Mitigation Potential of Environmental Optimized Aircraft Trajectories

How to perform environmental optimization of aircraft trajectories impact in Europe

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***Abstract*—Air traffic management as currently under development by the Single European Sky ATM Research program SESAR has an important role to play in reducing environmental impact of aviation by means of green trajectories, in addition to the improvements to be derived from new aircraft and engine technologies. A comprehensive modelling approach is presented which allows identifying aircraft trajectories having a lower environmental impact compared to the fuel optimal solution. Algorithmic environmental change functions are introduced which allow determining impact of aircraft emission at a given position and time from standard meteorological forecast parameters. A case study for three city-pairs is presented using reanalysis meteorological data. Mitigation potential of environmentally optimized trajectory options is analyzed, using a set of different climate impact metrics identifying robust routing options. This study presents results for a multi-criteria environmental assessment of aircraft trajectories relying on an advanced MET service as developed within the Exploratory Research Project ATM4E (SESAR2020). This framework allows studying and characterizing changes in traffic flows due to environmental optimization, as well as studying trade-offs between distinct strategic measures.**

Keywords-air traffic management, environment, climate impact, air quality, environmental impact mitigation, ATMF, environmental change functions, advanced MET services.

I. Introduction

Impact of aviation on environment can be reduced by adopting environmentally-optimized aircraft trajectories, which have a reduced impact on climate change, air quality and noise, so called green trajectories. Environmental impacts of aviation emissions vary with location and time of emission, in particular environmental impact of non-CO_2 emissions, e.g. nitrogen oxides, water vapor, and aerosols. A number of studies have explored opportunities to assess environmental impacts or to optimize environmental impacts of aviation emissions [1], by way of example [2] considering nitrogen oxide and contrail effects simultaneously. A concept of a multi-dimensional multi-criteria assessment of aircraft trajectories has been presented together with an overview on existing literature on trajectory optimization under environmental aspects [3]. However, application of such a comprehensive assessment to European air traffic which allows quantifying mitigation potential of environmental optimized trajectories versus fuel-optimal (or cost-optimal) trajectories using different climate impact metrics in order to assess robustness of trajectory options is missing.

Hence, the paper presents results from a comprehensive performance analysis of environmental optimized aircraft trajectories, focusing on climate impact. Specifically, objectives of this paper are (1) to quantify environmental and economic performance of air traffic in Europe under different optimization criteria, (2) to compare environmental optimized trajectories to cost-optimal and real world trajectories in order to provide an estimate of an overall mitigation gain associated with environmentally optimized aircraft trajectories for different types of climate impact metrics. Results presented here, focus on climate impact, while within ATM4E project, multi-phase simulation involving local air quality and climate were performed, and the overall system was enabled for noise modelling. In this paper we use the term environmental change function (ECF) as defined in [4] to be a quantitative measure of environmental impact of an emission at a specific location and time of emission, together with the expansion to an algorithmic ECF, as explained below.

II. Modelling approach for environmental optimized trajectories

Identifying climate optimal aircraft trajectories requires having environmental impact information available during the flight and trajectory planning process.

A. Overall modelling approach

In order to optimize aircraft trajectories with regards to their environmental impact, a modelling chain has been developed within the SESAR Exploratory Research project ATM4E [1]. The approach relies on expanding an air traffic management system with environmental information by making available temporally and spatially resolved information on environmental impact of aircraft emission.

B. Algorithmic environmental change functions (aECF)

Identification of an environmental optimized trajectory requires having available spatially and temporally resolved information on sensitivity of the atmosphere with regards to environmental impact of an emission. Such 4-dimensional data has been introduced as environmental change function and provides an environmental impact per emitted amount, e.g. for climate impact as average temperature response in 10^{-10} K per kg emission [4].

