date
DLR	Coordinator	31/08/2022
TUD	WP3 leader	31/08/2022
UC3M	WP4 leader	31/08/2022
TUHH	WP2 leader	31/08/2022

Rejected By - Representatives of beneficiaries involved in the project

Name and/or Beneficiary	Position / Title	Date

Document History

Edition	Date	Status	Name / Beneficiary	Justification
00.00.01	06/05/2022	Initial version	DLR	Initialisation
00.00.02	08/07/2022	Complete Draft	UC3M	Sent for internal review
00.01.00	12/07/2022	Submission	DLR	Internally reviewed
00.01.01	23/08/2022	Reviewed	UC3M	Sent for internal review
00.02.00	31/08/2022	Submission	DLR	Internally reviewed

FlyATM4E

FLYING AIR TRAFFIC MANAGEMENT FOR THE BENEFIT OF ENVIRONMENT AND CLIMATE

This deliverable is part of a project that has received funding from the SESAR Joint Undertaking under grant agreement No 891317 under European Union's Horizon 2020 research and innovation programme.

Abstract

This deliverable is part of the communication, dissemination, and exploitation activities of FlyATM4E. In particular, the focus is on the recommendations regarding the implementation of robust and climate-optimal trajectories in the ATM system. The recommendations we are providing are divided into two groups that coincide with the two solutions proposed in the FlyATM4E project.: (1) algorithmic Climate Change Functions in its Version 1.1 (aCCFs V1.1); and (2) climate optimal trajectories.

We describe the aCCFs V1.1, which we note should be considered as prototypes (calculated in the North Atlantic Region with winter and summer patterns), including recommendations on: the metrics used, the different emission scenarios and time-horizons, the concept of efficacy, and the consideration of uncertainties. In the end, we highlight that all the portfolio of options to configure the aCCFs V1.1 has been implemented and documented in an open-source python library coined CLIMaCCF. Overall, we provide CLIMaCCF as a foundation brick to build a meteorological (MET) service to inform on the climate effect of flight operations comprising CO_2 and non-CO_2 effects. In our overall concept we establish it as an interface between climate science and ATM, with the help of aCCFs V1.1 and suggest them as a MET enabler:

On the implementation of climate optimized aircraft trajectories, we provide a description of the elements needed to build and solve the problem, including: an objective function that combines the operational cost and the climate cost (noting that aCCFs V1.1 is to be used as input to build the climate objective); the dynamics of the aircraft (including flight envelope constraints); and, eventually, airspace constraint (including the structure of the airspace). We also discuss and provide recommendations on the different methods available to solve the problem.

We finally address some challenges linked to further improve aCCFs V1.1 and its usage in aircraft trajectory optimization problems.

Table of Contents

List of Tables

List of Figures

1 Introduction

The goal of this deliverable is to promote FlyATM4E results by issuing a series of recommendations regarding the implementation of robust and climate-optimal trajectories in the ATM system.

To provide a self-standing context, we first describe the FLyATM4E project (Section 1.1) and then frame the deliverable within the overall project (Section 1.1). Section 1.3 is devoted to providing the structure of the remaining chapters of the document, and Section 1.4 lists the reference material used.

1.1 FlyATM4E objectives

The overall objective of FlyATM4E is to develop a concept to identify climate-optimised aircraft trajectories in which 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 through MET data, ensemble prediction and eco-efficient trajectories. FlyATM4E will consider the effect of emissions of CO_2, NO_x, H_2O, and particulates (in-direct impact on contrail properties and the resulting climate effects) on the atmosphere via concentration changes of radiatively active species, comprising effects on ozone, methane, and contrail-cirrus.

This overall objective is subdivided into four specific objectives of the project FlyATM4E, which are to

- Objective O1: advance concepts to assess the climate impact of ATM operations which integrates an adequate representation of uncertainties, including CO_2, contrails, ozone, methane and water vapour climate effects, from weather forecast as well as climate science, and to provide concepts for climate information enabling eco-efficient aircraft trajectories.
- Objective O2: investigate aviation's climate impact mitigation potential by developing robust flight planning algorithms through the integration of uncertainties from the climate impact analysis and ensemble weather forecasts in ATM.
- Objective O3: identify eco-efficient aircraft trajectories and related weather situations, which enable a reduction of both climate impact and operational costs ("Win-Win") by avoiding ATM inefficiencies; or which largely reduce the climate impact of aviation at almost unchanged costs by avoiding extreme climatesensitive regions ("Cherry-Picking").
- Objective O4: provide recommendations for target stakeholders on policy actions and supporting measures to implement eco-efficient aircraft trajectories enabled by a better understanding of the climate impact of individual aircraft trajectories.

EUROPEAN PARTNERSHIP

Co-funded by the European Union

1.2 Purpose of the deliverable within FlyATM4E project

The present deliverable is part of the communication, dissemination, and exploitation activities, which are framed within FlyATM4E's WP4 (see Figure 1). Thus, WP4 is gathering the research activities conducted within the technical WPs, namely WP1, WP2, and WP3, with the aim at:

- Evaluating the project's results in relation to other ATM and MET related enablers and constraints, which includes a hindcast analysis (see Figure 2).
- Delivering recommendations for implementation of environmental-assessment of aircraft trajectories (environmental-optimization) jointly with stakeholders (see also Figure 2).
- Disseminating of project results at scientific conferences, in journal papers, to general stakeholders, especially industry, and the general public.

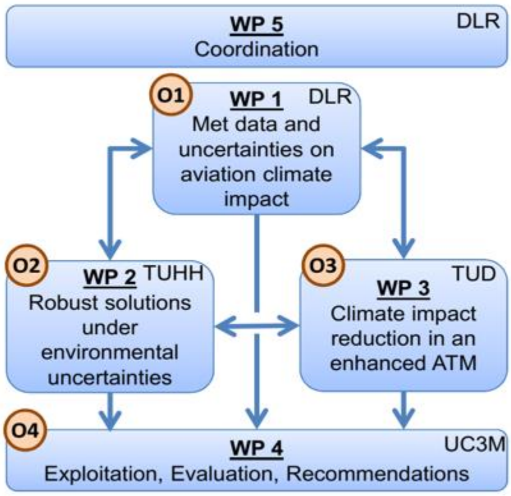

Figure 1: FlyATM4E WP structure

D4.1 [1] was focused on the dissemination, exploitation, and communication plan and its execution (partially reported in an updated version of D4.1). D4.2 [2] elaborated on the stakeholders' workshop to be organized in September/October 2022. In the present deliverable, D4.3, the focus is on the recommendations regarding the implementation of robust and climate-optimal trajectories in the ATM system. The evaluation of results will come in D4.4 [3].

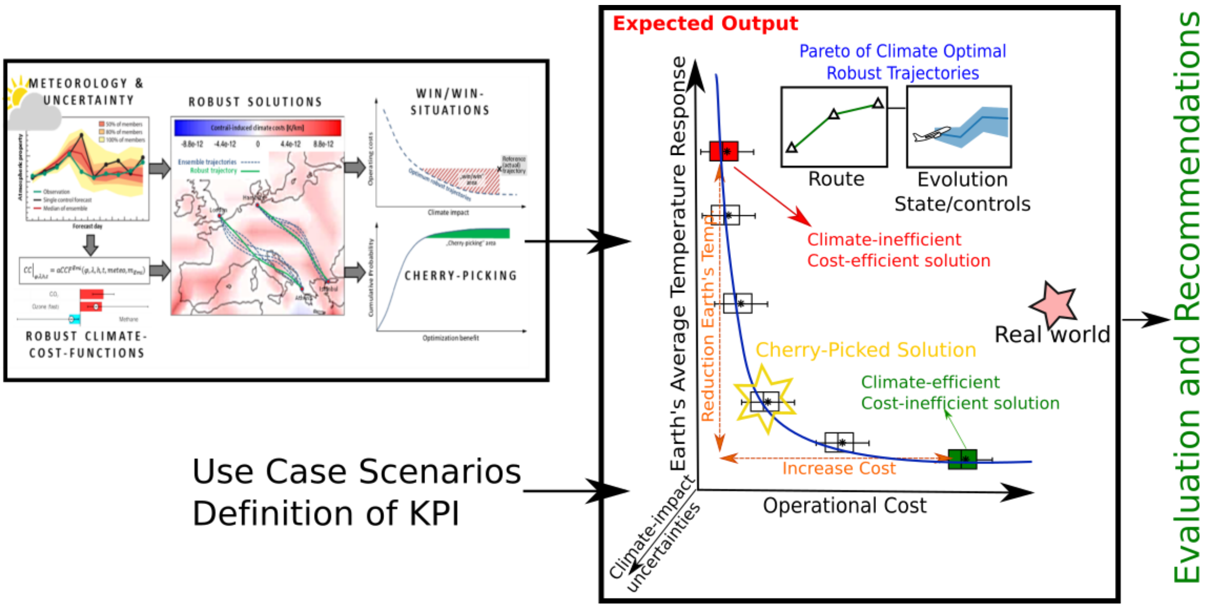

Figure 2: FlyATM4E evaluation and recommendations.

