EXPLORATORY RESEARCH

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Report on robust and climate impact reducing ATM operations including an overall environmental evaluation and implementation analysis from a hindcast analysis

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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

The goal of this deliverable is to promote FlyATM4E project by analysing the main results on robust and climate optimal trajectories in ATM operations including an overall environmental evaluation and implementation analysis.

We first describe the experimental plan, including the research hypotheses and questions that were initially formulated. We then describe the 4 experiments conducted to assess the hypotheses and answer the questions. The main results are presented and discussed.

We conclude that:

- **Ensemble data** from probabilistic weather forecast allows identifying the robustness of mitigation potential of alternative trajectory solutions.
- „Cherry-picking“ (also known as "**eco-efficient**") solutions exist and have been systematically identified for a subset of European flights using a newly implemented decision-making approach.
- "**Win-Win**" solutions exist and have been systematically identified. There is room for improvement in the European ATS route network to exploit the full potential of climate-optimised flight planning (unconstrained free-flight vs. constrained graph-based).
- The **climate impact mitigation potential** of climate-optimised flight planning in Europe is rather large (though with uncertainties) and at a relatively low cost. Results are obtained using three different trajectory optimizers (ROOST, TOM, EMAC/Air-Traf) and are consistent.

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1 Introduction

The goal of this deliverable is to promote FlyATM4E project by analysing the main results on robust and climate optimal trajectories in ATM operations including an overall environmental evaluation and implementation analysis.

To provide a self-standing context, we first describe FlyATM4E project (Section 1.1) and then frame the deliverable within the overall project (Section 1.2). Section 1.3 is devoted to providing the structure of the remaining chapters of the document and Section 1.4 to listing the reference material used.

1.1 FlyATM4E project description

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 (the indirect climate effects, i.e., the impact on contrails properties) on the atmosphere via concentration changes of radiative 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 climate-sensitive regions ("Cherry-Picking"/"eco-efficient flights").
- 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.

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 1Figure 2). 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.

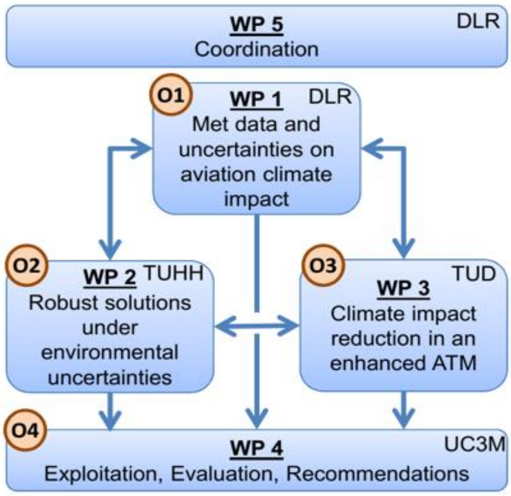

Figure 1: FlyATM4E WP structure

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 D4.3 [3], the focus is on the recommendations regarding the implementation of robust and climate-optimal trajectories in the ATM system. The evaluation of results is the purpose of this deliverable D4.4.

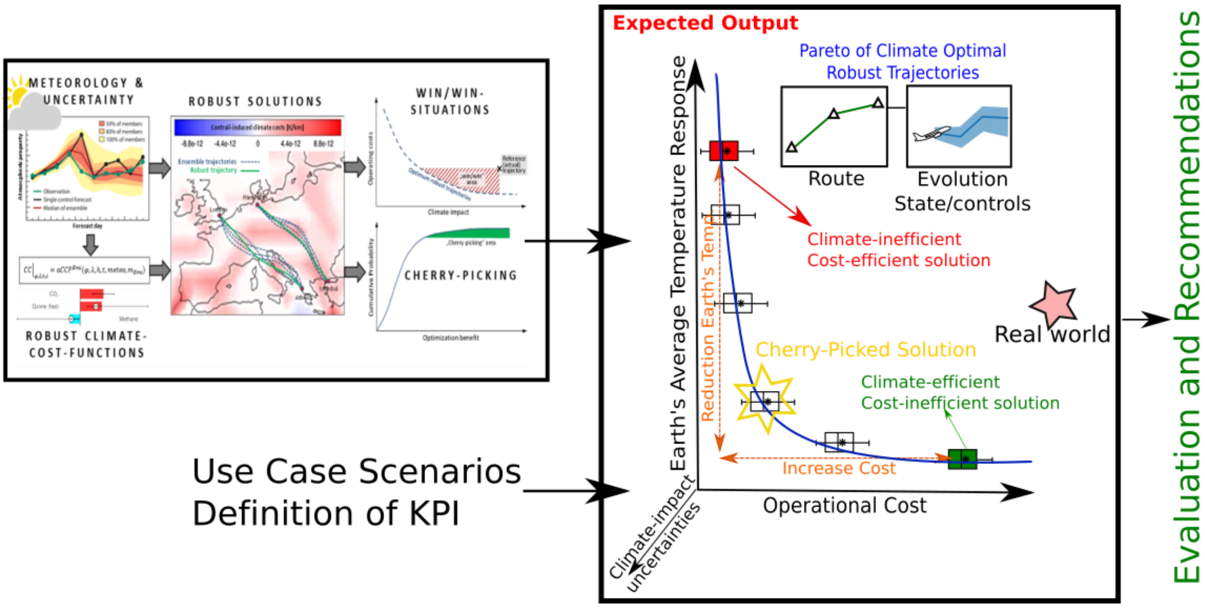

Figure 2: FlyATM4E evaluation and recommendations

1.3 Structure of the deliverable

We first summarize the experimental plan (Section 2), including the research hypotheses and questions that were initially formulated. We then describe the 4 experiments (Sections 3 to 6) conducted to assess the hypotheses and answer the questions, namely: Experiment #1: "Eco-efficient solutions" ("Cherry-picking" situations); Experiment #2: robust solutions under meteorological uncertainties and constraint airspaces (subject of WP2); Experiment #3: robust solutions under meteorological uncertainties and free-routing airspaces (subject of WP2); and Experiment #4: "Win/win situations" (subject of WP2). Finally, we draw some conclusions and discuss some implementation features.

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
ECAC	European Civil Aviation Conference
ECMWF	European Centre for Medium Range Weather Forecast
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
KPA	Key Performance Areas
ICAO	International Civil Aviation Organization
MET	Meteorology
RH	Research Hypothesis
ROOST	Robust Optimisation of Structured Airspace
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 Experimental set-up

We summarize the most important aspects of the experimental plan.

No contractual deliverable for the Experimental Plan (EP) was planned during the grant agreement preparation, but it has been agreed that an intermediate version of the EP shall be created, which was already delivered as the annex of D2.1 [7] as a living document. The final version is submitted as annex of the Final Project Results Report (D5.3 [8]). Interested readers are referred to both documents.

2.1 Definition and characteristics of the experiments

Experiments in the FlyATM4E context were defined for answering the following research questions reflecting the project‘s overall objective:

- How can climate-optimised aircraft trajectories be planned that support ATM in providing a robust and eco-efficient reduction in aviation's climate impact?
- How large is the mitigation potential, considering CO_2 and non-CO_2 emissions through meteorological data, ensemble prediction and eco-efficient trajectories?

The experiments are of **numerical** nature leading to **quantitative results**. Some of the results are used to create **Pareto fronts** that enable the **trade-off** of two usually conflicting variables. Those curves show how much one parameter is penalized, if the other is improved. In FlyATM4E, trade-offs between costs and climate impact reductions (**KPAs cost-effectiveness and environment**) are foreseen, while costs shall be measured in a simplified way.

The experiments were carried out in the course of the technical work packages WP1, WP2, and WP3. While WP1 provides the conceptual and algorithmic basis, in WP2 and WP3 this will be applied within numerical simulations and optimisation runs. The corresponding methodologies as well as findings have been therefore documented in the respective deliverables D1.2 [4], D2.1 [7], D2.2 [5], D3.1 [9] and D3.2 [6].

2.2 Research questions and hypotheses

Experiments in FlyATM4E were carried out to answer the following research questions and validate the following hypotheses:

- (RH/1) Ensemble data from probabilistic weather forecast allows identifying robustness of mitigation potential of alternative trajectory solutions.
- (RH/2) „Cherry-picking“ (also known as "eco-efficient") solutions do exist and can be identified.
- (RQ/3) How large is the climate impact mitigation potential of climate-optimised flight planning in Europe considering meteorological variability and uncertainty?
- (RQ/4) What would be an acceptable (eco-efficient) trade-off between costs and climate impact reduction (on a single mission basis / on average)?