In order to generate such environmental impact information, which can be made available as an advanced MET service [5] during the flight planning process, ATM4E has developed an approach, which links respective environmental or climate impact to a standard meteorological quantity, e.g. temperature or geopotential [7]. Such environmental change functions are called algorithmic ECFs, as they rely on an algorithm which evaluates meteorological standard quantities at time of emission, in order to calculate the respective environmental change introduced by an emitted amount. During the flight planning process these aECFs are then multiplied with the amount of emission in order to derive environmental impact induced. This means they can be used in a similar way as ECFs as introduced in earlier studies [8][9]. Using these algorithmic climate change functions enables to derive ECFs directly from standard meteorological data, which is a direct advantage for an efficient implementation, as an online calculation of the required impact functions is possible.

C. Aircraft trajectory optimisation

Trajectory optimization is performed within the TOM (trajectory optimization model) which relies on optimal control techniques. In order to enable environmental optimization of aircraft trajectories in TOM an overall objective function is expanded by environmental impacts. When optimizing simultaneously for climate impact and air quality issues, optimization is performed subsequently on three distinct flight segments [4]. For each city pair a set of optimized trajectories is calculated with TOM by varying respective weights of economic and environmental impacts in the objective function. Each set contains more than 60 different possible trajectory options, each optimized for a different weighting of environmental versus economic costs. From this set of trajectories, for each city pair marginal costs of reducing environmental impacts can be deduced.

These individual trajectory options are combined in order to generate a Pareto front for the traffic sample. On the Pareto front those solutions are located which represent the minimum environmental impact for given direct operating cost or overall fuel consumption, equivalent to a respective fuel penalty compared to a fuel-optimal solution. Additionally, a hot spot analysis was performed, where we analyzed interaction of individual trajectories within the traffic sample.

D. Quantifying climate impact with climate metrics

Environmental impact of a trajectory in the overall objective function is calculated by using a specific climate impact metric, an air quality metric, and a noise metric. In the modelling chain used the respective impact function can be adopted to user preferences, according to policy and regulatory issues.

In order to investigate sensitivity of environmental optimization to different climate impact metrics we calculate environmental mitigation gains for a set of different climate impact metrics. Such a sensitivity study allows investigating if proposed trajectory options are robust environmentally-optimized trajectories under different climate impact metrics. A robust routing option requires that environmental impact of green trajectory is lower than from the economically optimal option. Beside average temperature response over 20 years (ATR20) which has been used for environmental optimization we calculate average temperature response over 50 and 100 years (ATR50, ATR100), absolute global warming potential (GWP) and absolute global temperature potential (GTP), both over time horizons of 20, 50 and 100 years.

III. Feasibility study and Case Study for Europe

In this study we present results for three different city pairs an environmental optimized trajectory between two European Cities. The meteorology used for the analysis corresponds to the 18 December 2015 based on ECMWF reanalysis data. The environmental change functions for that specific day are calculated by using meteorological parameters in order to calculate impacts of nitrogen oxides, water vapor and contrails. The objective function combines economic costs with environmental impacts. Within the traffic sample we have analyzed importance of individual city pairs for capacity in European airspace. Trajectories we are analyzing in this paper belong to the top ten connections in terms of available seat kilometers in the reference year. Fig. 1 shows horizontal track and flight profiles (fuel-efficient, and 5% extra cost for the benefit of environment) with an overlay of total environmental impact function.

The overall approach has been applied in a feasibility study for Europe using algorithmic climate change functions and optimizing a full one day full traffic sample of European air traffic. The overall analysis showed a possible mitigation gain in the order of 60 % climate impact (using ATR20) for a fuel penalty of 1% [5]. The validity of algorithmic climate change functions has been evaluated by applying them in a global earth