1.3 Structure of the deliverable

We first describe the FlyATM4E solutions in Section 2, namely algorithmic Climate Change Functions (aCCFs V1.1) and the methods to calculate climate optimal trajectories. Then, in Section 4, we provide recommendations on the solutions previously described. Section 5 is devoted to a discussion and to presenting the challenges.

1.4 Applicable Reference material

As reference material, we have used FlyATM4E deliverables, namely D1.2 [4], D2.2 [5], and D3.2 [6].

1.5 Acronyms and Terminology

Non-exhaustive list of acronyms used across the text.

Acronym	Description
aCCF	algorithmic Climate Change Function
ATM	Air Traffic Management
ATR	Average Temperature Response
ATS	Air Traffic Services
ASK	Available Seat Kilometres
BADA	Eurocontrol Base of Aircraft Data
CSR	Climate-Sensitive Regions
ECAC	European Civil Aviation Conference
ECMWF	European Centre for Medium Range Weather Forecast
EMAC	ECHAM/MESSy Atmospheric Chemistry
EPS	Ensemble Prediction System
ERA5	ECMWF Reanalysis v5
EP	Experimental Plan
EU	European Union
F-ATR	Future (Scenario)-Average Temperature Response
F-ATR20	Future (Scenario)-Average Temperature Response at 20 years' time horizon
GTP	global temperature change potential
GWP	Global Warming Potential
KPA	Key Performance Areas
ICAO	International Civil Aviation Organization
MET	Meteorology
RH	Research Hypothesis
ROOST	Robust Optimisation of Structured Airspace

EUROPEAN PARTNERSHIP

Co-funded by the European Union

RQ	Research Questions
SOC	Simple Operation Cost
TOM	Trajectory Optimisation Module
WP	Work Package

Table 1: Acronyms

FlyATM4E Consortium

Acronym	Description
DLR	DEUTSCHES ZENTRUM FUER LUFT - UND RAUMFAHRT EV
TUD	TECHNISCHE UNIVERSITEIT DELFT
TUHH	TECHNISCHE UNIVERSITAT HAMBURG
UC3M	UNIVERSIDAD CARLOS III DE MADRID

Table 2: FlyATM4E consortium acronyms

2 Description of FlyATM4E solutions

The recommendations we are providing (see Section 4) are divided into two groups that coincide with the two solutions proposed in FlyATM4E project. Thus, to have a self-standing document, we shortly describe the two solutions that FlyATM4E is proposing, namely:

- ID Solution: SOL-FlyATM4E-01: Increased situational awareness on climate change effects relying on algorithmic climate change functions
- ID Solution: SOL-FlyATM4E-02: Identifying robust climate-optimized flight planning in trajectory-based operations

Details insight about the two solutions are provided in D5.3 [7].

2.1 ID Solution: SOL-FlyATM4E-01

2.1.1 Solution Title

Increased situational awareness on climate change effects relying on algorithmic climate change functions

2.1.2 Solution Definition

Having spatially and temporally resolved information on climate effects of aviation emissions in the airspace available is a prerequisite for assessing climate effects of aircraft operations. An efficient integration (in flight planning and airspace management) relies on combining algorithmic climate change functions (aCCFs) with operational numerical weather prediction data of key variables and specific aircraft emissions.

This solution provides information as an efficient meteorological (MET) service to inform on the climate effect of flight operations comprising CO_2 and non-CO_2 effects. This solution increases the situational awareness of the airspace user and this climate effect information can be provided as a spatially and temporally resolved data field. Resolved climate effect is measured in units of a dedicated climate metric.

This solution targets to enable assessment and optimization of environmental performance of aircraft operations, more specifically the overall climate effect comprising CO_2 and NO_x-induced, H_2O-induced and contrail cirrus effects.

2.2 ID Solution: SOL-FlyATM4E-02

2.2.1 Solution Title

Identifying robust climate-optimized flight planning in trajectory-based operations

EUROPEAN PARTNERSHIP

Co-funded by the European Union

2.2.2 Solution Definition

This solution defines the process and provides guidance for calculating aircraft trajectories that are optimized with respect to an objective function comprising both economical (i.e. operating costs) and environmental (climate impact) criteria.

It describes the necessary extension of aircraft trajectory planning processes to implement a well-informed and robust multi-objective flight planning with the goal to consider the overall climate impact (CO2 and non-CO2 effects) of a flight while ensuring the compliance with conventional flight planning boundary conditions and operational constraints.

These planning processes comprise graph-based approaches in structured airspace as well as optimal control based techniques in flexible airspace environments. Robustness with respect to uncertainty in weather forecast is ensured by incorporating numerical ensemble prediction data in the process implementation.

Guidance is provided as to how flights with a high climate impact reduction potential can be identified. The algorithmic climate change functions as defined per Sol-FlyATM4E-01 serve as an enabler for this solution.

The solution targets primarily airspace users as key stakeholders, but also supports the Network Manager and local ANSPs in making informed decisions and in providing a framework for sustainable air traffic in the European ATM Network. It mainly addresses the KPA Environment.

EUROPEAN PARTNERSHIP

Co-funded by the European Union

3 Algorithmic Climate Change Functions (a-CCFs) and trajectory optimization tools

The two solutions that FlyATM4E is proposing, already described in Section 2, are linked to different outcomes (libraries and tools) of the project, which we describe in this section.

In particular, ID Solution: SOL-FlyATM4E-01: Increased situational awareness on climate change effects relying on algorithmic climate change functions, is linked the Python library that we have developed, which embeds the algorithmic Climate Change Functions (aCCFs V1.1).

On the other hand, ID Solution: SOL-FlyATM4E-02: Identifying robust climate-optimized flight planning in trajectory-based operations, is linked to different trajectory optimization tools and its associated features.

3.1 Algorithmic Climate Change Functions (aCCFs V1.1)[1]

aCCFs V1.1 describe the expanded prototype algorithmic climate change functions (aCCFs), which have been applied in the overall FlyATM4E multi-modelling concept to explore the mitigation potential of climate optimized aircraft trajectories.

aCCFs V1.1 represent spatially and temporally resolved information on the climate impact in terms of future temperature changes of aviation emissions at a given time and location in the atmosphere. They include CO_2 and non-CO_2 effects, comprising NO_x, water vapour and contrail-cirrus. These aCCFs V1.1 can be simply derived from meteorological weather forecast data.

