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MITIGATION POTENTIAL OF CLIMATE-OPTIMIZED ROUTING: CONCEPT STUDY FOR EUROPE

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ABSTRACT:

Aviation aims to reduce its contribution to climate change by its CO_2-emission and non-CO_2 effects, e.g. contrail-cirrus and ozone. One option to reduce climate impact is the implementation of operational measures which aim to avoid those atmospheric regions that are in particular sensitive to non-CO_2 aviation effects. Quantitative estimates of mitigation potentials of such eco-efficient routings and climate-optimized aircraft trajectories are required, when working towards sustainable aviation.

A comprehensive modelling approach is presented which is working towards identification of aircraft trajectories having a lower climate impact compared to the fuel optimal solution. A one-day case study for European air traffic using reanalysis meteorological data estimated an overall climate impact reduction of about 30% for an increase of costs of 0.5%, relying on best estimate climate impact information. The climate impact reduction and mitigation potential varies strongly with different routes and climate metrics used. As future steps, air traffic management (ATM) needs to integrate comprehensive environmental impacts and associated forecast uncertainties into route optimisation in order to identify robust eco-efficient trajectories.

1. INTRODUCTION

Impact of aviation on environment can be reduced by adopting climate-optimized aircraft trajectories, which preferably fly into regions where aviation emissions have lower climate impact, so called green trajectories, e.g. [1]. Climate 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 vapour, and aerosols causing changes in atmospheric ozone, methane, particle distribution and aviation induced clouds. A number of studies have explored opportunities to assess environmental and climate impacts or to optimize environmental impacts of aviation [2], by way of example [1] considering nitrogen oxide, water vapour and contrail effects simultaneously.

A concept of a multi-dimensional multi-criteria assessment of aircraft trajectories with a trajectory optimization under climate change aspects has been presented [3], with a more comprehensive overview on existing literature. In a feasibility study [4] this modelling concept of trajectory optimisation was applied for the North Atlantic air traffic and estimated for a set of about 800 trans-Atlantic flights an overall climate impact mitigation potential of up to 25% in overall climate impact (comprising CO_2 and non-CO_2 effects) for an investment of 0.5% costs (DOC, direct operating costs) [5]. Such an expanded Air Traffic Management system has performed a one day case study of European air traffic considering climate change [6] as part of the project ATM4E (SESAR 2020, exploratory research). Fuel-optimal and alternative climate-optimized trajectories of individual connections were presented, on which individual non-CO_2 were drivers of mitigation efforts, e.g. contrail formation, and nitrogen oxide effects [6]. Having such an initial set of alternative trajectory options available, an important question towards implementation is how individual flights change, due to climate impacts taken into account during trajectory optimisation. And how large is the mitigation gain in terms of climate impact.

Hence, this study explores climate optimisation of connections in Europe based on a one-day set of alternative climate optimized trajectories of air traffic. Specifically, objectives of this paper are (1) to present environmental and economic performance of individual connections from a one day case study 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. Finally, paper objective is (3) to present lessons learned from the concept study and to give an outlook on future research.

In this paper we use the term climate change function (CCF) or environmental change function (ECF) as defined in [3], initially established in [7] and applied in [5], to be a quantitative measure of climate impact of an emission at a specific location and time of emission, together with the expansion to an algorithmic ECF, as introduced in [3], and applied in [8]. These ECFs provide a quantitative measure on climate impact by using standard climate metrics, e.g. global warming potential (GWP) or average temperature response (ATR).

2. MODELLING APPROACH FOR CLIMATE OPTIMIZED TRAJECTORIES

Assessing climate impact of aircraft operations and identifying climate optimal aircraft trajectories requires having environmental impact information available during the flight and trajectory planning process. In order to calculate climate impact of aircraft operations, both CO_2 and non-CO_2 effects have to be taken into account, in order to provide total climate impact. While climate impact of CO_2 emission is proportional to the emitted amount, climate impact of non-CO_2 effects shows a strong dependency on location, geographic position and altitude, as well as background conditions and/or time of emission. Such climate impact information is provided in our methodology to the ATM trajectory planning by using 4-dimensional climate change functions.

Our methodology to optimize aircraft trajectories, while taking into account climate impact simultaneously, relies on a concept explored within the Aeronautics research project REACT4C by expanding an air traffic management system with climate impact information [1]. A modelling chain for European Air Traffic has been developed within the SESAR Exploratory Research project ATM4E [3]. During optimization temporally and spatially resolved information on climate impact of aircraft emission is made available to the modelling system for integration as one component in the overall target function [6].