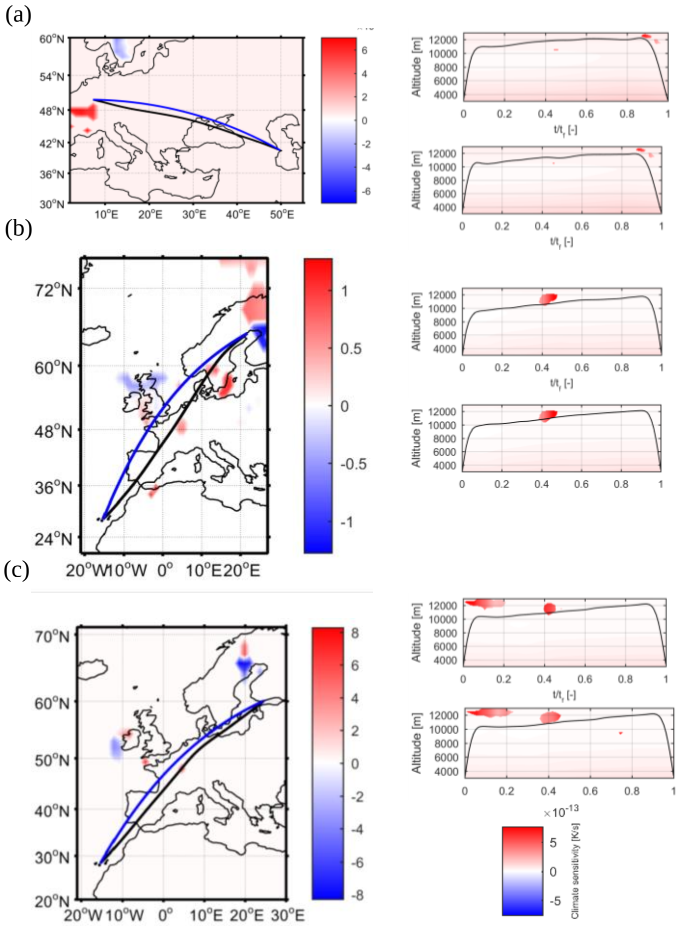

Figure 1. Aircraft trajectories horizontal track (left) for Baku-Lichenstein (a), Lulea-Gran Canaria (b), Helsinki-Gran Canaria (c): great circle (blue) and fuel-optimized trajectory (black). Altitude profile (right): cost optimal case (upper) and environmental optimized case with 0.5% cost increase mitigating climate impact by 32% (lower).

system model [10] with results being available on avoidance of contrails [11].

IV. Performance Assessment of Environmental and Fuel-Optimal Trajectories

Within the ATM framework it is essential to provide performance data for aircraft trajectories resulting from route optimization, comprising fuel efficiency, time efficiency, and also emission information. Additionally, when implementing environmental assessments or optimizations additional performance data is required relating to environmental issues. Typically such information comprises emitted amounts of carbon dioxide, nitrogen oxides, but also information on impacts is desirable, e.g. climate impact, impact on air quality or on noise level.

One important element to assess performance of aircraft operations are performance data relating to individual key performance areas as spelled out within the ATM master plan. Hence the overall ATM system has to be able to demonstrate benefits in terms of environmental performance in order to create an incentive for environmental optimization.

Environmental optimized trajectories require a MET service which provides an environmental impact associated with aircraft operations. Such a MET service provides information on areas where contrails will be formed, Additionally the information is required, which climate impact formed contrails have, together with local effects of emissions with regards to air quality and noise issues. Having such a MET service available enables to perform an environmental assessment and an environmental optimization.

However, no standard procedure has been (identified) defined how to generate such environmental impact information, in order to provide such a service. We present an initial approach and suggest a procedure, how such information can be derived from standard operational weather forecast information (METEO data). Such an approach has three major advantages: (1) efficient generation from available data, (2) high accuracy as directly linked to forecasted weather, (3) development within the weather forecast systems can be directly implemented to improve data product. That means no independent development of forecast abilities is required. ECFs are consistent with overall METEO data used within the system.