The characteristic patterns of aCCFs V1.1 are as follows:

- The water vapor aCCF V1.1 shows positive (warming) values and highly varies for the different synoptical situations, i.e., increase as the altitude increase.
- The total NO_x aCCF V1.1 combines the positive (warming) ozone aCCF V1.1 and the negative (reduced warming, i.e., net-cooling effect) methane (and the relating primary mode ozone (PMO)) aCCF V1.1. The ozone aCCF V1.1 is positive as NO_x emission from aviation lead to ozone formation, and the methane aCCF V1.1 is negative as NO_x emission are destroying methane. The PMO aCCF V1.1 is negative as the depletion of methane causes the reduction of background ozone formation (PMO), hence the cooling effect of PMO aCCF V1.1. Overall, the total NO_x aCCF V1.1 is mainly positive, as the short term ozone effect is more dominating. Moreover, NO_x aCCFs V1.1 are highly influenced by different weather situations.
- Night-time contrail cirrus aCCFs V1.1 determine a warming effect with positive values. This is explained by the longwave radiative impact of contrails during night. During the day, contrails have both longwave and shortwave radiative impact, thus the day-time contrails can have negative and positive values as contrail formation and contrail climate impact are very

[1] Note, please, that all the references to aCCFs in this document correspond to aCCFs V1.1.

sensitive to the atmospheric conditions, contrails aCCFV1.1 show a large geographical and day to day variability.

It has also been shown that by combining the individual aCCFs V1.1 of water vapour, NO_x and contrail-cirrus, merged non-CO_2 aCCFs V1.1 can be generated. Both individual and merged aCCF V1.1 patterns were analysed and show the dominating effect of the contrail aCCF V1.1 in areas where contrails are forming. Further analysing the variability in aCCFs V1.1 reveals a clear seasonal cycle in NO_x and contrail aCCFs V1.1 and a strong variability with different synoptical weather situations and cruise altitudes.

3.2 Climate optimal trajectories

The aCCFs V1.1 information (which provides spatially and temporally resolved information on aviation induced climate effects) is handed over to aircraft trajectory planning processes. The aim is to optimize the associated climate effects of aircraft operations and assess the mitigation potential. Such trajectory optimization problem requires an expanded mathematical objective function, which contains both economic and climate-impact effects (the latter relying on aCCFs V1.1).

In FlyATM4E, we employ three different aircraft trajectory optimizers, namely:

1. ROOST (robust optimization of structured trajectories), a heuristic graph-based optimization method for the structured airspace [8, 9],
2. TOM (trajectory optimization module) [10], a direct optimal control approach for the free-route airspace, and
3. AirTraf [11], a submodel of the global chemistry-climate model EMAC [12], uses a genetic algorithm to calculate aircraft trajectories [13].

Within these three approaches, the cost optimal trajectories (in terms of fuel and time via cost index) are compared to alternative trajectories with a lower total climate effect. The total (both CO_2 and non-CO_2) climate effects of aviation emissions are quantified by means of aCCFs V1.1, which are mathematically included in the objective function.

3.2.1 Robust optimization of structured trajectories (ROOST)

ROOST is a fast graph-based optimization algorithm capable of determining robust aircraft trajectories in the structured airspace considering meteorological uncertainty, characterized by Ensemble Probabilistic Systems (EPS) forecast. The concept of robustness in this method is the determination of aircraft trajectory considering the performance of all possible realizations of meteorological variables provided within the EPS weather forecast. In other words, instead of planning a trajectory based on one forecast in a deterministic manner, the trajectory is optimized considering the overall performance obtained from ensemble forecasts. In this respect, from the operational point of view, the optimized trajectory is tracked as determined. The performance in terms of variables such as fuel burn, arrival time, and climate impact is affected by uncertainty resulting from uncertainty in the meteorological forecast.

3.2.2 Trajectory Optimization Module (TOM)

TOM employs a direct optimal control approach to calculate optimized aircraft trajectories for flight planning. It solves an unconstrained optimization problem, i.e., “free-flight” trajectories are obtained. Hence, it is well suited to determine improvement potentials for flight planning. TOM can apply arbitrary cost functionals and therefore determines, e.g., wind-optimal (i.e., minimum time track), DOC-optimal or environmentally optimal flight plans, whereas its particular strength is the calculation of climate-optimized trajectories, as successfully demonstrated in the project ATM4E [14]. In general, optimal control seeks for the temporal development of a control variable u(t), e.g., heading and throttle setting, that leads to a minimization of the specific cost functional, while certain dynamic constraints are applied that ensure the consideration of the aircraft’s flight mechanics. To determine robust aircraft trajectories, optimization runs are carried out, in a similar way as in ROOST, for every member of the ensemble forecast and analysed with respect to the variability in the results and achieved mitigation.

3.2.3 Trajectory optimization in a chemistry-climate model (EMAC/AirTraf)

AirTraf is implemented as a submodel in the modular global chemistry climate model EMAC. The modelling concept EMAC/AirTraf enables an optimization of aircraft trajectories while reflecting the variability of synoptic weather pattern in a continuous representation of the global atmosphere. To identify trajectories that largely reduce the climate impact with almost unchanged costs (“eco-efficient” trajectories) analysis is required. Numerical experiments with the modular global chemistry-climate model EMAC are performed using meteorological conditions based on reanalysis data integrated with the help of nudging of meteorological variables.

4 Recommendations

As already anticipated in Chapter 2, the recommendations we are providing are divided into two groups that coincide with the two solutions proposed in the FlyATM4E project (already described in Chapter 2), namely:

- ID Solution: SOL-FlyATM4E-01: Increased situational awareness on climate change effects relying on algorithmic climate change functions
- ID Solution: SOL-FlyATM4E-02: Identifying robust climate-optimized flight planning in trajectory-based operations

Recall that these two solutions are linked to:

- SOL-FlyATM4E-01 is linked to the algorithmic Climate Change Functions (aCCFs V1.1)
- SOL-FlyATM4E-02 is linked to the tools to calculate climate optimal trajectories

4.1 Recommendations on aCCFs V1.1

4.1.1 aCCFs V1.1 are prototype formulas

aCCFs V1.1 have been derived from numerical simulations on the North Atlantic Flight corridor region in winter and summer. Extensions to other geographical domains and weather patterns are needed. The development of the currently available aCCFs V1.1 relied on a comprehensive climate chemistry model for the North Atlantic flight corridor during the summer and winter months and the construction of a set of archetypical synoptic situations, to represent atmospheric variability in these two seasons: 5 weather patterns in winter, and 3 in summer. Hence, the aCCFs V1.1 currently available need to be seen as **prototypes,** and their applicability has the limited geographic and seasonal coverage **being representative of the North Atlantic flight corridor in the summer and winter seasons.**

4.1.2 Climate metrics

aCCFs V1.1 rely on **Average Temperature Response (ATR) as a climate metric**.

Nonetheless, there are other metrics to quantify the climate impact, e.g.:

- **Global warming potential**: One climate metric that allows comparing the climate impacts of all agents (i.e., greenhouse gases) is the global warming potential (GWP) [15,16]. GWP estimates how much energy (calculated using time-integrated RF) is absorbed for the emission of a trace gas compared to that of 1 kg carbon dioxide (CO_2) over a given period. Thus, the larger the GWP, the more a given gas warms the earth in relation to CO_2 over that period.

- **Global temperature change potential**: Unlike the GWP, estimating heat absorbed over a given period caused by a greenhouse gas emission, global temperature change potential (GTP) provides the temperature change at the end of the period. This metric adapts a linear system for modeling the global temperature response to aviation emissions and contrails. In this metric, similar to the GWP, the changes are estimated compared to CO_2.

- **Average temperature response**: Another metric that measures the climate impact in terms of temperature change is average temperature response (ATR) [17]. ATR is a derivative metric of GTP which combines the integrated temperature change for different emission scenarios and time horizons. As already anticipated, aCCFs V1.1 have been developed to quantify the climate impacts of each agent in terms of ATR.

- The climate impacts can also be quantified with different derivatives of GWP, GTP, and ATR, such as mean GTP (MGTP) and absolute GTP (AGTP) [18].

The units and dependencies, and validity ranges for the individual aCCFs V1.1 can be checked in Table 3. For the merged aCCFs V1.1 we use K/Kg(fuel) as units.