3. CASE STUDY IN EUROPE

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. In this study we present results for individual city pairs between European cities, in order to illustrate the concept when comparing the fuel-optimal solution with climate-optimized solutions. Additionally, we present initial results on application of algorithmic climate change functions for the top 2000 routes. The meteorology used for the case study 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 vapour and contrails. The objective function combines economic costs with environmental impacts. Within the traffic sample we have analysed the importance of individual city pairs for capacity in European airspace. Trajectories we are analysing in this paper belong to the top ten connections in terms of available seat kilometres in the reference year

4. PERFORMANCE ASSESSMENT

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 relating to key performance areas

One important element to assess the performance of aircraft operations are performance data relating to individual key performance areas as spelled out within the ATM master plan, e.g. cost effectiveness, capacity, flight efficiency and flexibility. When implementing environmental assessments and/or optimizations, 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. For that purpose, additional performance data is required relating to environmental impact. Currently such information comprises in particular amounts of emitted carbon dioxide, nitrogen oxides, but for a comprehensive environmental assessment also information on specific impacts are required, e.g. climate impact, impact on air quality or on noise level.

Environmental optimized trajectories require a MET service which provides quantitative information on environmental impact associated with aircraft operations. Such a MET service might provide information on areas where contrails will form. Additionally the information is required, which climate impact those formed contrails have, in order to assess and optimise climate impact. Similar information is required for all non-CO_2 impacts from aviation comprising NO_x-induced effects, water vapour and aerosols. Having such a MET service available enables to perform climate impact assessment and climate-optimization of aircraft trajectories.

However, for the time being, no standard procedure has been identified or defined how to generate such environmental and climate impact information, in order to provide such a service. Within the case study on European Air Traffic, an initial approach was presented and a procedure was suggested, how such information can be derived from standard operational weather forecast information (METEO data) relying on algorithms [3]. Such an approach has three major advantages: (1) efficient generation from available data, (2) 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.

5. MITIGATION POTENTIAL FROM CLIMATE-OPTIMISED ALTERNATIVE ROUTING

Aviation climate impact is, in addition to CO_2, strongly caused by non-CO_2 emissions, such as nitrogen oxides, influencing ozone and methane, and water vapour, which can lead to the formation of persistent contrails in ice-supersaturated regions, as well as aviation-induced cloudiness. To quantify the climate impact of aviation, climate impact metrics are used. Among those climate impact metrics, a metric which is typically used is e.g. average temperature response (ATR), global warming potential (GWP) and carbon dioxide equivalents. The choice of metric corresponds to priority and societal issues, in terms 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. Recent studies are proposing novel concepts to overcome challenges for an adequate representation of short-term effects [8], which can be integrated in the concept developed.

5.1. Change in average temperature response on individual trajectories

Aircraft trajectories of individual connections in Europe have been identified having a lower climate impact (8-42% reduction), for an increase of 0.5% in fuel consumption (Fig. 1).

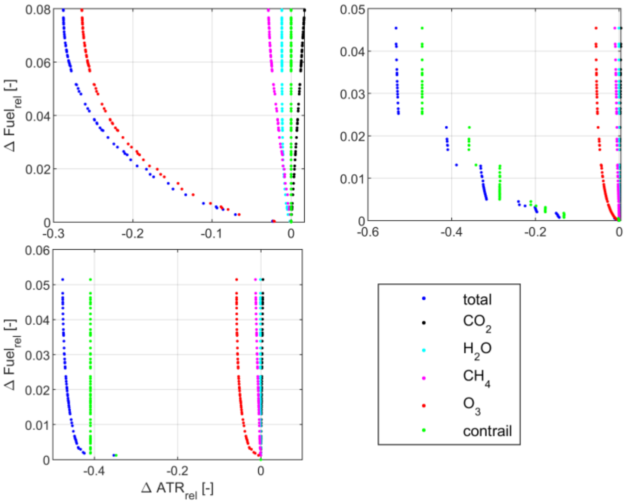

Figure 1: Pareto fronts showing mitigation of climate impact as average temperature response (ATR20) versus fuel increase: Baku-Luxembourg (top left), Lulea-Gran Canaria (top right), Helsinki-Gran Canaria (bottom) from [5].

Mitigation gain versus change in fuel is presented on Pareto fronts, which provide benefit in terms of lower climate impact versus change in fuel consumption based on aircraft trajectory optimisation performed with an expanded ATM system.

5.2. Robustness analysis considering different climate impact metrics

Different metrics to measure climate impact are defined beside ATR, e.g. global warming potential (GWP) and global temperature potential (GTP) for 20, 50 and 100 year time horizons. To analyse robustness of identified climate-optimized solutions we apply different metrics to evaluate if routing options are still showing a lower climate impact compared to the fuel optimal case.

In Figure 2 we present climate impact mitigation potentials for nine different climate metrics on the city pair between Sweden and Spain (Lulea-Gran Canaria). The trajectory optimization was performed based on the metric ATR20. Re-evaluating the optimized trajectories with different climate metrics shows that allowing 0.5% cost increase, the mitigation potentials vary between 20% and 38%, depending on the applied metric. All metrics lead to lower climate impacts compared to the fuel-optimal case. Hence, this sensitivity analysis shows that mitigation gain is robust for different climate impact metrics and over all considered time horizons.