V. Mitigation Potential: Comparision of Environmental and Fuel-Optimal Trajectories

Aviation climate impact is, in addition to CO_2, strongly influenced by non-CO_2 emission, such as nitrogen oxides, influencing ozone and methane, and water vapour, which can lead to the formation of persistent contrails in ice-supersaturated regions, and aviation-induced cloudiness. Climate impact of aviation is quantified with climate impact metrics. Among those climate impact metrics typically used are average temperature response (ATR), global warming potential (GWP) and carbon dioxide equivalent. Choice of metric corresponds to priority and societal issues, in term of selected time horizon, with typical values ranging from 20 to 100 years. Average temperature response provides mean change of surface temperature over a selected time horizon.

A. Short- term climate impact (ATR 20)

In this study we used ATR 20 in order to consider short-term climate impacts of aviation. For the three city pairs we show Pareto fronts resulting from environmental optimization of aircraft trajectories following above approach. Overall optimization results in a set of optimized trajectories under differing weighting of economic costs and environmental impacts in the overall objective function. The economically-optimized case (no weight on environment) lies at one end of the Pareto front (right), while the environmental-optimized case lies at the other end (left) representing minimal environmental impacts for this city-pair connection. In between all other optimal solutions are located which consider both criteria with varying weights.

We present results for three distinct city pairs, which range amongst the top 10 connections in Europe with regards to passenger kilometers. The second flight (Figure 1b) is a connection between Sweden and Spain. The flight corridor is located in an area where contrails can form. Trajectory

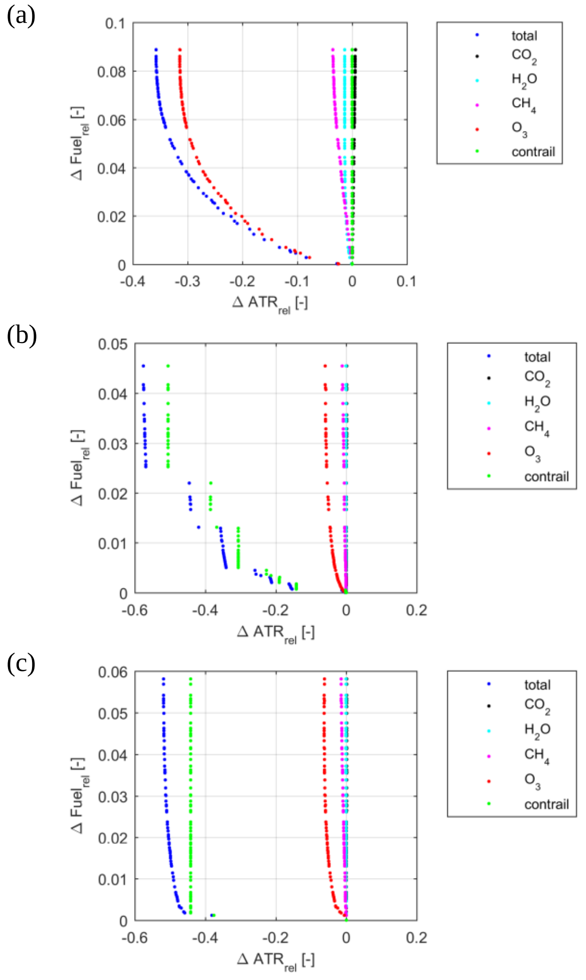

Figure 2. Pareto fronts for aircraft trajectory optimisation showing mitigation of climate impact as average temperature response (ATR20) versus fuel increase for Baku-Luxembourg (*top*), Lulea-Gran Canaria (*middle*), Helsinki-Gran Canaria (*bottom*).

calculation in TOM results in environmental-optimized trajectories which avoid this region by flying slightly lower in order to avoid high values of the environmental change function associated with contrails.