- (RH/5) There is room for improvement in the European ATS route network to exploit the full potential of climate-optimised flight planning (unconstrained free-flight vs. constrained graph-based).

2.3 Case studies in FlyATM4E

In FlyATM4E, three different use cases are studied in detail. Those are the robust solutions under meteorological uncertainties (subject of WP2), "Eco-efficient solutions" ("Cherry-picking" situations) and "Win/win situations" (subject of WP3). Those case studies target different research questions/hypotheses (see above) and therefore differ with respect to the requirements for the input data or the temporal scope of the study.

2.4 Definition of the experiments

The experiments are carried out in the following sequence:

no.	title	actor	scenario			timing
			model	routes	weather	
#1	"Eco-efficient solutions" campaign	WP3 researcher, TUD (F. Castino)	EMAC/AirTraf	Top 100 real routes	One year, every day (1 Dec 17 to 1 Dec 18), two departure times (0000z and 1200z), no ensembles (deterministic)	Start: 6 months before D3.2 delivery; end: 4 months before D3.2 delivery
#2	"Robust solutions" campaign – part 1 (constrained)	WP2 researcher, UC3M (A. Simorgh)	ROOST	Top 100 real routes (5 Pareto points)	5 days in Jun 2018, 5 days in Dec 2018, two departure times (0000z and 1200z), 10 ensembles (stochastic)	Start: 5 months before D2.2 delivery; end: 3 months before D2.2 delivery
#3	"Robust solutions" campaign – part 2 (unconstrained)	WP2 researchers, DLR (B. Lührs), TUHH (M. Meuser)	TOM	Top 10 fictitious routes (50 Pareto points)	5 days in Jun 2018, 5 days in Dec 2018, two departure times (0000z and 1200z), 10 ensembles (deterministic)	Start: 4 months before D2.2 delivery; end: 2 months before D2.2 delivery
#4	"Win/win situations" campaign	WP3 researchers, UC3M (A. Simorgh), DLR (B. Lührs), TUHH (M. Meuster)	ROOST & TOM	9 selected real routes	One day (5 Dec 2018), one departure time (0000z), one ensemble (#1), no uncertainties	Start: 3 months before D3.2 delivery; end: 1 month before D3.2 delivery

Table 3: FlyATM4E experiments

2.4.1 Top 100 routes

The air traffic sample has been provided by the WP2 (for more details see D2.2 [5]) using the following main criteria:

1. Be representative for the European air traffic: to this end, an analysis of the European air traffic has been performed, and the top 100 routes by Available Seat Kilometres (ASK) for the European Civil Aviation Conference (ECAC) area in 2018 have been selected. The location of the origin/destination pairs is indicated in Figure 3. Moreover, the A320-214 (CFM56-5B4) aircraft type was selected based on the total traffic share in ASK for ECAC in 2018.

2. Enable to identify seasons/times of the day which are more likely to present conditions allowing for eco-efficient trajectories: to make this possible, the same origin/destination pairs are repeated on each simulation day at two fixed departure times (00:00, 12:00).

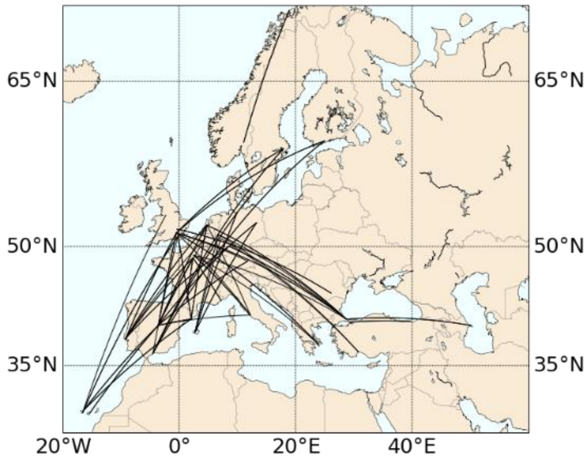

Figure 3 – Top 100 origin/destination pairs included in our representative European air traffic sample.

2.4.2 Selection of dates

The objective of this selection exercise was to identify enough days with weather variability to demonstrate the FlyATM4E concept feasibility for different weather situations. This selection was subject to the following constraints:

- Avoid days with high number of weather regulations, as these would impede the traffic situation and affect the analysis (convection activity)
- Consider data availability for traffic and meteorology data
- Set a maximum number of days to limit computational effort

Initially, it was decided on the following 20 study days:

- March: 5, 10, 15, 20, 25
- June: 13, 15, 18, 23, 27
- September:7, 11, 15, 20, 25
- December: 5, 10, 15, 20, 25

However, as the aCCFs have been developed considering summer and winter weather patterns, the focus of the analysis is restricted to only days within June and December.

2.4.3 aCCFs V1.1 as input

The enhanced MET service based on the aCCFs version 1.1 (including the newly introduced educated guess factors) is used as input to quantify both the CO_2 and non-CO_2 climate effects for airspace users in flight planning. See D1.2 for more details. Indeed, we have used the newly developed Python Library based on the merged aCCFs V1.1.

3 Experiment #1: "Eco-efficient solutions"

To analyse eco-efficient solutions, in WP3, simulations were conducted over a period of one year on the Top 100 routes with the air traffic simulator AirTraf coupled to the chemistry model EMAC. These model developments are described in more detail in Section 2.1.2 of D3.2 [6] and Section 2.1.3 of D3.2 [6], respectively.

3.1 Experiment #1: main Results

In this Section, we describe the results of the long-term simulations with respect to different optimization objectives. We compare the F-ATR20 and Simple Operating Cost (SOC) that characterize four trajectory optimization strategies:

(1) cost-optimal,
(2) climate-optimal,
(3) trade-off solutions, leading to a +0.5% cost increase for each flight, and
(4) eco-efficient trajectories, selected by a flexible decision-making algorithm.

Figure 4 compares the changes in SOC and F-ATR20 with respect to cost-optimal trajectories, which were obtained employing three different optimization strategies: climate-optimal (green), +0.5% SOC (red), and eco-efficient (blue). The percentages shown in Figure 4 are calculated by comparing the total SOC and F-ATR20 values, found summing over all the flights and days included in our simulations. Firstly, we can notice that the total increase in SOC obtained with the "fixed +0.5% SOC" solution-picking strategy is slightly lower than the target, i.e., the SOC change is +0.44% instead of +0.5%. This is motivated by the fact that, in some situations, the maximum SOC increase in the Pareto front is lower than the target of +0.5% (this will be further discussed in Section 5.1). This fact lowers the actual SOC change to +0.44%, both for daytime and night-time flights.

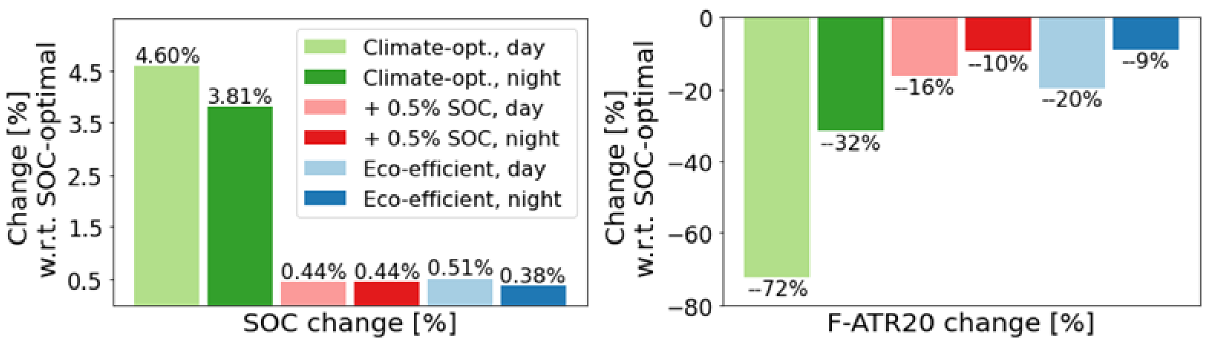

Figure 4: Relative changes [%] in SOC and F-ATR20 with respect to SOC-optimal trajectories.