Function	Unit	Dependency	Range
$aCCF_{O_3}$	K/Kg(NO_2)	Geopotential, temperature	$aCCF_{O_3} \geq 0$ (warming effect)
$aCCF_{CH_4}$	K/Kg(NO_2)	Geopotential, solar radiation	$aCCF_{CH_4} \leq 0$ (cooling effect)
$aCCF_{H_2O}$	K/Kg(fuel)	Potential vorticity unit	$aCCF_{H_2O} \geq 0$ (warming effect)
$aCCF_{dCont.}$	K/Km(contrail)	Outgoing longwave radiation, relative humidity, temperature	$-10^{-10} \leq aCCF_{dCont.} \leq 10^{10}$ (cooling and warming effects)
$aCCF_{nCont.}$	K/Km(contrail)	Temperature, relative humidity	$aCCF_{nCont.} \geq 0$ (warming effect)

Table 3: Dependencies and validity ranges for the individual aCCFs V1.1.

4.1.3 Emission scenario and time horizon

All the metrics described above in Section 4.1.2, including ATR; depend on both the emission scenario and time horizons. Thus, aCCFs V1.1 also depend on them.

The emission scenario can be Pulse (P-), Future (F-), and Sustained (S-): The sustained emission scenario assumes constant emission of gas for the considered period, while pulse emission regards the emission of gas for one year and zero thereafter. The Future scenario is similar to the sustained, though it contains a growth rate to represent the expected growth of traffic.

As for the time horizon, IPCC established 20 years, 50 years, and 100 years.

As an example, the pulse emission scenario for the time horizon of 20 years can be a suitable option for representing the short-term climate impacts. In contrast, 50- and 100-years' time horizons can be used to capture medium-range and long-term climate impacts, respectively.

4.1.4 Efficacy

The aCCFs V1.1 are further scaled by using efficacy parameters to account for the effectiveness of non-CO_2 forcing agents in changing global mean temperature compared to that of CO_2.

4.1.5 Selection of aircraft/engine types

The selection of aircraft/engine type is an important factor in determining reliable merged aCCFs V1.1. By selecting the aircraft type, the altitude dependent NO_x emission indices and flown distances per kg burnt fuel are calculated.

4.1.6 Uncertainties

Readers should understand that there are large uncertainties associated with the climate impact of aviation. The assessment of those uncertainties has been one of the tasks within WP1 activities.

Overall, we distinguish between:

- uncertainties related to meteorological forecast and background conditions,
- uncertainties related to the calculation of the overall climate impact (e.g., caused by radiative transfer calculation, by the representation of atmospheric processes, or by the used physical climate metric).

Moreover, due to the statistically based approach that was used to develop the aCCFs V1.1:

- additional uncertainties have been introduced by these algorithms, as well as
- uncertainties related to aircraft-engine emission calculations exist.

For each of the identified sources of uncertainty, one needs to quantify the associated range of uncertainty with adequate methods, e.g., with the help of results from sensitivity studies, expert guess, statistical methods, or comparison with measurements. The resulting uncertainty intervals can be described either by continuous values over an interval (between lower and higher range values) with equal, normal, or lognormal distribution or by a set of discrete values, e.g., when using distinct physical climate metrics with various time horizons.

Table 4: aCCFs V1.1 sources of uncertainty (Source - D2.1)

Source of uncertainty	Origin of uncertainty
Meteorological Forecast	
Quality of meteorological forecast	Weather forecast data contains deviation from real world situations measured by the quality of the forecast and its skill.
Calculation of climate effects and impact	
Representation of atmospheric processes	Chemistry scheme (e.g., O_3 production), cloud parametrization, horizontal and vertical resolution
Change in GHG concentration/contrails	Background (e.g., temperature bias in EMAC)
Radiative forcing	Estimate of RF depends on radiative transfer calculations.
Temperature calculation	Temperature change calculation depends on assumptions on efficacy and temporal evolution of emissions/RF
Physical climate metric	Climate Metric has to be appropriate for the targeted climate objective but still allows some variations with respect to assumptions on background emission scenario/model, emissions evolution (pulse/ sustained/future scenario), climate indicator, such as averaged temperature response, and time horizon (e.g., ATR20)
Development of Algorithms to represent CCFs (aCCFs V1.1)	
Development of algorithms in aCCFs V1.1	Due to the fitting of CCF data to meteorology at the location of emission, imperfections in the relationships are identified.
Emission calculation in emission model	
Emission index/conversion merged aCCFs V1.1	Emission model

The incorporation of meteorological uncertainties into aCCFs V1.1 can be done using Ensemble Probabilistic Systems (EPS), which already provide a description of the uncertainty expected in the meteorological variables. By evaluating the aCCFs V1.1 in the member of the EPS forecast, one gets an ensemble of aCCFs V1.1 (representing the expected climate impact in a set of scenarios).

4.1.7 aCCFs V1.1 implemented in a Python lib

aCCFs V1.1 have been implemented on an open-source Python Library coined CLIMaCCF. It allows to create the merged non-CO_2 aCCFs V1.1 for height dependent emission amounts for three different aggregated aircraft-engine types. Moreover, user selection of different physical climate metrics (i.e. average temperature response for future emission scenario or pulse emission over future time horizons of 20, 50, 100 years) is possible.

Overall, we provide an efficient meteorological (MET) service to inform on the climate effect of flight operations comprising CO_2 and non-CO_2 effects. In our overall concept, we establish it as an interface between climate science and ATM, with the help of aCCF and suggest them as a MET enabler:

- aCCFs V1.1 are algorithms that use MET data for the calculation; thus, they could also be directly implemented in numerical weather prediction models as advanced MET info for flight planning.
- Efficient implementation of aCCFs V1.1 as a MET enabler should rely on a direct link to the numerical weather prediction data (MET interface).

We recommend the usage of this library, which we ambition to set as a standard and continue to develop in the near future.

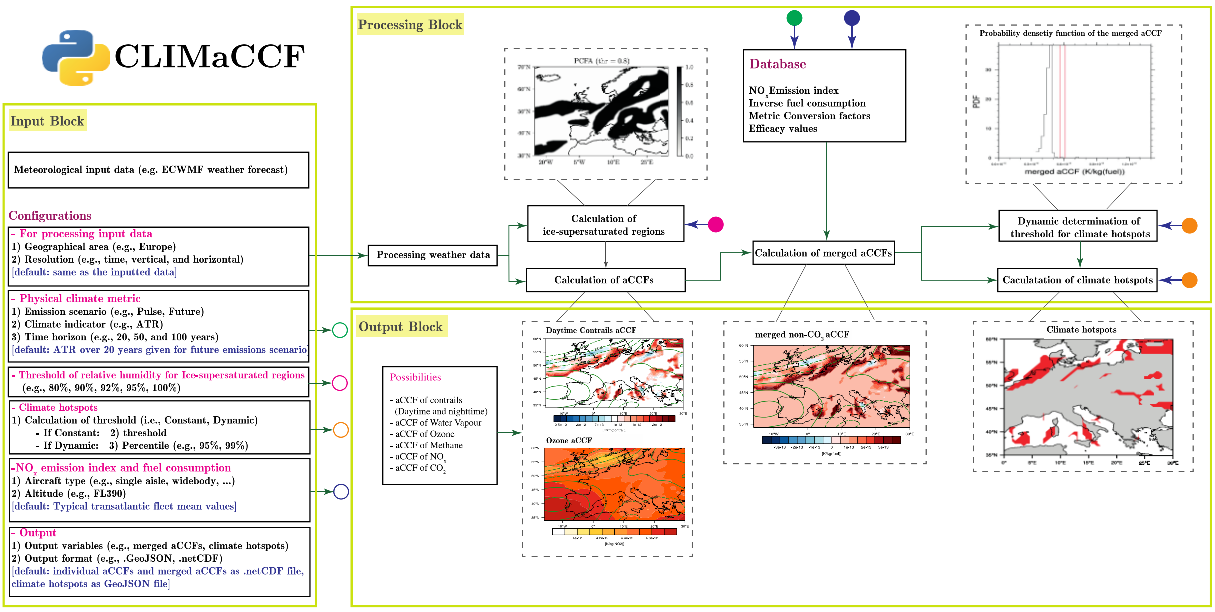

Table 5: Diagrammatic scheme of the **CLIMaCCF** Python Library (source D2.1 [19])

4.2 Recommendations on climate optimized aircraft trajectories

The reduction of aviation's contribution to climate change relies on the continuous development of more efficient aircraft, the use of alternative fuels or novel propulsion (i.e., mainly reducing CO_2 effects (it can also be beneficial to reduce emissions such as NO_x and soot)), and the avoidance of climate-sensitive regions at an operation level (i.e., reducing non-CO_2 effects).

