ROBUSTNESS OF CLIMATE-OPTIMIZED TRAJECTORIES AND MITIGATION POTENTIAL: FLYING ATM4E

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Abstract. Aviation can reduce its climate impact by controlling its CO_2-emission and non-CO_2 effects, e.g. aviation-induced contrail-cirrus and ozone caused by nitrogen oxide emissions. One option is the implementation of operational measures which aim to avoid those atmospheric regions that are in particular sensitive to non-CO_2 aviation effects, e.g. where persistent contrails form. Quantitative estimates of mitigation potentials of such climate-optimized aircraft trajectories are required, when working towards sustainable aviation. Results are presented from a comprehensive modelling approach which is working towards identifying such climate-optimized aircraft trajectories. The overall concept relies on a multi-dimensional environmental change function concept, which is capable of providing environmental impact information to air traffic management (ATM) and which in principal could include the noise and air quality impacts. A one-day case study with a weather situation containing regions with high contrail impacts for European air traffic estimated an overall climate impact reduction of about 30% for an increase of costs of 0.5%, relying on best estimate for climate impact information. The climate impact reduction and mitigation potential varies strongly with individual routes. By using a range of different climate metrics, the robustness of proposed mitigation trajectories is assessed. Sustainable ATM needs to integrate comprehensive environmental impacts and associated forecast uncertainties into route optimisation in order to identify robust eco-efficient trajectories.

Keywords: climate optimisation, air traffic management, eco-efficient trajectories

INTRODUCTION

The impact of aviation on the environment can be reduced by adopting climate-optimized aircraft trajectories, which preferentially fly in regions where aviation emissions have lower climate impact, so-called green trajectories, e.g. Green (2005). The climate impact of aviation is caused by CO_2 and non-CO_2 effects; hence for climate-optimisation, individual effects have to be taken into account simultaneously, in order to assess and minimize the total climate impact. Impacts of non-CO_2 effects depend on the location and time of emission, e.g. contrail formation and photochemical ozone production. Hence, planning green trajectories requires spatially and temporally resolved information on climate impact of aviation emissions to be available. A methodology for performing a multi-criteria environmental and climate impact assessment of aircraft trajectories has been established (Matthes et al., 2017) within the SESAR Exploratory Project ATM4E. It relies on a concept of climate change function (CCF) or environmental change function (ECF) (which in principal can also include metrics to measure noise and air quality impacts) as described in Matthes et al. (2012). This was applied to North Atlantic Air Traffic in Grewe et al. (2014a,b), to provide a quantitative measure of climate impact of an emission at a specific location and time of emission. When working towards climate-optimisation of air traffic trajectories in Europe, the identification of mitigation potential is crucial. It is necessary to provide a quantitative estimate of the possible reduction of climate impact of aviation, its mitigation potential, due to climate-optimized trajectories compared to an associate increase in direct operation costs. However, identifying climate-optimized trajectories has to overcome the issue of uncertainties related to quantitative estimates of aviation climate impact. In addition to uncertainties of weather forecast and climate impact estimates, also the choice of climate metric constitutes a source of uncertainty. However, the overall climate objective largely determines the choice of the climate metric (Grewe and Dahlmann, 2015). Here, we evaluate the climate impact as near-surface temperature change, or indicators thereof, for a strategic change in routing (Grewe et al. 2014a), not only applied once, but generally in future. This largely limits the choice of climate metrics, but still some choices are to be made, such as the time horizon, e.g. 20, 50 or 100 years, on which physical climate impacts are analysed. In order to deal with uncertainties, methodologies are required which have the capability to identify robustness of an alternative trajectory.

Hence, this paper presents a methodology on how to investigate and integrate uncertainty when identifying climate-optimized trajectories, in order to characterise and consider the robustness of an identified mitigation trajectory. As a case study for introducing a robustness measure in climate-optimisation of trajectories we use a one-day traffic sample of air traffic in Europe using realistic weather reanalysis data to characterise the atmosphere from ERA-Interim. Objectives of this paper are (1) to present environmental and economic performance of individual city pairs under different optimization criteria resulting in a set of distinct alternative aircraft trajectories, (2) to compare climate optimized trajectories to fuel optimal trajectories in order to provide an estimate of overall mitigation gain associated with environmentally optimized aircraft trajectories. We evaluate the climate impact using a set of different climate impact metrics in order to identify robustness of proposed solutions. We do not consider here explicitly the important issue of the reliability of weather forecasts, which are required to enable flight planning in practice, nor do we take into account that, in reality, many real world trajectories depart from fuel-optimal trajectories.