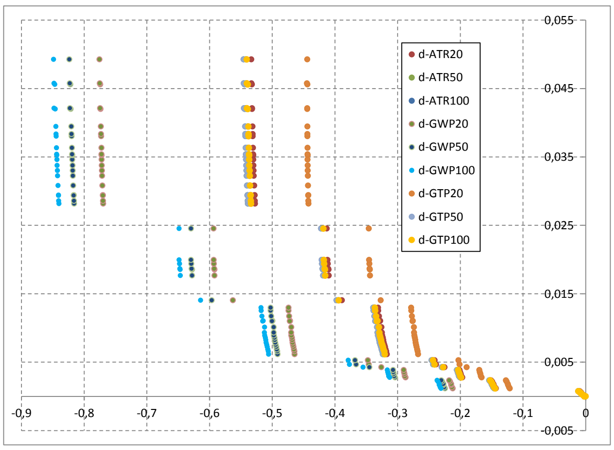

Figure 2: Climate impact mitigation potential (rel. change) versus cost-optimal solution (rel. change) (Lulea-Gran Canaria) using different climate impact metrics: average temperature response (ATR), absolute global warming potential (GWP), absolute global temperature potential (GTP).

5.3. Mitigation gain in European Air Traffic

For an increase of 0.5% in fuel, on individual connections, a climate impact mitigation gain between 8 and 42% has been identified originating from contrail and contrail cirrus avoidance as well as avoiding nitrogen oxide warming. When combining the top 2000 European trajectories, an overall Pareto front can be generated (Fig. 3) which shows a reduction of about 30% in ATR20 for an increase of 0.5% in fuel consumption.

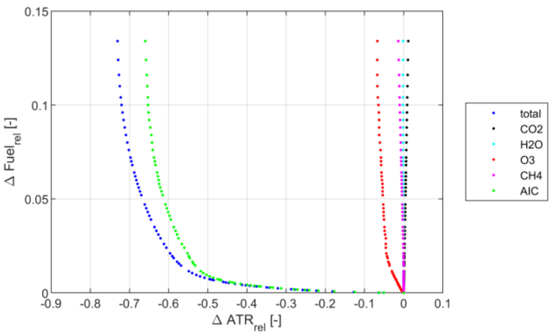

Figure 3: Pareto front showing reduction in average temperature response (ATR20) versus fuel increase on top 2000 routes in Europe (adapted from [9]).

In the meteorological situation prevailing on that specific day, mitigation gain is by a large extend achieved by avoiding contrail and contrail cirrus regions, and to a much lesser extend from avoiding warming due to nitrogen oxide emissions. Such mitigation gains need to be captured in performance indicators. Hence an expansion with new performance metrics on environment and climate impacts is required [10].

6. DISCUSSION

Results from this study demonstrate feasibility of an approach 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. The validity of algorithmic climate change functions has been evaluated by applying them in a global earth system model [11] with results being available on avoidance of contrails [8].

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 reanalysis, 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 [3]. 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 [12].

7. SUMMARY

A study on climate-optimized aircraft trajectories in Europe is presented in order to quantify 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. 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 vapour 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 is to use algorithms which calculate 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 each location and time of emission.
- Potential mitigation gains 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.
- Implementation of state of the art knowledge on aviation non-CO_2 effects is required, comprising contrail, contrail cirrus, water vapour, aerosols and nitrogen oxides.

8. CONCLUSION AND OUTLOOK

With the help of advanced MET-services providing information on climate impact of aviation emissions during trajectory optimisation, ATM is enabled to identify aircraft trajectories in the European airspace which have a lower climate impact. A prerequisite for the implementation of climate-optimized aircraft routing is to have available such spatially and temporally resolved information on climate impact.

The concept of algorithmic climate change functions has been established and explored in the European Airspace to represent an efficient option to derive such climate impact information from standard meteorological (forecast) data products. Validation of these algorithmic climate change functions for nitrogen oxide emission impact has been successfully demonstrated [8]. Further validation of algorithmic climate change functions is required, both for other non-CO_2 emissions impacts, e.g. contrails and water vapour, as well as for other regions of the globe.

Estimating impact of aviation emissions in terms of their contribution to climate change is still subject to research and recent results indicate, that individual non-CO_2 effects might be underestimated depending on method applied, e.g. [13]. In the light of identifying options to reduce overall climate impact, it is required to evaluate robustness of impact mitigation for these alternative trajectories not only using different metrics, but also by integrating further knowledge on uncertainties and variability in trajectory optimisation.

An assessment of the mitigation potential for aviation climate impacts due to alternative routing, comprising CO_2 and non-CO_2 impacts, also in terms of global air traffic needs to be provided, in order to estimate potential benefits from such alternative aircraft routing strategies. Such assessments, taking into account most recent scientific understanding, provide a basis for future research on how to mitigate climate impact of aviation, which is within the scope of two new research projects (2020-2023, Aeronautics). ACACIA (Advancing the Science for Aviation and ClimAte) is improving scientific understanding on non-CO_2 impacts of aviation comprising with a particular focus on aerosol indirect effects and nitrogen-oxide induced effects. ClimOP (Climate Assessment of Innovative mitigation strategies towards operational improvements in aviation) is focussing on identifying, evaluating and supporting the implementation of promising mitigation options towards sustainable aviation.

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