While the use of alternative propulsion, jet fuels, and the continuous improvement of aircraft efficiency present themselves as necessary developments towards the achievement of sustainable aviation, these solutions lack immediacy. Aside from large implementation time scales, they require substantial investment in research, production, testing, and certification. Consequently, employing alternative solutions that can bridge this time horizon is crucial. Here is where climate-optimized aircraft operations can make a difference.

In contrast to CO_2 emissions, non-CO_2 effects highly depend on the geographical location, altitude, time of day, and current spatial and synoptic conditions. By considering the dependencies of non-CO_2 effects in the aircraft trajectory planning, operational mitigation towards climate optimized aircraft trajectories is possible. Thus, to consider the climate impact of aviation in the aircraft path planning, information on the climate-sensitive regions, i.e., regions where those non-CO_2 effects are significantly enhanced, needs to be available (e.g., via aCCFs V1.1). Moreover, aircraft dynamical models and the optimization approach are crucial factors affecting the performance and mitigation potential of the optimized trajectories.

Numerous studies on climate-optimized trajectories exist. During FlyATM4E, we conducted a comprehensive survey on operational strategies proposed in the literature to mitigate aviation's climate impact [20]. These approaches are classified based on their methodology, climate metrics, reliability, and applicability.

4.2.1 Operational Mitigation Strategies

From the operational point of view, the mitigation of aviation climate impact is achieved by modifying aircraft manoeuvres to avoid areas where those non-CO_2 effects are significantly enhanced, called climate-sensitive regions (CSR). The manoeuvres can be the change of departure time, cruise altitude, lateral path, speed profile, and combinations of them. Therefore, to select a proper climate-aware trajectory for aircraft, information regarding climate-sensitive regions needs to be available, allowing to evaluate trajectories in the sense of contribution to climate impact. Besides, the approach to determining eco-efficient trajectory based on the considered metric plays an important role in the net mitigation potential. Thus, to mitigate the climate impact of aviation using operational strategies, the following two questions may be considered:

1. **How to integrate climate effects in aircraft trajectory planning?**
2. **Which methods to generate optimized trajectories considering an objective function expanded by climate effects?**

To answer question number 1, **there is a need for a procedure that provides an enabler (as a MET service), informing on spatially and temporally resolved climate effects of aviation emissions by relying on numerical weather prediction data. The aCCFs V1.1 incorporated in the** CLIMaCCF **Library can play this Met Service role**, as already discussed in Section 4.1.

EUROPEAN PARTNERSHIP

Co-funded by the European Union

When it comes to the question number 2, we first should say that the operational mitigation strategies for aviation's climate impact can be classified into two categories: non-trajectory optimization (NTO) (or, in some cases, simulation-based) strategies and trajectory optimization (TO) techniques (see Figure 3). Within NTO methods, after analysing the properties of the climate impact of non-CO_2 emissions, the route, time, or altitude of flights is slightly changed, and the mitigation potential is explored (through simulating aircraft performance with trajectory predictors). As for trajectory optimization, optimization techniques are employed to determine the aircraft trajectory such that a cost function containing some user-defined objectives (i.e., climate impact in this case) gets minimized. In fact, such strategies aim at finding the best possible and admissible trajectory among a wide range of options that meets some user-defined objectives. In other words, for instance, within simulation-based strategies, we might mitigate the climate impact of aviation by reducing 2000 ft of the flight level, but it may not be the best mitigation option. This is where optimal trajectories are more beneficial because, in such strategies, the optimizer seeks over possible trajectories by means of the employed optimization approach to select an optimal trajectory in the sense of considered objectives.

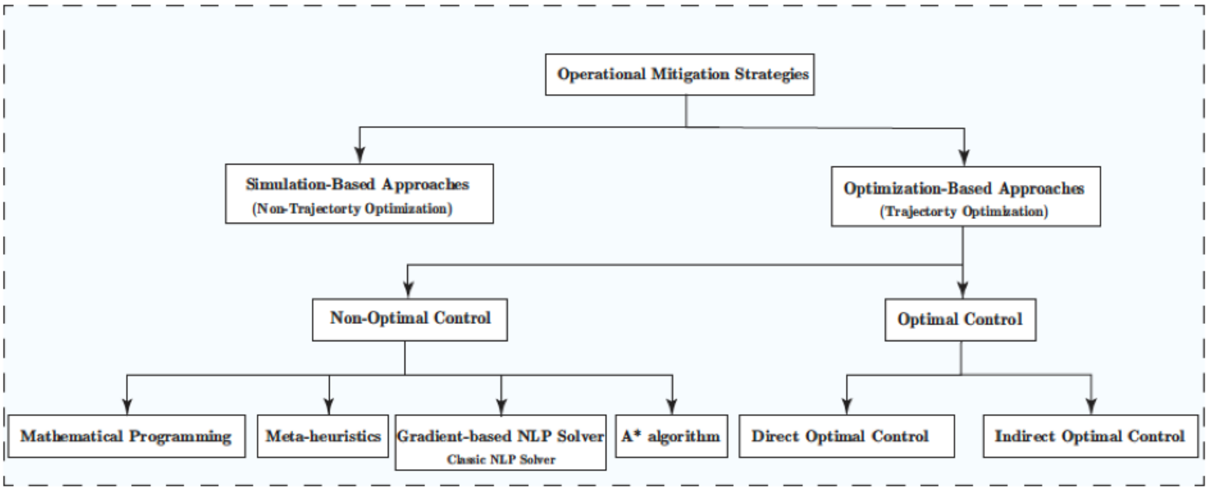

Figure 3: Operational mitigation strategies for climate-aware trajectory planning.

A second recommendation when looking for operational climate mitigation strategies is to look for optimization-based approaches. In FlyATM4E we have explored some of them, though each with their pros and cons, all of them showing maturity and robustness in tackling the problem.

4.2.2 Trajectory optimization

In general, optimization is the process of determining the best element among a set of feasible and available alternatives. Trajectory optimization seeks the best possible trajectory of a dynamical system (e.g., aircraft dynamics in our case) in a finite dimensional manifold with respect to some user-defined objectives as well as constraints and boundary conditions. There exist various classifications of trajectory optimization techniques. We classify those methods focused mainly on mitigating aviation's climate impacts in two categories: optimal control and non-optimal control approaches (see also Figure 3):

- The optimal control is known as one of the most reliable dynamic optimization techniques since it works in continuous time, considers the system's dynamical behaviour, can provide analytic solutions to some types of problems, and adopts numerical methods. Within optimal flight planning, the aim is to determine feasible trajectories for aircraft considering practical constraints and the objectives specified by the flight planner.