B. Mitigation potential and associated fuel penalty

The optimization of these three routing options identifies also a mitigation potential which we consider as being the expected mitigation gain relative to the associated fuel penalty (or economic costs) as defined in [4]. This quantity is required in order to decide in a system approach which routing options offers the most efficient mitigation option, corresponding to the highest mitigation gain. Mitigation gain is measured in climate impact metrics per economic costs, e.g. K per fuel penalty. In Tab. 1 we indicate mitigation gain for a 0.5% fuel penalty of the three analyzed city pairs. These three values (provided as 10^{-13} K/kg fuel) vary strongly between individual flights by up to an order of magnitude. These results show that for an efficient implementation it will first be crucial to identify trajectory options where mitigation gain is highest, and second that efficient means of transfer between individual flights are defined, equivalent to a trading of emissions or environmental costs.

TABLE I. COMPARISION OF MITIGATION GAINS

ATR 20	**Climate impact mitigation gain**				
	City pair	***ΔATR20 [%]***	***ΔATR20 [10^{-11} K]***	***Δfuel [kg]***	***ΔATR20 / Δ cost***
(a)	UBBB-ELLX[a]	-14.2	-9.7	180.7	-5.3
(b)	ESPA-GCLP[b]	-25.9	-27.7	75.9	-36.5
(c)	EFHK-GCLP[c]	-47.4	-44.8	56.0	-80.0

a. Baku-Luxembourg, b. Lulea-Gran Canaria, c. Helsinki-Gran Canaria

C. Climate metrics for long term climate impact

During the trajectory optimization in this feasibility study we use ATR20 within the objective function. In order to verify robustness of identified routing options and green trajectories, we additionally calculate a set of different metrics. A robust solution has to present a migration gain which means a lower environmental impact compared to the fuel optimal solution.

In order to study robustness of identified routing options presented in Fig. 2, additional climate impact metrics are hence calculated for different time horizons. Typical duration for analyzing the response of the climate system to a respective atmospheric perturbation resulting from emissions vary between short term and long term, from 20 years up to 100 years. In Fig. 3 we present for a set of nine different climate impact metrics Pareto fronts of the city-pair Lulea and Gran Canaria. We show mitigation gain average temperature response, absolute global warming potential (GTP) and absolute global warming potential (GWP), over time horizons of 20, 50 and 100 years. This sensitivity analysis shows that mitigation gain is robust for different climate impact metrics and over all time horizons considered.

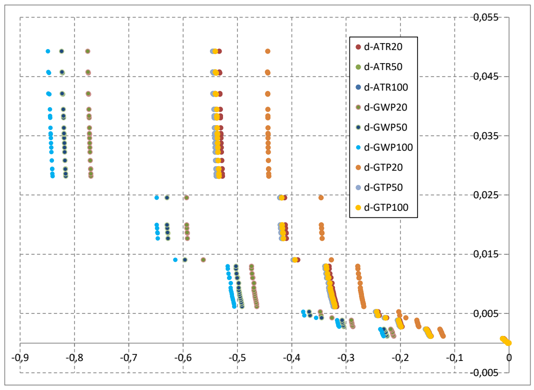

Figure 3. Pareto fronts for aircraft trajectory optimisation showing deltas using a set of climate impact metrics: average temperature response (ATR), absolute global warming potential (GWP), absolute global temperature potential (GTP) for Lulea-Gran Canaria (b).

VI. Discussion

Results from this study demonstrate feasibility of an approach how to optimize aircraft trajectories in order to reduce their environmental impact. We have applied this approach for a full traffic sample in Europe, showing results in more detail for three European city-pairs. Analysis shows potential how to optimize for environment and economic aspects simultaneously, by avoiding non-CO_2 effects in particular from nitrogen oxides, and contrails.

Sensitivity analysis of different climate impact metrics shows as expected that with longer time horizons the non-CO_2 effects become less important. However values remain important as the indirect effect of nitrogen oxides on ozone and hence indirectly on methane has much longer lifetime than contrails. The presented study considers aircraft performance, realistic meteorological conditions from re-analyis, and algorithmic climate change functions originating from complex chemistry-climate model simulations which were evaluated by [7]. However, analysis presented does not take into account airspace structure, e.g. ATC sectors, route charges.