Figure 4 also compares the mitigation potential of day-time flights (bars in lighter colours) and night-time flights (bars in darker colours). We can see that the reductions in climate impact are larger during the day than they are during the night. In particular, the F-ATR20 reduction of climate-optimal trajectories during the day is more than double the night-time mitigation potential, while the SOC increase is less than double. This suggests that there is a higher potential for eco-efficiency during the day, than during the night. The **higher mitigation potential of day-time flights** is not only visible for climate-optimal trajectories, but also for trade-off solutions, for which the same increase in SOC (+0.44%) leads to a larger F-ATR20 reduction (-16% during the day vs. -10% at night). A possible interpretation for this day-time higher mitigation potential is that, during the day, cooling effects from contrail can be exploited by the model to reduce the F-ATR20 values.

3.2 Research Hypothesis and Research Questions verification

Comparing eco-efficient and cost-optimal trajectories, we found that an increase of about 0.5% in operating costs allows to reduce the climate impact of day-time flights by about 20%, and the impact of night-time flights by about 10%, in terms of F-ATR20.

Thus, we can say that:

(RH/2) „Cherry-picking“ (also known as "eco-efficient") solutions do exist and can be identified.

Needless to say, these aggregated results have been also analyzed in terms of:

(1) seasonality.

(2) Contribution of the different species.

(3) Sensitivity to the time horizon

In terms of **seasonality**, it has been shown (see D3.2 [6] for details) that the climate mitigation potential is larger during the summer.

The absolute values of the F-ATR20 from our air traffic sample follow a seasonal cycle, with a higher climate impact during the summer (June, July, August), than during the winter (December, January, February). We observe this seasonal cycle under all the trajectory optimization strategies that we considered, i.e., cost-optimal, climate-optimal, and eco-efficient solutions.

In terms of the **contribution of the different species** to the overall aviation-induced climate impact, Figure 5 shows the individual effects of CO_2, H_2O, NO_x (differentiating CH_4 and O_3 contributions), and contrails.

Changes in contrail effects provide the largest contribution to the reduction in climate impact on almost every day and night – with some exceptions in winter, when the reduction in the F-ATR20 from NO_x-ozone is also contributing-. Moreover, in winter, the climate-optimization strategy takes advantage from cooling effects of contrails.

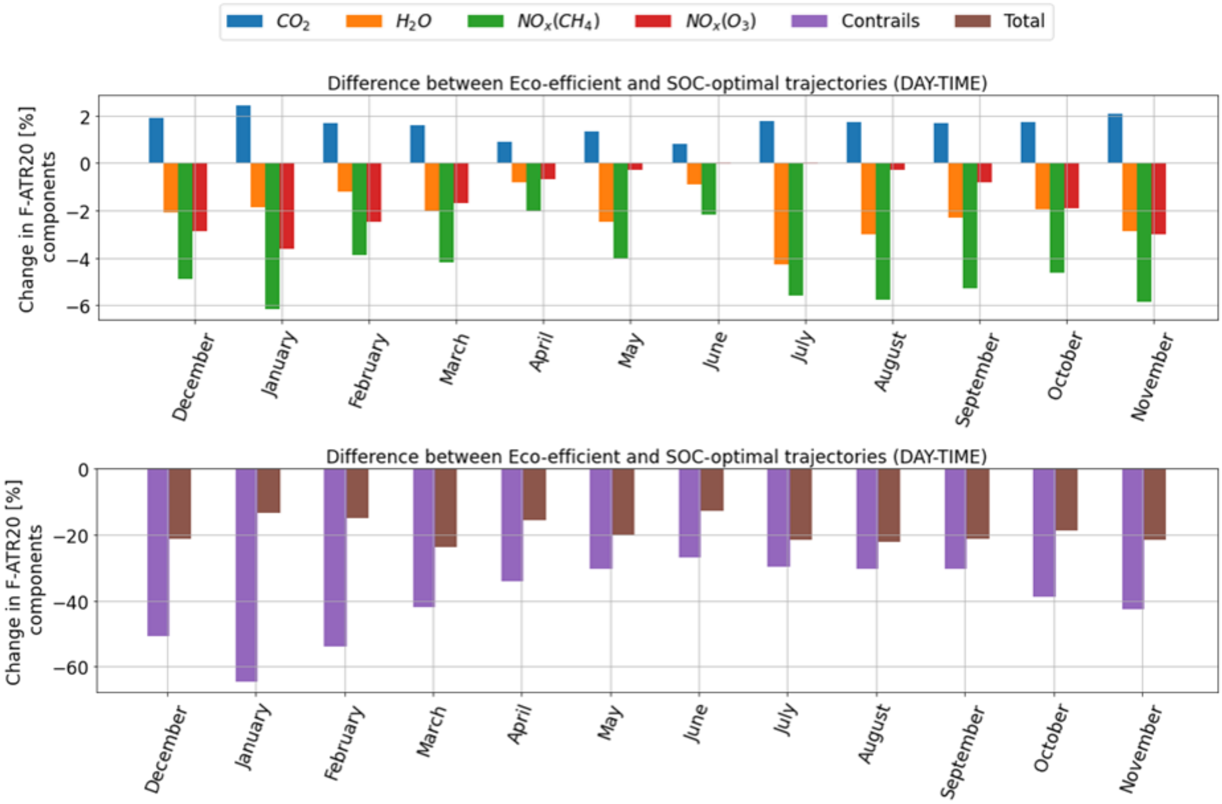

Figure 5: Relative changes in the F-ATR20 [%] components, relative to the climate impact from different aviation climate forcings, comparing eco-efficient and SOC-optimal trajectories. Upper panel: relative changes in non-dominant effects; lower panel: change in the climate impact of contrails (dominant contributor) and change in total F-ATR20. Departure time of all flights is 12:00 UTC.

In terms of the **sensitivity** of the results **to the time horizon**, the same simulation has been conducted changing the metric from F-ATR20 to F-ATR100, i.e., looking into mitigation potential at 100-years' time horizon. Results show that the mitigation potential is also present (though lower, with similar orders of magnitude), thus RH/2 would also be valid for looking into the climate impact in 100 years' time.

4 Experiment #2: "Robust solutions" (constrained)

To explore climate-optimized trajectories and to estimate the mitigation potential of climate optimized aircraft trajectories in the European airspace (considering structured airspaces), optimization of typical daily traffic samples has been performed in a series of case studies using realistic meteorological information in WP2 (see D2.2 [5]). For this purpose, we use the so-coined Robust optimization of structured airspace (ROOST), which is a fast graph-based optimization algorithm capable of determining robust aircraft trajectories in the structured airspace (see Figure 6) considering meteorological uncertainty, characterized by EPS forecast [9] [10].

The concept of robustness that we refer to in this experiment is the determination of the aircraft trajectory considering 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 aim is to determine a trajectory that is optimal considering the overall performance obtained from ensemble forecasts.