- Non-optimal control methods try to solve dynamical optimization problems in a more simplified manner. Some of the simplifications commonly assumed within these techniques are disregarding aircraft dynamics and constraints or considering them in a streamlined way, such as linearized ones. These methods aim to provide fast and, to some extent, reliable solutions, even if they do not result in the best trajectories. To tackle such optimization problems, various approaches, such as geometric methods, path-planning algorithms (e.g., well-known A* and D* algorithm), combinatorial optimization, and meta-heuristics are usually employed. Within these methods, the optimization problem is formulated normally without considering aircraft dynamics or considering it partially to predict the performance of trajectories such as speed, fuel burn, emission indices, and climate impacts. Then, by making use of optimization techniques, the formulated problem is solved. For instance, if the trajectory of an aircraft is given as a sequence of discrete or/and continuous variables, and its performance can be quickly predicted, a suitable choice is a meta-heuristic approach, applying combinations of randomized heuristic procedures iteratively to enhance the candidate solution. Simulated annealing, genetic algorithms, variable neighbourhood search, and particle swarm optimization are some algorithms that are used as meta-heuristics solvers.

In FlyATM4E we have explored both optimal control (TOM) and Non-Optimal Control (ROOST and EMAC/AirTraf) methods. We will expose advantages and disadvantages in the sequel (see Section 4.2.2.1). Before it, we should also discuss something that is common to any type of trajectory optimization approach: **the objective function**.

To optimize aircraft trajectories, consideration of operating cost is a crucial aspect that needs to be addressed. This is because today's aircraft operations are designed and implemented based on minimum economical cost. There exist different definitions for cost in the literature, such as simple operating cost (SOC), presenting cost with linear relation to the flight time and fuel consumption, or via the so-called cash operating cost (COC), as a comprehensive economic criterion that considers different aspects of cost such as flight crew, cabin crew, landing fee, fuel, insurance, and maintenance for both airframe and engines. In the simplest cases, only flight time or fuel burn is considered as conflicting objectives to the climate impacts (which, again, can be incorporated using aCCFs V1.1).

4.2.2.1 Benchmarking of optimization methods used in FlyATM4E

Now we describe the advantages and disadvantages of the three methods (ROOST, TOM, EMAC/AirTraf) used to find climate optimal trajectories. Depending on the problem to be solved, one may be more suitable than others. Thus, readers can take them as recommendations.

	ROOST	TOM	EMAC/AirTraf
Method	Meta-Heuristic (GPU parallel)	Optimal Control (Direct Collocation)	Meta-Heuristic (Genetic Algorithm)
Convergence	Almost always with no-guarantee of optimality	Guarantee of local Optima. Convergence heavily depends on the initial guess.	Almost always with no-guarantee of optimality
CPU time	Very fast (~1-10 sec)	Medium (~1-5min)	fast (~1 min)
Objective Function	Cost and Climate	Cost and Climate	Cost and Climate

Aircraft Dynamics	Yes (including climb, curise, descent)	Yes (including climb, curise, descent)	Yes (though limited to cruise performances)
Airspace	Structured airspace (vertical and horizontal)	Free routing airspace	Free routing airspace
Uncertainties	Ensemble based (Robust formulation)	Scenario Based	-

Table 6: Benchmarking of tools to calculate climate optimal trajectories

All in all, the optimizers employed within FlyATM4E provide a complete package for analysing different aspects of climate-aware trajectory planning. In the following, one can find a summary of the features of the optimization methods:

- All the methodologies can efficiently mitigate the climate effects of non-CO_2 emissions with trajectory optimization.
- TOM and AirTraf are efficient for determining climate optimized trajectory for the free-route airspace, while ROOST enables exploring the mitigation potential within the currently structured airspace.
- AirTraf as a submodel of the EMAC model, is suitable for analysing mitigation potentials for long-term simulation (e.g., whole 2018). It employs a Genetic algorithm for finding climate optimized trajectories.
- TOM is an optimal control-based method (i.e., employs direct optimal control approach) capable of determining at least local optimal solutions (highly depends on the initial condition). Within FlyATM4E, TOM employs EPS weather forecast to analyse the robustness via scenario-based optimization. In other words, it optimizes the aircraft trajectory N (i.e., number of ensemble members) times in a deterministic manner, each associated with one ensemble member. Then, through some post-processing, robustness is analysed.
- ROOST solves the robust aircraft trajectory optimization problem directly by employing EPS weather forecast with a heuristic graph-based algorithm.
- TOM and AirTraf are CPU-based solvers. In contrast, ROOST uses GPU to parallel the computations, generating optimized aircraft trajectories faster.

Interested readers are referred to the deliverables of the associated work packages (WP3: AirTraf, WP2: TOM and ROOST) for detailed description.

5 Discussion and Challenges

Based on the reviewed studies, we present some challenges and scientific gaps that are crucial to be addressed in future studies in this field. In the following, the challenges will be presented in terms of required items to formulate aircraft trajectory optimization problems considering climate impact, i.e., objective function, aircraft dynamics, and solution approaches. The challenges that will be discussed regarding the objective function are referred mainly to how to model climate metrics and how to consider and quantify the associated uncertainties in the modelled metrics and the inputted meteorological variables.

5.1 Objective Function: Physical Understanding and Predictability of Aviation Climate Impacts

The determination of climate optimal trajectories relies on aircraft performance (captured by dynamic model), physical and operational constraints, and the climate impacts included in the objective function. In this respect, the actual mitigation potential relies highly on the dependability of the quantified climate impacts (from the considered metric). As it has been identified and reported during FlyATM4E project, there are different types of uncertainties to understand and quantify the climate impacts associated with aviation, such as uncertainties from climate science, uncertainties in calculating engine emissions, and uncertainties in the weather forecast. Standard weather forecasts are associated with uncertainties due to the imperfect understanding of the atmosphere, modelling errors of physical parameterization, and nonlinear, sometimes chaotic, dynamics. Uncertainties from climate science are mainly related to the current level of scientific understanding, which is still not mature. Representation of atmospheric processes, estimation of RF, and selection of physical climate metrics are the main uncertainties related to climate science. To have a reliable estimation of mitigation potential within operational strategies, these sources of uncertainty need to be further investigated and quantified. The sources of uncertainty, if not considered in the aircraft trajectory planning, will lead to unreliable solutions.

Some specific directions of research aligned with these topics include to:

- Improve forecast quality of dedicated meteorological fields, e.g., representation of Ice Super Saturation Regions (ISSR), and humidity in NWP models. Such developments might consider the usage of two-moment schemes in cloud representation.
- Explore implementation of intermediate MET products, which are expected to be similar in their nature to full aCCFs V1.1, e.g., information on those regions where contrails could form, or where persistent contrails could form, which can already today be retrieved from the NWP forecast model data. Such trials allow the ATM tools to evaluate how to best integrate such additional information in their overall planning process, and to explore the feasibility of considering such additional information targeting on sustainable aviation.
- Evaluate how to consider and best integrate uncertainties which prevail on the non-CO_2 aviation effects in decision making, to identify robust alternative eco-efficient trajectories. The robustness is currently explored, and the aim is to develop and apply R-aCCFs within FlyATM4E

- Identify favourable meteorological conditions, i.e., with a high mitigation potential, or mitigation efficiency/gain. These weather situations (patterns) will be candidates for subsequent verification exercises. An initial step is currently performed in FlyATM4E in a systematic approach using an Earth-system chemistry-climate model.

5.2 Aircraft Dynamics and Constraints: New Models for H_2 and Hybrid Vehicles

While the current and short-term aviation propulsion systems are mainly based on kerosene-driven jet engines, new entrants are expected in the medium-term. This is the case of electric propulsion, H_2 driven propulsion, hybrid artifacts that may combine electric/H_2 driven engines with kerosene jet, and the use of sustainable aviation fuels. In all cases, additional studies of emissions and their impact would be needed, together with new dynamical models to capture adequately the dynamical behaviour of such systems.

One of particular importance is H_2-powered aircraft. According to the EU's Horizon Europe and the EU's Clean Aviation funding programs, hydrogen propelled aircraft are thought to play a leading role in what concerns environmentally friendly aeronautics. Hydrogen can potentially overcome issues related to the low capacity (mainly specific energy) of current and forthcoming battery technology. There are two main ways to use hydrogen as an energy provider; the first one leverages on fuel cells, devices that use the chemical energy of hydrogen (or other fuels) to cleanly and efficiently produce electricity; the second strategy would use hydrogen as propellant directly in the combustion chamber of the modified engines. In both cases, hydrogen needs to be stored in tanks. Even though hydrogen-propelled aircraft are referred to as zero-carbon aircraft, this does not mean their environmental impact is negligible: Their contribution to non-CO_2 emissions, especially when it comes to water vapor and the potential formation of linear and persistent contrails, can play an equally or even larger noxious role to the environment when compared to kerosene-engine exhausts.