METHOD TO IDENTIFY CLIMATE-OPTIMISED AIRCRAFT TRAJECTORIES

The concept applied in this study to optimize aircraft trajectories, while simultaneously taking into account climate impact, relies on a concept explored within the Aeronautics research project REACT4C by expanding an air traffic management system to include climate impact information (Matthes et al., 2012; Grewe et al., 2017). In this study we perform a multi-criteria trajectory optimisation under different target functions (Matthes et al., 2017). Our methodology to assess the climate impact of aircraft operations, and to identify climate optimal aircraft trajectories, requires having environmental impact information available during the flight and trajectory planning process. In order to calculate total climate impact of aircraft operations, both CO_2 and non-CO_2 effects have to be taken into account. While climate impact of CO_2 emission is proportional to the emitted amount of CO_2 (and fuel), and is independent of where that emission occurs, the 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. We apply an expansion of the CCF concept (Frömming et al., 2020) to an algorithmic CCF (aCCF) as developed in van Manen and Grewe (2019) and Yin et al. (2018), partially verified in Yin et al. (2018) and applied, e.g., in Yamashita et al. (2019). These algorithmic CCFs provide an easy to use estimate of the climate impact of a local emission and hence constitute a tradeoff between applicability (fast calculation time) and accuracy. They provide a quantitative measure of climate impact by using standard climate metrics, such as the global warming potential (GWP) or average temperature response (ATR), derived from standard meteorological parameters though following the overall climate objective (see above). This climate impact information is provided in our methodology to the ATM trajectory planning by integrating 4-dimensional climate change functions, during trajectory optimisation within TOM (trajectory optimisation module) into the overall target function (Matthes et al., 2012). By varying weights of individual components in this overall target function (e.g. by putting more weight on environmental and climate impacts) a set of distinct aircraft trajectory optimisation solutions is calculated for individual city pairs (Lührs et al., 2020). In our analysis of routing options we calculate for each city pair a set of 75 alternative trajectories using different weights. Overall climate impact of alternative trajectory solutions is provided as CO_2 and non-CO_2 effects of emissions comprising NO_x (on ozone and methane), contrail cirrus and water vapour.

PERFORMANCE AND ROBUSTNESS ASSESSMENT OF CLIMATE-OPTIMIZED TRAJECTORIES

Within a collaborative decision making framework it is crucial to quantify potential benefits and associated costs of alternative routing strategies. For this purpose, in our study of climate-optimized trajectories we have expanded performance assessment of key performance areas by a comprehensive climate impact assessment. Standard performance indicators we provide in our performance assessment are estimates on fuel efficiency, time efficiency as well as emissions and associated climate impact. As a novel aspect in our overall performance assessment we provide estimates of robustness parameters of proposed alternative climate-optimized trajectory solutions. We introduce robustness of a climate-optimized trajectory with a parameter characterising if climate impact of a trajectory under variation of relevant external parameters remains lower than impact of reference solution. Specifically, we assess if the alternative solution has a lower climate impact under different physical metrics over different time horizons (e.g. ATR_{20}, GWP_{100} where the number indicates the time horizon in years). A robust solution is characterised by presenting a benefit under every variation. However, if a variation exists, e.g. one metric indicates a higher climate impact while another indicates a lower climate impact, such an alternative trajectory is not a robust solution in terms of climate-optimization. As a parameter of robustness, we present for each alternative trajectory solution its range of mitigation benefits. As part of our robustness analysis, we calculate climate impact for a set of different available climate impact metrics, comprising GWP, ATR and global temperature change potential (GTP). In practice, the particular choice of emission/climate metric depends on the overall aims of a mitigation policy and policymaker preference.

ONE-DAY CASE STUDY OF EUROPEAN AIR TRAFFIC

This methodology of identifying climate optimized trajectories is applied in a case study for Europe, simulating and optimising one full day of air traffic using realistic meteorological data from weather reanalysis data. Performance analysis of aircraft routing comprises, beyond fuel and time efficiency, additional quantification of total emissions and an assessment of total climate impact due to CO_2 and non-CO_2 effects. The meteorology used for this case study corresponds to real world meteorological situation from 18 December 2015 based on ECMWF reanalysis data. This day is characterised by a high traffic volume, a low number of regulations (weather-, ATC-, and aerodrome related) as well as an interesting weather situation. For a one day traffic sample trajectory optimisation was performed within an expanded TOM calculating for each city pair a set of alternative aircraft trajectories (Lührs et al., 2020). In the next step, air traffic has been climate-optimized in four different dimensions focusing on the climate impact of the en-route segment of the flight.