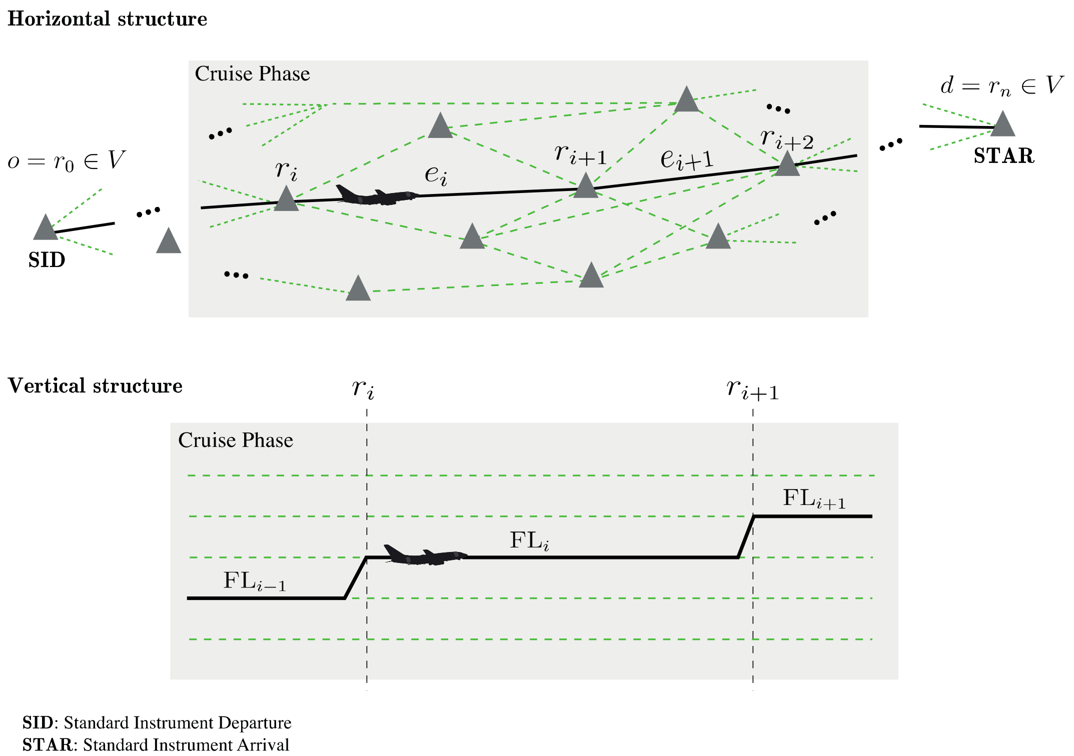

Figure 6: Structure of airspace.

4.1 Experiment #2: main Results

For a set of city-pairs corresponding to the Top-100 connections in Europe (see Section 2.4.1), aircraft trajectory optimization was performed using ROOST and considering the climate effects of aviation emissions. By varying weights in the overall objective function, different sets of alternative trajectories are identified, comprising both “cost optimal” and the “climate optimal”. By applying concepts of how to integrate uncertainties in the trajectory performance assessment, the robustness of the benefits and mitigation potential of the identified alternative routes was assessed at the same time. We summarize herein the main results, and interested readers are referred to D2.2 for a thorough analysis.

The simulation results employing ROOST are presented in two parts: single route analysis and aggregated results of optimizing the top 100 routes.

4.1.1 Single route analysis

The effectiveness of the proposed optimization algorithm to plan robust climate optimal aircraft trajectories with respect to uncertain meteorological conditions was analyzed for a flight from Frankfurt to Kyiv on three different days: on 13th of June 2018, 0000UTC, a scenario in which aircraft flies through areas favorable for the formation of persistent contrails (i.e., warming contrails), 20th of December 2018, 1200UTC, a scenario with cooling contrails, and 10th of December 2018, 1200UTC, a scenario with no formation of persistent contrails. The dominant climate impact of contrails is the main reason for selecting these scenarios, providing better insight into the mitigation potentials.

The lateral profile and vertical profiles (on the structured airspace), together with speed profiles, the cost, and the climate impact of the different species (including their uncertainties) are shown in each of the three scenarios, showing that indeed the methodology works. Indeed, the ROOST algorithm has always been shown to converge to good-enough values in computational times of an order of magnitude of 10 sec.

The summary of the results for the three individual flights is as follows:

- For a flight from Frankfort to Kyiv on three different days, the **mitigation potentials** were **different due to** the change in **meteorological conditions**.
- The mitigation potentials for scenarios with contrails effects (warming or cooling) were higher due to dominant climate impact and non-smooth spatial behavior of contrails. In such cases, the optimizer’s first choice was to reduce the warming impact or increase the cooling impact of contrails.
- The **climate effects of contrails** were **highly uncertain**. The relatively high uncertainty in contrails' climate impact is related to the high variability among the ensemble members of relative humidity provided by the EPS required to determine the areas favorable for forming persistent contrails.
- The generation of cooling contrails was associated with high uncertainty as the aircraft tends to fly within uncertain persistent contrail formation areas. However, the results were received almost deterministic for the scenarios with no contrails or the cases where aircraft trajectories avoid the formation of contrails.

4.1.2 Top-100 routes analysis

The top-100 routes results will be presented to highlight the daily and seasonal variability and impact of atmospheric conditions on the optimized trajectories. The variability of the contrails' climate impact was quantified by aCCFs V1.1 of contrails over the selected days in June and December at midnight (i.e., 0000UTC) and midday (i.e., 1200UTC). At **midnight**, the **contrails climate impact is warming**, while at **midday**, **in addition** to warming impacts, there are **some areas with cooling climate effects**.

Figure 7 shows the results (please, refer to D2.2 for a more detailed overview). One can readily see that **there is always a mitigation potential**, though its quantity differs across days (typically driven by the appearance of contrails) and the hours of the day (the mitigation potential is larger at night)

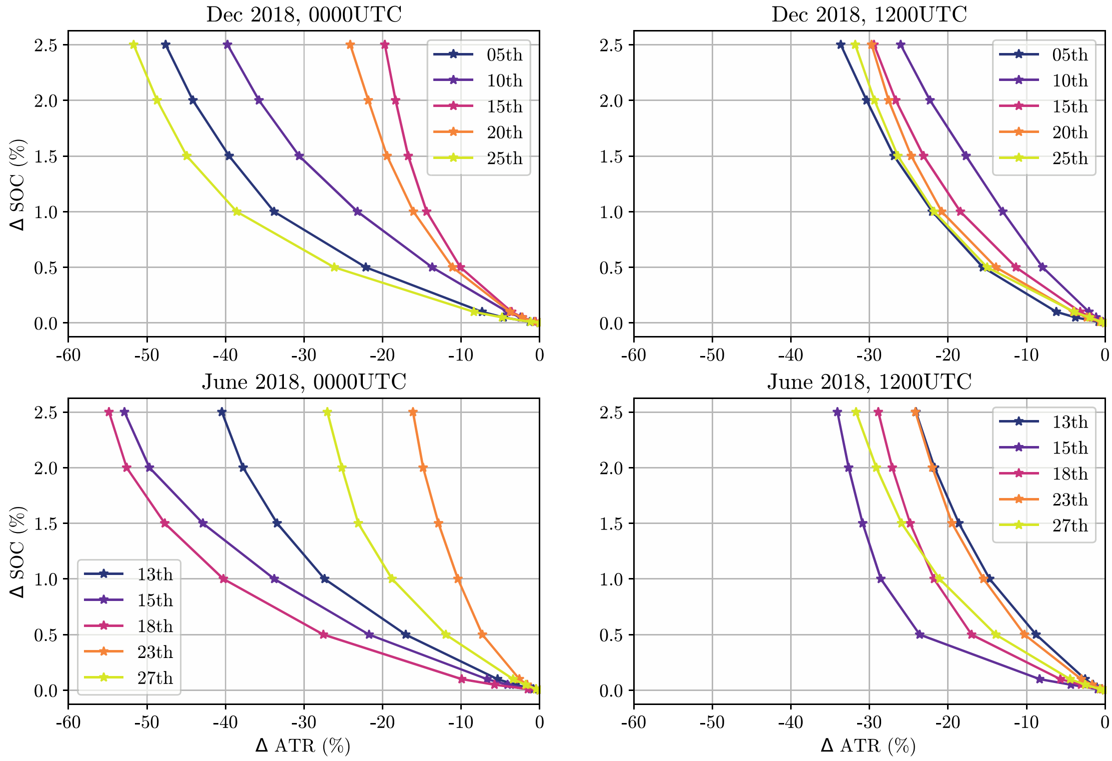

Figure 7: Aggregated results of optimizing the top 100 routes: Trade-off between reducing climate impact and relative increase in SOC considering normalized relative values in percentage.

The summary of the results for the top-100 aggregated results is as follows:

- The **mitigation potentials** are **highly variable due to** changes in **atmospheric conditions**.
- For the considered case studies, in general, the night-time flights resulted in a higher reduction of climate impacts (≈ 20-50%) compared to day-time (≈ 20-30%).
- The **mitigation potentials** were **mainly achieved by** the **reduction of** the **warming impact or increase of cooling impact of contrails**.
- Overall, allowing a maximum **3% increase in standard operational cost** could **reduce** the **climate impact by 20-50%** .
- The uncertainties on those results achieved by generating cooling contrails were high due to the tendency to fly through uncertain persistent contrail formation areas.