5.3 Solution Approach: Development of Efficient Deterministic/Stochastic Dynamical Optimization Solvers

The optimal control is known as one of the most efficient techniques to solve dynamic optimization problems, including aircraft trajectory optimization. However, there exist some drawbacks with the numerical optimal control techniques in this type of problems. These issues are mainly related to the computational time and local optimality with the direct method, difficulty in deriving necessary conditions of optimally for complex problems and solving a 2-Point Boundary Value Problem with the indirect method, and curse of dimensionality with Dynamic Programming. In addition, to have reliable aircraft trajectories, the consideration of possible sources of uncertainty is necessary. After introducing suitable quantification of uncertainties (e.g., EPS forecast for meteorological uncertainty), a stochastic dynamical optimization problem needs to be solved. Considering uncertainties in the dynamical optimization problem is challenging. One of the main issues besides suitable problem formulation is the computational time. For instance, within the ensemble weather forecast, instead of considering one realization of weather variables, the optimization is to consider N probable forecasts. In conclusion, aircraft trajectories are to be generated with acceptable accuracy in a computationally fast manner and robust to different sources of uncertainty. Thus, developing robust dynamical optimization solvers (mainly optimal control approach) that can satisfy these objectives is beneficial.

EUROPEAN PARTNERSHIP

Co-funded by the European Union

5.4 Network-Scale Climate Optimal Trajectories

The operational mitigation strategies using aircraft trajectory techniques has been performed on single flights. Though some studies have run simulations with hundreds or thousands of flights, each of those flights has been tackled independently, without the consideration of interactions and network effects. Thus, the analysis of the climatic impact at the network scale is simply non-existent.

Climatic effects have not been considered as a factor to limit the capacity of the ATM system (e.g., as it is done in some European cities to limit road transportation), nor incorporated in any of the network-wide modelling and solution approaches presented in the literature. Indeed, these approaches require considering large-scale airspaces and thousands of flights, including their interactions (propagation of uncertainties at the network level and models to consider resilience). In such scenarios, the problem becomes cumbersome and very difficult to solve using classical optimization techniques.

Identifying climatic hotspots and incorporating them into network-wide models and solution approaches for problems related to, e.g., demand and capacity balancing, network complexity, and resiliency, are open scientific gaps.

EUROPEAN PARTNERSHIP

Co-funded by the European Union

6 Conclusions

To conclude, we summarize the main elements of the deliverable, highlighting the main recommendations and the future directions of research. Further insight and the rationale can be found in the body of the deliverable.

6.1 Summary of recommendations

6.1.1 Recommendations on aCCFs

- aCCFs V1.1 have been implemented on an **open-source Python Library coined CLIMaCCF**. It allows to create the merged non-CO_2 aCCFs V1.1 for height dependent emission amounts for three different aggregated aircraft-engine types. **Overall, we provide an efficient meteorological (MET) service to inform on the climate effect of flight operations comprising CO_2 and non-CO_2 effects. We recommend the usage of this library, which we ambition to set as a standard and continue to develop in the near future**

- The aCCFs V1.1 currently available need to be seen as **prototypes,** and their applicability has the limited geographic and seasonal coverage **being representative of the North Atlantic flight corridor in the summer and winter seasons**

- aCCFs V1.1 rely on **Average Temperature Response (ATR) as a climate metric**.

- The climate **metrics depend on both the emission scenario and time horizons**

    - **The emission scenario can be Pulse (P-), Future (F-), and Sustained (S-):** The sustained emission scenario assumes constant emission of gas for the considered period, while pulse emission regards the emission of gas for one year and zero thereafter. The Future scenario is similar to the sustained, though it contains a growth rate to represent the expected growth of traffic.

    - As for the **time horizon**, IPCC **established 20 years, 50 years, and 100 years**.

    - The selection of the emission scenario and the time horizon is up to the user. As an example, **the pulse emission scenario for the time horizon of 20 years can be a suitable option for representing the short-term climate impacts**. In contrast, **50- and 100-years' time horizons can be used to capture medium-range and long-term climate impacts**, respectively.

- The aCCFs V1.1 are further scaled by using efficacy parameters to account for the effectiveness of non-CO_2 forcing agents in changing global mean temperature compared to that of CO_2.

- The **selection of aircraft/engine type** is an important factor in determining reliable merged aCCFs V1.1. By selecting the aircraft type, the altitude dependent NO_x emission indices and flown distances per kg burnt fuel are calculated.

- Readers should understand that there are **large uncertainties** associated with the climate impact of aviation. Whereas most of them should be still subject to future research (see Section 6.2), the incorporation of meteorological uncertainties into aCCFs V1.1 can be done using Ensemble Probabilistic Systems (EPS), which already provide a description of the uncertainty expected in the meteorological variables. By evaluating the aCCFs V1.1 in the member of the EPS forecast, one gets an ensemble of aCCFs V1.1 (representing the expected climate impact in a set of scenarios).

6.1.2 Recommendations on climate optimized aircraft trajectories

- Numerous studies on climate-optimized trajectories exist. During FlyATM4E, we conducted a comprehensive survey on operational strategies proposed in the literature to mitigate aviation's climate impact [20]. We recommend interested readers to use it as an up to date, thorough reference on the matter.

- To mitigate the climate impact of aviation using operational strategies, the following two questions may be considered:

  - **How to integrate climate effects in aircraft trajectory planning?** To answer this question, **there is a need for a procedure that provides an enabler (as a MET service),** informing on spatially and temporally resolved climate effects of aviation emissions by relying on numerical weather prediction data. **The aCCFs V1.1 incorporated in the** CLIMaCCF **Library can play this Met Service role** and we recommend its usage**.**
  - **Which methods to generate optimized trajectories considering an objective function expanded by climate effects?** In FlyATM4E we have explored different methods (related to ROOST, TOM, and EMAC-AIrTraf), though each with their pros and cons, all of them showing maturity and robustness in tackling the problem:

- All the methodologies developed to obtain climate optimal trajectories (ROOST, TOM, and EMAC-AIrTraf) can efficiently mitigate the climate effects of non-CO_2 emissions with trajectory optimization, however they exhibit different features that may recommend the usage of one over the other depending on the type of analysis one would like to conduct:

  - TOM and AirTraf are efficient for determining climate optimized trajectory for the free-route airspace, while ROOST enables exploring the mitigation potential within the currently structured airspace.
  - AirTraf as a submodel of the EMAC model, is suitable for analysing mitigation potentials for long-term simulation (e.g., whole 2018). It employs a Genetic algorithm for finding climate optimized trajectories.
  - TOM is an optimal control-based method (i.e., employs direct optimal control approach) capable of determining at least local optimal solutions (highly depends on the initial condition). Within FlyATM4E, TOM employs EPS weather forecast to analyse the robustness via scenario-based optimization. In other words, it optimizes the aircraft trajectory N (i.e., number of ensemble members) times in a deterministic manner, each associated with one ensemble member. Then, through some post-processing, robustness is analysed.
  - ROOST solves the robust aircraft trajectory optimization problem directly by employing EPS weather forecast with a heuristic graph-based algorithm.
  - TOM and AirTraf are CPU-based solvers. In contrast, ROOST uses GPU to parallel the computations, generating optimized aircraft trajectories faster

6.2 Summary of future research directions

6.2.1 Physical Understanding and Predictability of Aviation Climate Impacts

Some specific directions of research aligned with these topics include to:

- **Improve forecast quality of dedicated meteorological fields, e.g., representation of Ice Super Saturation Regions (ISSR), and humidity in NWP models**. Such developments might consider the usage of two-moment schemes in cloud representation.
- Explore **implementation of intermediate MET products**, which are expected to be similar in their nature to full aCCFs V1.1, e.g., information on those regions where contrails could form, or where persistent contrails could form, which can already today be retrieved from the NWP forecast model data. Such trials allow the ATM tools to evaluate how to best integrate such additional information in their overall planning process, and to explore the feasibility of considering such additional information targeting on sustainable aviation.
- Evaluate how to consider and best **integrate uncertainties** (e.g., uncertainties related to the calculation of the overall climate impact, uncertainties related to meteorological forecast and background condition, uncertainties related to aircraft-engine emission calculations, uncertainties introduced by the hypotheses assumed in the calculation of aCCFs), which prevail on the non-CO_2 aviation effects in decision making, to identify robust alternative eco-efficient trajectories.
- **Expand the aCCFs V1.1**, which is representative of the North Atlantic flight corridor in the summer and winter seasons, **to other geographical domains and spring/autumn seasons**.
- **Identify favourable meteorological conditions, i.e., with a high mitigation potential, or mitigation efficiency/gain**. These weather situations (patterns) will be candidates for subsequent verification exercises. An initial step is currently performed in FlyATM4E in a systematic approach using an Earth-system chemistry-climate model.

6.2.2 New Models for H_2 and Hybrid Vehicles

While the current and short-term aviation propulsion systems are mainly based on kerosene-driven jet engines, new entrants are expected in the medium-term. This is the case of electric propulsion, **H_2 driven propulsion, hybrid artifacts that may combine electric/H_2 driven engines with kerosene jet, and the use of sustainable aviation fuels**. In all cases, **additional studies of emissions and their impact would be needed, together with new dynamical models to capture adequately the dynamical behaviour of such systems**. One of particular importance is H_2-powered aircraft. According to the EU's Horizon Europe and the EU's Clean Aviation funding programs, hydrogen propelled aircraft are thought to play a leading role in what concerns environmentally friendly aeronautics.

6.2.3 Development of Efficient Deterministic/Stochastic Dynamical Optimization Solvers

Aircraft trajectories are to be generated with acceptable accuracy in a computationally fast manner and robust to different sources of uncertainty. Thus, **developing robust dynamical optimization solvers (mainly optimal control approach)** that can satisfy these objectives is beneficial.

6.2.4 Network-Scale Climate Optimal Trajectories

The operational mitigation strategies using aircraft trajectory techniques has been performed on single flights. Though some studies have run simulations with hundreds or thousands of flights, each of those flights has been tackled independently, without the consideration of interactions and network effects. I**dentifying climatic hotspots and incorporating them into network-wide models and solution approaches for problems related to, e.g., demand and capacity balancing, network complexity, and resiliency, are open scientific gaps.**

7 References

[1] FlyATM4E Deliverable D4.1, 2022: Data Management Plan (DMP)

[2] FlyATM4E Deliverable D4.2, 2022: Organisation of a Stakeholder Webinar for dissemination of final FlyATM4E results.

[3] FlyATM4E Deliverable D4.4, 2022: Report on robust and climate impact reducing ATM operations including an overall environmental evaluation and implementation analysis from a hindcast analysis

[4] FlyATM4E Deliverable D1.2, 2022: Report on expanded algorithmic climate-change functions including robustness and eco-efficiency aspects

[5] FlyATM4E Deliverable D2.2, 2022: Report on results and assessments of the robustness of eco-efficient trajectories.

[6] FlyATM4E Deliverable D3.2, 2022: Report on final results on eco-efficient trajectories

[7] FlyATM4E Deliverable D5.3, 2022: Final Project Report

[8] González-Arribas, D., Jardines, A., Soler, M., García-Heras, J., & Andrés-Enderiz, E., . Probabilistic 4D Flight Planning in Structured Airspaces through Parallelized Simulation on GPUs. International Conference for Research in Air Transportation (ICRAT) 2020

[9] Simorgh, A. Soler, M., González-Arribas, D., Matthes, S., Grewe, V., Dietmüller, S., ... & Meuser, M. M. (2022). Robust 4D path planning in structured airspace for the benefit of environment using parallelized simulation on GPUs . Geoscientific Model Development (In preparation).

[10] Lührs, B.; Niklaß, M.; Frömming, C.; Grewe, V.; Gollnick, V.: Cost-Benefit Assessment of 2D and 3D Climate and Weather Optimized Trajectories. 16th AIAA Aviation Technology, Integration, and Operations Conference (ATIO), 13.-17. June 2016, Washington. DOI: 10.2514/6.2016-3758

[11] Yamashita, H., Yin, F., Grewe, V., Jöckel, P., Matthes, S., Kern, B., Dahlmann, K., and Frömming, C., 2021: Analysis of aircraft routing strategies for North Atlantic flights by using Airtraf 2.0, Aerospace,8(2), 1–19. doi:10.3390/aerospace8020033.

[12] Jöckel, P. et al., 2010: Development cycle 2 of the Modular Earth Submodel System (MESSy2). Geoscientific Model Development, 3 (2), 717–752. doi: 10.5194/gmd-3-717-2010.

[13] Yamashita, H.; Yin, F.; Grewe, V.; Jöckel, P.; Matthes, S.; Kern, B.; Dahlmann, K.; and Frömming, C. Newly developed aircraft routing options for air traffic simulation in the chemistry–climate model EMAC 2.53: AirTraf 2.0, *Geosci. Model Dev*. **2020**, *13*, 4869–4890, doi:10.5194/gmd-13-4869-2020.

[14] Lührs, Benjamin und Linke, Florian und Matthes, Sigrun und Grewe, Volker und Yin, Feijia (2021) Climate Impact Mitigation Potential of European Air Traffic in a Weather Situation with Strong Contrail Formation. Aerospace, 8 (50). Multidisciplinary Digital Publishing Institute (MDPI)

[15] Fuglestvedt, J.S.; Shine, K.P.; Berntsen, T.; Cook, J.; Lee, D.; Stenke, A.; Skeie, R.B.; Velders, G.; Waitz, I. Transport impacts on atmosphere and climate: Metrics. Atmos. Environ. 2010, 44, 4648–4677. [CrossRef]

[16] Grewe, V.; Frömming, C.; Matthes, S.; Brinkop, S.; Ponater, M.; Dietmüller, S.; Jöckel, P.; Garny, H.; Tsati, E.; Dahlmann, K.; et al. Aircraft routing with minimal climate impact: The REACT4C climate cost function modelling approach (V1. 0). Geosci. Model Dev. 2014, 7, 175–201.

[17] Dallara, E.S.; Kroo, I.M.; Waitz, I.A. Metric for comparing lifetime average climate impact of aircraft. AIAA J. 2011, 49, 1600–1613.

[18] Lee, D.; Arrowsmith, S.; Skowron, A.; Owen, B.; Sausen, R.; Boucher, O.; Faber, J.; Marianne, L.; Fuglestvedt, J.; van Wijngaarden, L. Updated Analysis of the Non-CO2 Climate Impacts of Aviation and Potential Policy Measures Pursuant to EU Emissions Trading System Directive Article 30(4). 2020. Available online: https://www.easa.europa.eu/document-library/researchreports/report-commission-european-parliament-and-council

[19] FlyATM4E Deliverable D2.1, 2022: Report on methodology to include uncertainties and robustness metrics in trajectory optimisation and MET data requirements

[20] Simorgh, Abolfazl*, Manuel Soler, Daniel González-Arribas, Sigrun Matthes, Volker Grewe, Simone Dietmüller, Sabine Baumann, Hiroshi Yamashita, Feijia Yin, Federica Castino, Florian Linke, Benjamin Lührs, Maximilian Meuser. A Comprehensive Survey on Recent Climate Optimal Aircraft Trajectory Planning. *Aerospace* 2022, *9*(3), 146; https://doi.org/10.3390/aerospace9030146