Integration of such an advanced MET service is suggested to be done via the meteorological information interface, due to the fact that algorithmic environmental change functions are calculated as a function of specific weather forecast meteorological information [12]. Combination of environmental and climate impact services can be done with services for the purpose of safety relating to weather events, e.g. thunderstorm and convective hazards [13].

VII. Summary and Conclusion

In this paper we apply an approach for calculation of environmental-optimized aircraft trajectories in Europe in order to quantify environmental mitigation potential by using green trajectories. Such green trajectories result in a reduction of overall climate impact, as they avoid regions which are more sensitive to aviation emissions. Our study considers overall environmental impacts, which means climate impact, and air quality. With regards to climate impact our optimization approach considers effects of CO_2 and non-CO_2 emissions, which is required when aiming to minimize total climate impact. In particular our case study considers effects of nitrogen oxides (on ozone and methane), contrails, as well as direct water vapor emissions.

- Environmental optimization of aircraft trajectories can be enabled by expanding an ATM system with an **advanced MET service** for environmental impacts relying on **Environmental change functions (ECFs).**
- An efficient way to generate environmental change functions, which we propose in this paper, is to use an algorithm which calculates impact from standard meteorological parameters as available in a weather forecast system. For this we introduced the **algorithmic environmental change functions** which enable to provide environmental impact directly from standard meteorological forecast parameters at location and time of emission.
- **Potential mitigation gains** and potentials and robustness of green trajectories can be quantified for each optimized trajectory by using a set of distinct climate impact metrics, in order to identify robust mitigation options.
- **Mitigation potential** in the order of 10's of percent can be achieved for an increased fuel burn of a few percent.

VIII. Outlook

The implementation of such environmental optimized routing would need quantitative performance indicators to be able to demonstrate benefits for the environment relating to the key performance area KP05, in order to gain the confidence of the stakeholder community. An optimization of noise levels has been implemented in the overall concept, but no results have been shown in this study. Results will be presented in a future study.

This concept lays the basis for performing route optimizations in the European airspace using advanced MET information in the light of environmental assessment and optimization of aircraft movements in Europe. To further advance efficient implementation of eco-efficient (green) trajectories a strategic roadmap has been defined [14] of how to implement such a multi-criteria and multi-dimensional environmental assessment and optimization framework into current ATM infrastructure by integrating tailored MET components, in order to make future aviation sustainable.

ATM4E roadmap identified as future research and development activity to increase the technological readiness level of algorithmic environmental change functions. Using aECFs allows efficient implementation of environmental optimization in an overall information infrastructure. Specifically such research needs to address the enhancement of the current concept to fully cover all aircraft impacts, comprising indirect nitrogen oxide effects (ozone, methane), contrail and contrail cirrus, water vapor as well as aviation induced cloudiness resulting from indirect aerosol effect. It further needs to address the incorporation of information on the robustness of the environmental aircraft trajectories, considering uncertainties from weather and climate impact data, as well as representations of aircraft/engine dependence.

The ultimate goal of such a concept is to make available an efficient, comprehensive assessment framework for environmental performance of aircraft operations, by providing key performance indicators on climate impact, air quality and noise, as well as a tool for environmental optimization of aircraft trajectories. This framework would allow studying and characterizing changes in traffic flows due to environmental optimization, as well as studying trade-offs between distinct strategic measures.

ACKNOWLEDGMENT

This work has received funding presented here is part of the project ATM4E which has received funding from the SESAR Joint Undertaking under grant agreement No 699395 under European Union's Horizon 2020 research and innovation program.

The authors of this study would like to thank the team of the SESAR ER project ATM4E, in particular Stavros Stromatas, Envisa SAS and the external experts' advisory board chaired by Herbert Pümpel, WMO for valuable discussions. Work in this article was supported by DLR project Eco2Fly (2018-2020). High performance supercomputing resources were used from the German DKRZ Deutsches Klimarechenzentrum Hamburg.

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