4.2 Research Hypothesis and Research Questions verification

The following hypothesis (RH/1) and research questions (RQ/3 and RQ/4) are linked to Experiment #2:

- (RH/1) Ensemble data from probabilistic weather forecast allows identifying robustness of mitigation potential of alternative trajectory solutions.
- (RQ/3) How large is the climate impact mitigation potential of climate-optimised flight planning in Europe considering meteorological variability and uncertainty?
- (RQ/4) What would be an acceptable (eco-efficient) trade-off between costs and climate impact reduction (on a single mission basis / on average)?

Indeed, we can affirm that **RH/1 has been verified** since we have successfully used EPS weather forecasts to characterize atmospheric uncertainties. This uncertainty has been incorporated in ROOST to find robust trajectories. We include here the results of ROOST applied to the first individual example (see Figure 8), where uncertainties are represented as whisker plots. It is shown that we can reduce uncertainty.

As for RQ/3, we can also affirm that we have answered to the question. In this case, considering the current structure of the airspace, we have quantified the mitigation potential for different flights in different atmospheric conditions. For instance, in Figure 8 we can see that the mitigation potential can go up to 60% reduction in ATR20.

Similarly, **RQ/4 has been successfully answered.** Again, considering the current structure of the airspace, we have quantified trade-offs between costs and climate impact reduction both on a single mission basis and on average. For instance, in Figure 8 we can see that we can obtain a mitigation potential of 40% reduction in ATR20 at 2% increase in operational cost for a particular flight. These values also come with their associated uncertainty.

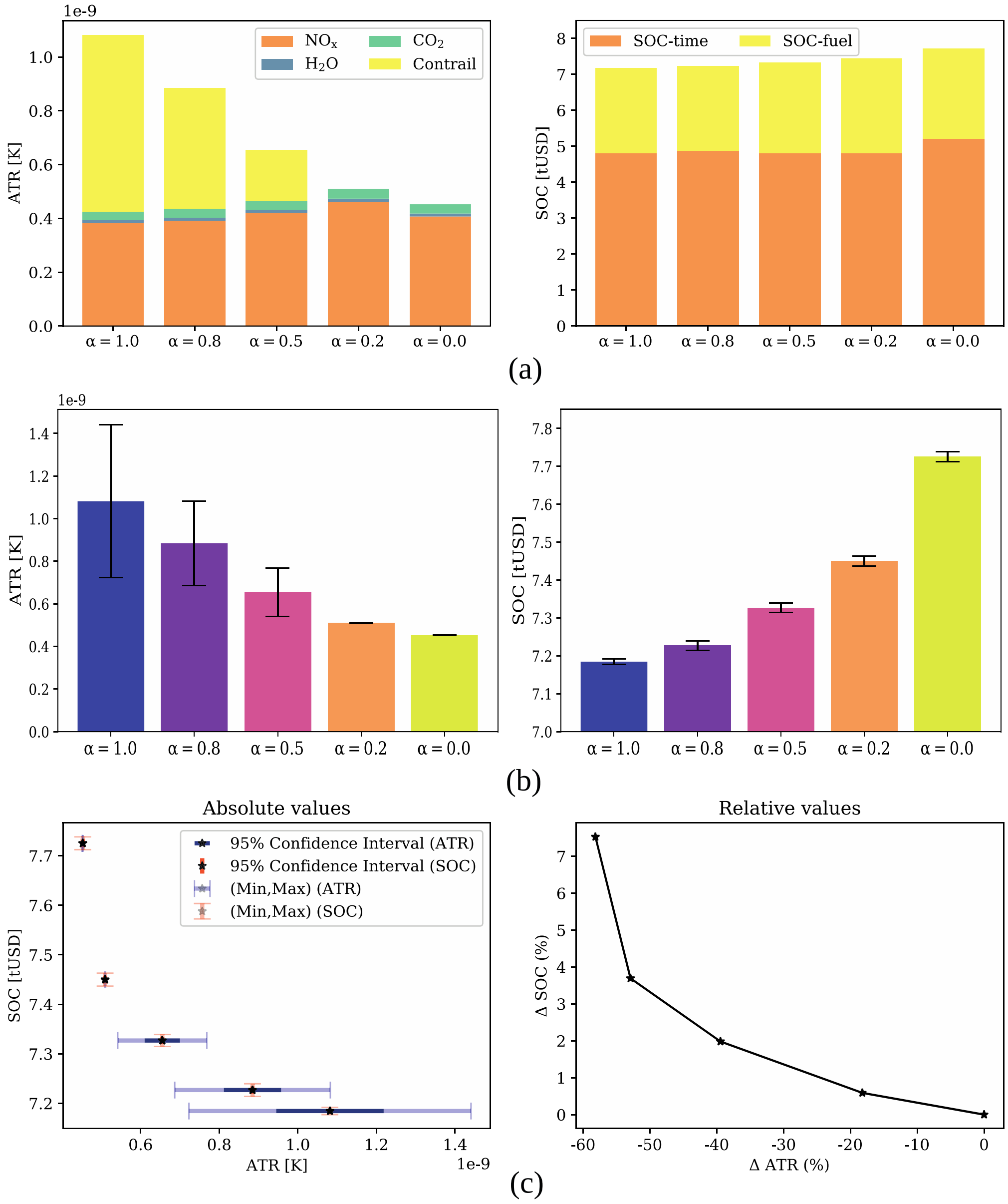

Figure 8: Overall performance of the optimized trajectories in terms of ATR and SOC for Case 1 (13th of June 2018, 0000UTC). (a) Contribution of each species to the total ATR, and costs of flight time and fuel consumption to net SOC (mean values), (b) ATR and SOC with ranges of uncertainty (min-max) for different routing options. (c) Pareto-frontiers considering absolute values (with uncertainty ranges) and relative values (only mean).

5 Experiment #3: Robust solutions (unconstrained)

To explore climate-optimized trajectories and to estimate its climate mitigation potential in the European airspace (considering free-routing airspaces), optimization of typical daily traffic samples has been performed in a series of case studies using realistic meteorological information in WP2 (see D2.2). For this purpose, the Trajectory Optimisation Module (TOM) was used as an optimisation tool based on optimal control. The workflow of TOM is illustrated in Figure 9.

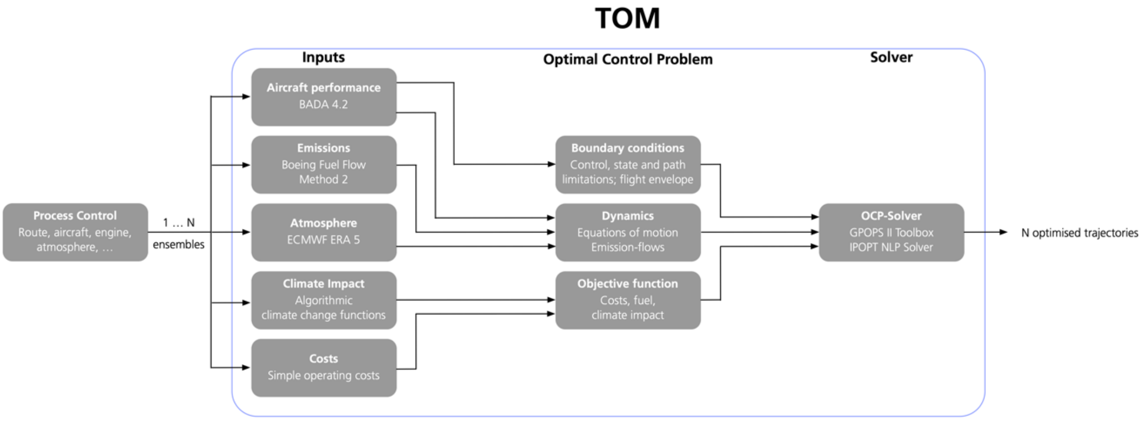

Figure 9: Workflow of the Trajectory Optimization Module (TOM)

5.1 Experiment #3: main Results

The results estimated with TOM are summarized in the sequel (interested readers can consult all the results in D2.2). The overall mitigation potential is estimated using a three-step procedure: First, a deterministic Pareto-front is generated for each route and each ensemble member of the weather forecast. Secondly, for each route, the Pareto fronts of all ensemble members are combined in order to obtain probabilistic Pareto fronts. Finally, the results are aggregated for the top 10 routes of the route network for the summer and the winter period (June and December) and for different times of the day (00:00 UTC and 12:00 UTC).

The simulation results employing TOM are presented in two parts: single route analysis and aggregated results of optimizing the top 10 routes.

5.1.1 Single route analysis

The effectiveness of the proposed optimization algorithm to plan climate optimal aircraft trajectories with respect to uncertain meteorological conditions was analysed on two individual flights: one without contrails; one with contrails. The 3D profile, together with speed profiles, fuel consumption and climate impact are provided for these two flights. The mitigation potential and its associated cost are also presented (again, see all the details in D2.2 [5]).

In addition to it, there is an analysis on the effects of EPS weather forecast on the uncertainties associated to the mitigation potential. Figure 10 illustrates it.

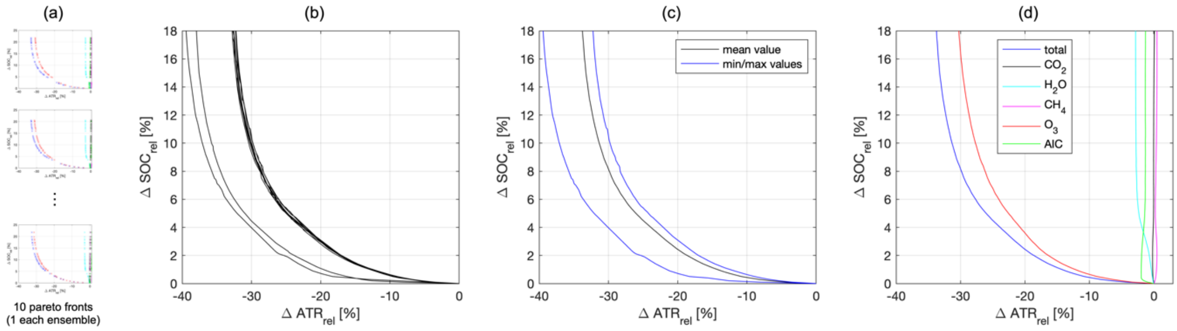

Figure 10: Probabilistic Pareto-fronts for the most relevant fictitious route. Individual Pareto-fronts (a) are aggregated (b) to evaluate min., max. and mean values for each optimization step (c). Contributions of individual emission species (d) are determined for the trajectory and 10 weather scenarios of 13th June 2018.

5.1.2 Top-10 routes analysis

An aggregated analysis has also been conducted on the top 10 routes of the fictitious scenario. The ten most relevant routes from the fictitious route network account for an equivalent 100 real routes in terms of ASK. We have calculated the mean values of the Pareto front to generate aggregated results. In this instance, absolute values are averaged values per trajectory. In general, we observe large mitigation potential across both seasons and times.

Figure 11 shows the results. Table 4 gives a simplified overview of the mitigation potential associated with SOC increases of 2,5 and 10%.

	Δ ATR20			
Δ SOC	June 00:00 UTC	June 12:00 UTC	December 00:00 UTC	December 12:00 UTC
10%	55%	53%	62%	70%
5%	53%	48%	56%	65%
2%	46%	41%	45%	46%

Table 4: Total relative mitigation potential for summer and winter months at day- and night-time for given increases of relative SOC.

The results for the aggregated scenario of TOM can be summarized as follows:

- The **overall mitigation potential** applying the continuous optimization approach (considering a full 3D free routing airspace) yields results **in the order of 40-80%**.
- The highest relative mitigation potentials come at a high increase of costs (often above 10%).
- For the investigated routes (top 10 routes), as well as seasons (June and December) and times (midnight and midday), for a given increase of SOC we can observe **mitigation potential variability across ensembles between 10 and 25%** between best- and worst-case scenarios.
- Higher absolute mitigation potentials could be achieved in the winter month.
- When contrails are present, they dominate the mitigation potential and generate strong gradients of mitigation potential at low cost increases.

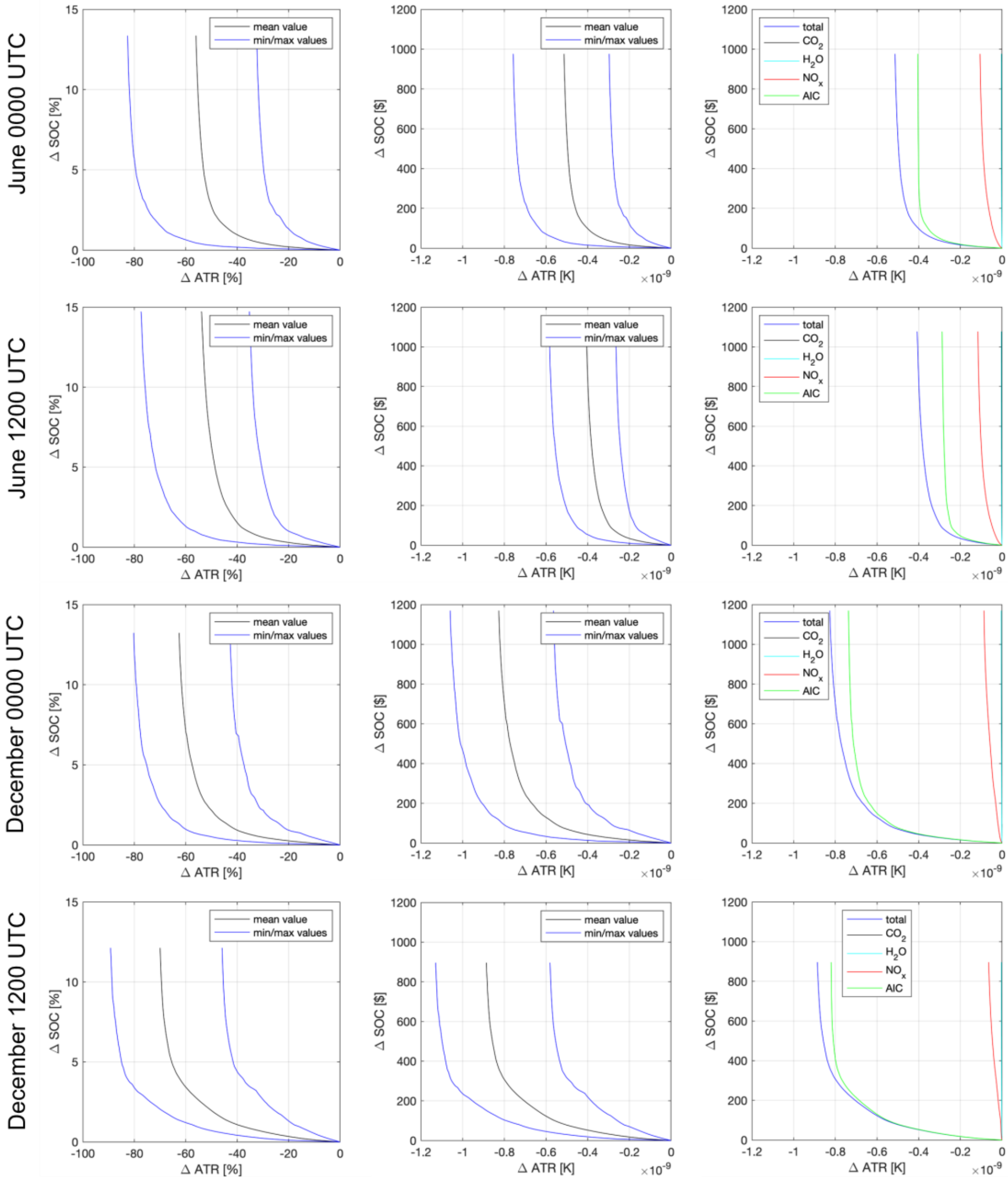

Figure 11: Aggregated pareto fronts of the Top 10 Routes of the fictitious route network scenario for December, 00:00 UTC. Relative pareto front including uncertainties (left), absolute pareto front including uncertainties (middle), absolute pareto front with contribution of individual species (right).

5.2 Research Hypothesis and Research Questions verification

The following hypothesis (RH/1) and research questions (RQ/3 and RQ/4), which were already discussed in Experiment #2, are also linked to Experiment #3:

- (RH/1) Ensemble data from probabilistic weather forecast allows identifying robustness of mitigation potential of alternative trajectory solutions.
- (RQ/3) How large is the climate impact mitigation potential of climate-optimised flight planning in Europe considering meteorological variability and uncertainty?
- (RQ/4) What would be an acceptable (eco-efficient) trade-off between costs and climate impact reduction (on a single mission basis / on average)?

As in the case of Experiment #2, we can herein (via Experiment #3) ratify that **RH/1 has been verified and we have provided answers to RQ/3 and RQ/4.** It is important to highlight that Experiments #2 and #3 are conceptually similar though the methods and the airspace considered are totally different. The fact that we can confirm the hypotheses and research questions with different methods and constraints is a clear strength of FlyATM4E.

Indeed, we can affirm that **RH/1 has been verified** since we have successfully used EPS weather forecasts to characterize atmospheric uncertainties. This uncertainty has been incorporated in TOM.

As for RQ/3, we can also affirm that we have answered to the question. In this case, considering a futuristic free-routing airspace, we have quantified the mitigation potential for different flights in different atmospheric conditions.

Similarly, **RQ/4 has been successfully answered.** Again, considering a futuristic free-routing airspace, we have quantified trade-offs between costs and climate impact reduction on a single mission basis and on average.

6 Experiment #4: “Win/win situations”

“Win-win” situations may emerge in the case of exploiting airspace inefficiencies, e.g., associated to structured airspaces. In other words, by fairly comparing flights enforced to fly through structured airspaces (constrained to fly through the network of ATS routes and to follow a vertical structure of Flight Levels) with flights that are planned to use a complete (horizontal and vertical) free routing airspace, once can find solutions that are better in terms of cost and climate. This would result in a win-win solution that may be worth exploring.

Indeed, there is an initiative in the ECAC area to make the European airspace completely a free-routing Airspace (FRA), see Figure 12. A FRA is a specified airspace within which users may freely plan a route between a defined entry point and a defined exit point. Subject to airspace availability, the route can be planned directly from one to the other or via intermediate (published or unpublished) way points, without reference to the ATS route network.

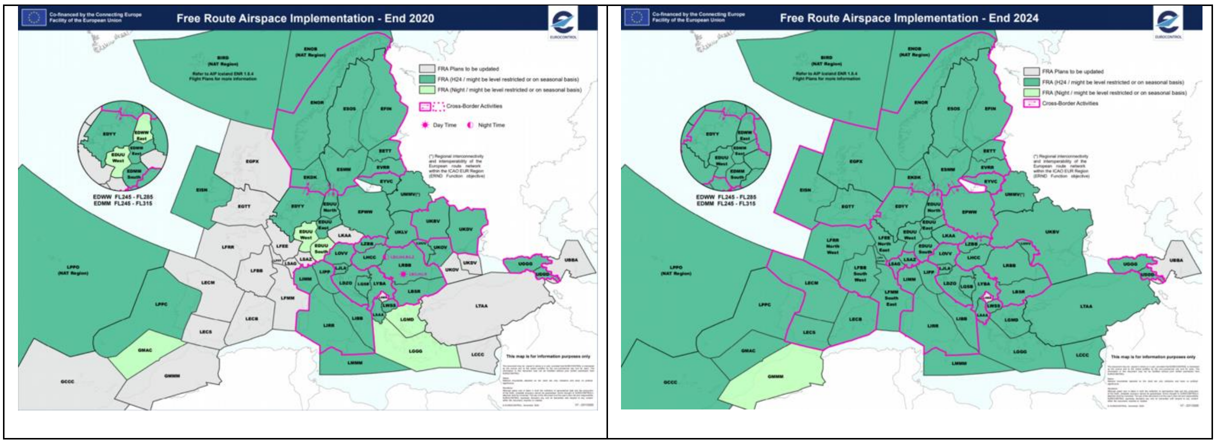

Figure 12: FRA in Europe in 2020 (a) and expected in 2024 (b)

In the FlyATM4E project, “win-win” solutions are determined by comparing the optimisation results of ROOST (structured airspace, which mimics the current network of ATS routes relying on DDR2 data) and TOM (continuous optimization on a full 3D free routing airspace). Though the FRA initiative applies only to the horizontal airspace (the vertical airspace structure remains as it is), win-win analysis may provide insights into the potential climate benefits of FRA or, eventually, a free-vertical airspace.

6.1 Results

The Pareto fronts (from cost-optimal solutions to minimum climate solutions) of nine routes have been estimated with ROOST and TOM for the 1st ensemble weather forecast of 5th Dec., 2018, 00:00 UTC and the associated algorithmic climate change functions. The points of both Pareto fronts (costs and climate impact) are normalized with respect to the minimum cost trajectory of the structured airspace simulation (red circles in Figure 13).

As indicated in Figure 13 (a)-(i), "win-win" solutions have been identified for all nine investigated routes (grey shaded area), which reflects the inefficiencies caused by the route structure (we do not differentiate between horizontal and vertical inefficiencies).

At reference cost level (i.e., same cost), the climate impact can be reduced between 15% (b) and up to 80% (i) for the investigated routes by assuming a free route airspace.

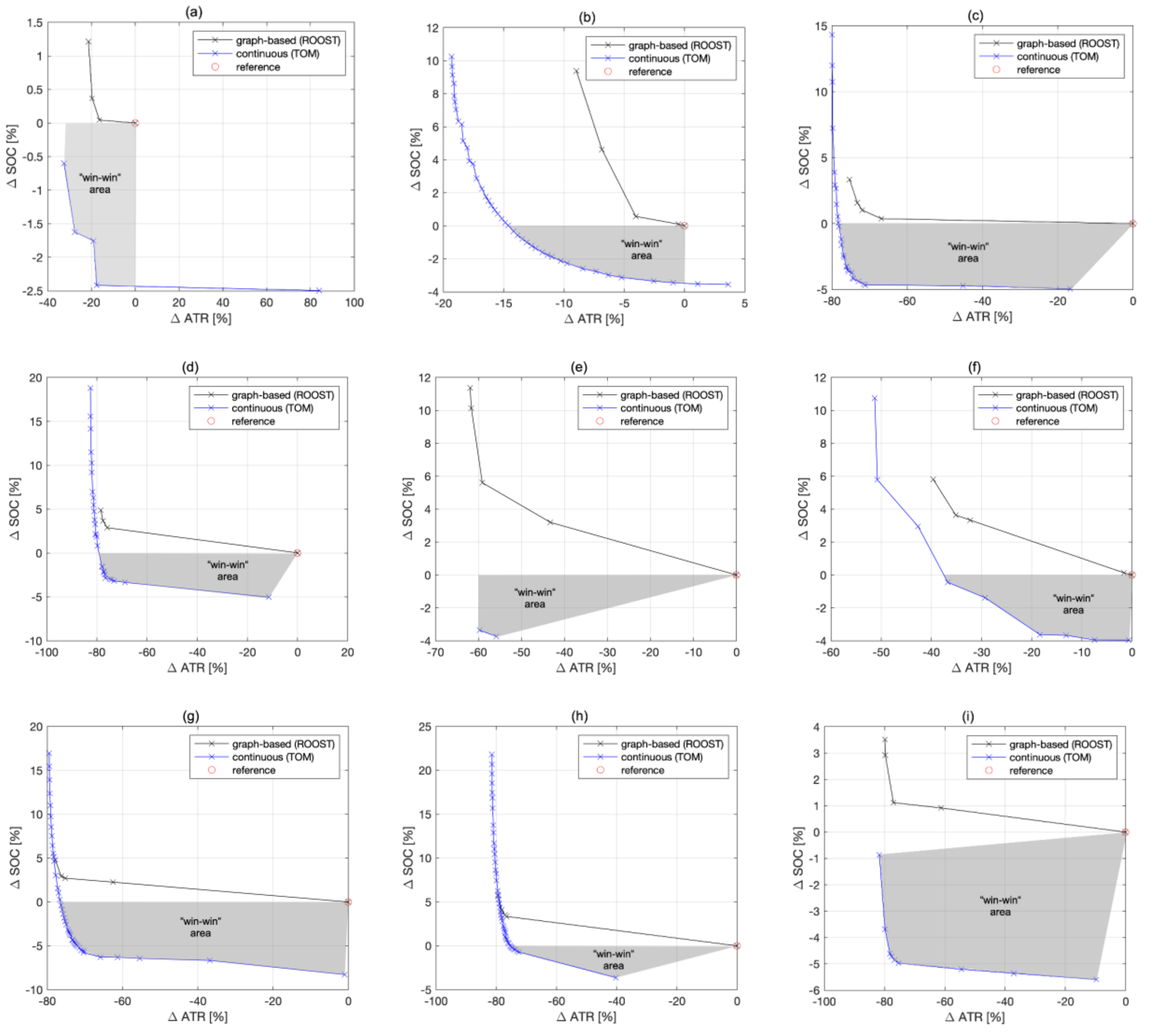

Figure 13: Pareto-fronts for the routes LTFM-EGLL (a), GCXO-LEMD (b), LFPO-LPPT (c), LEMD-EGLL (d), EHAM-LTFM (e), EGLL-LGAV (f), EHAM-LEBL (g), LEMD-EDDF (h), EHAM-LPPT (i) on 5th Dec., 2018, 00:00 UTC, 1st ensemble, generated with ROOST (black curves) and TOM (blue curves). The reference point is indicated with a red circle, "win-win" areas are shaded in grey.

6.2 Research Hypothesis and Research Questions verification

The following hypothesis (RH/5) is linked to Experiment #4:

- (RH/5) There is room for improvement in the European ATS route network to exploit the full potential of climate-optimised flight planning (unconstrained free-flight vs. constrained graph-based).

We can affirm that **RH/5 has been verified**. We have shown that win-win situations with large climate mitigation potential systematically appear when comparing optimal solutions under constraint airspace with full free-routing airspaces.

However, these large mitigation gains and cost reductions might not be feasible in real world operations due to airspace congestion and additional boundary conditions. Nevertheless, the results indicate that a large climate impact reduction potential might be associated with the allowance of more flexibility when using the airspace, especially linked to altitude changes.

7 Conclusions and implementation

This section summarizes the main conclusions based on the results and links to the evidence collected during the project with some remarks about ATM implementation.

7.1 Main conclusions

On the usage of merged aCCFs V1.1 to characterize aviation's climate impact:

- The enhanced MET service based on the aCCFs V1.1 (including the newly introduced educated guess factors) is in line with the state-of-the-art understanding of aviation's climate impact and provides information on the CO_2 and non-CO_2 climate effects for airspace users in flight planning. Indeed, the **merged non-CO_2 aCCFs V1.1 describe the overall climate impact of aviation's non-CO_2 emissions by considering technical specifications** of e.g., aircraft type and physical climate metric.
- The newly developed **Python Library** based on the merged aCCFs V1.1 **allows** an open and convenient **implementation of the aCCFs' formulas in the air traffic simulation environment** and **provides direct link between non-CO_2 climate effects to fuel consumption** as a common assessment indicator.

On the obtention of eco-efficient and climate optimal trajectories:

- Merged aCCFs have been successfully integrated in different types of trajectory generators (TOM, ROOST, EMAC/AirTraf), all of them capable of finding optimal trajectories that weight cost and climate.
- The robustness analysis using **ensemble probabilistic forecast shows that mitigation potentials vary due to the variability of atmospheric conditions** and the uncertainty in weather forecast can be addressed by incorporating the numerical ensemble data while implementing the aCCFs. Indeed, **ensemble data from probabilistic weather forecast allows identifying robustness of mitigation potential of alternative trajectory solutions**. It has been shown that the climate effects of contrails are highly uncertain.
- The climate-optimized flight trajectories using different flight trajectory optimization tools (TOM, ROOST, and EMAC/AirTraf) show a consistent seasonal pattern of climate mitigation potential (higher in winter than summer), which provides evidence to the air space users where the large mitigation gain can be expected.
- „Cherry-picking“ (also known as **"eco-efficient") solutions do exist and can be identified**. Indeed, using the EMAC/AirTraf optimizer on the top 100 routes over different days and seasons has systematically shown „cherry-picking“ solutions, i.e., high climate mitigation gain at a relatively low cost. These aggregated results have also been analyzed in terms of: seasonality (higher climate impact during summer than during winter); contribution of the different species (contrails are dominant); sensitivity to time horizon (mitigation potential is also present).
- **„Win-Win“ solutions do exist and can be identified**. In FlyATM4E case, "win-win" solutions are determined by comparing the optimisation results of ROOST (structured airspace, which mimics the current network of ATS routes relying on DDR2 data) and TOM (continuous optimization on a full 3D free routing airspace). "Win-win" solutions have been identified for all nine investigated routes, which reflects the inefficiencies caused by the route structure (we do not differentiate between horizontal and vertical inefficiencies).

Co-funded by the European Union

We have also assessed how large the climate impact mitigation potential of climate-optimised flight planning in Europe could be considering meteorological variability and uncertainty:

- Using EMAC/AirTraf optimizer on the top 100 routes (and a wide variety of days), we have found climate **mitigation potentials (F-ATR20) of about 20% with 0.5% increase in operational cost in day-time flights (10% mitigation at night)**.

- Using ROOST optimizer (that considers structured airspaces) on the top 100 routes (and a wide variety of days), we have found that the **mitigation potentials are highly variable due to changes in atmospheric conditions**. For the considered case studies, in general, the night-time flights resulted in a higher reduction of climate impacts (≈ 20-50%) compared to daytime (≈ 20-30%). Overall, allowing a **maximum 3% increase in standard operational cost could reduce the climate impact by 20-50%. Allowing a 0.5% cost increase, we could have mitigation potentials of 10 to 30 % at night and 10-20% during the day**.

- Using TOM optimizer (that considers free routing airspaces) on the top 10 routes (and a wide variety of days), we have found that the **mitigation potentials of around 40% at the cost of 2% increase**.

- In the case of win-win situations, by comparing solutions to ROOST and TOM, we have found that, at the reference cost level (i.e., same cost), the climate impact can be reduced between 15% and up to 80% for the investigated routes.

Even though we cannot know (because it is market-driven) what would be an acceptable trade-off between costs and climate impact reduction, **we provide Pareto-optimal solutions that allow to analyse the whole set of possible solutions**.

7.2 Implementation

In terms of implementation in the ATM System, we claim FlyATM4E results present two threads: on the one hand, the usage of aCCFs V1.1 as a MET service enabler; on the other, the possibility of calculating climate-optimal (or eco-efficient) flight plans.

On the usage of aCCFs as a MET service enabler, we can say that:

- The **Python Library based on the merged aCCFs could act as an enabler of the MET service**, thus providing forecasts on aviation's potential climate impact to ATM stakeholders. This would eventually allow decision making to mitigate climate impact in real operations.

- The **Python Library based on the merged aCCFs could be integrated in flight dispatcher software tools**, paving the road towards its implementation in ATM.

- **Further scientific understanding of aviation climate impact and its associated uncertainties is needed**, which would eventually result in an updated version of the library.

On the possibility of calculating climate-optimal (or eco-efficient) flight plans:

- Quantifying the cost of mitigating climate impact in aviation is key to incentivizing climate optimal (or eco-efficient) flights. Though FlyATM4E has started to quantify trade-offs between cost and climate mitigation potential, the development of key performance indicators is lacking.

- We have shown that **"cherry-picking" solutions with large climate mitigation potential at a relatively low cost systematically appear**. However, these large mitigation gains and cost reductions might not be feasible in real world operations due to congestion of airspace, complexity and additional ATM system related considerations. ATM scale assessment is needed to assess the real mitigation potential of the ATM system.

- We have also shown that **"win-win" situations with large climate mitigation potential systematically appear when comparing optimal solutions under constraint airspace with full free-routing airspaces**. Nevertheless, the results indicate that a large climate impact reduction potential might be associated with the allowance of more flexibility when using the airspace, especially linked to altitude changes. This is today not on the table. Understanding whether this mitigation potential is due to horizontal or vertical may be of interest. Note that, according to Eurocontrol[1], "Free route operations offer significant opportunities to airspace users. Once fully implemented in Europe, it should allow the saving of 500.000 nautical miles, 3000 tonnes of fuel, 10.000 tonnes of CO_2 and 3 M€ in fuel cost, every day." They say nothing about climate mitigation potential, but should also be incorporated as an additional benefit.

[1] https://www.eurocontrol.int/concept/free-route-airspace

8 References

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[3] FlyATM4E Deliverable D4.3, 2022: Report on recommendations on regarding the implementation of robust and climate impact reducing ATM operations

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

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[9] 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

[10] 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).