Based on this meteorological data, we calculate algorithmic climate change functions for non-CO_2 impacts on that specific day comprising impacts of nitrogen oxides (on ozone and methane), water vapour and contrail cirrus. The target function in the optimisation combines economic costs with environmental impacts. Within the traffic sample described above we have analysed the importance of individual city pairs for capacity in European airspace and ranked them according to their transport capacities. Individual trajectories analysed in this paper represent the top-10 connections in terms of available seat kilometres, as identified in an analysis of seat kilometres in the reference year according to scheduled flights data.

MITIGATION POTENTIAL OF CLIMATE-OPTIMIZED TRAJECTORIES

We present results on climate-optimized trajectories comparing flight altitude and position of trajectories on top-10 connections in Europe showing overall performance in terms of fuel efficiency and environmental efficiency by comparing the fuel-optimal solution with climate-optimized solutions. We analyse individual components in the total climate impact, identifying role and importance of non-CO_2 contributions. Additionally, we will present an overall climate-optimisation of the top-2000 routes by identifying routing options with lowest mitigation costs.

Alternative trajectories with lower climate impact

As a result of the climate optimisation of aircraft trajectories between each city pair we achieve from our modelling approach a set of alternative trajectories. We present horizontal track and vertical profile of three top-10 connections in Europe (Fig. 1).

Climate impact metrics are used to quantify the climate impact of aviation. 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. Recent studies are proposing novel concepts to overcome challenges for adequate representation of short-term effects (Etminan et al., 2016; Allen et al., 2016; Grewe et al., 2019) which can be integrated in the concept developed.

We present results for distinct city pairs, which are amongst the top-10 connections in Europe with regard to passenger kilometres. Flight corridors are located in areas where contrails can form (e.g. the dark red patches shown in Fig. 1). Trajectory calculation in TOM results in environmental-optimized trajectories which avoid these regions by flying slightly lower in order to avoid high values of the aCCF associated with contrails. By comparing mitigation potentials [pK/kg fuel] it is possible to identify those alternative city pairs where most efficiently climate-optimisation of trajectories should be implemented.

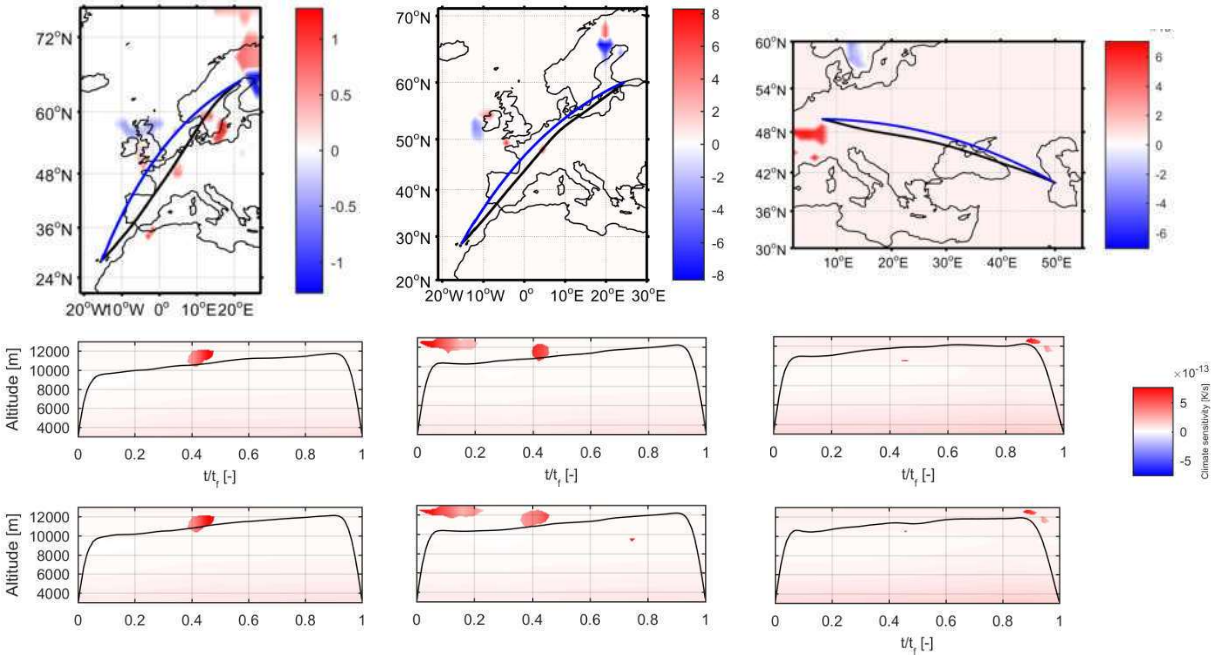

Figure 1. Aircraft trajectories (*top*) Lulea-Gran Canaria (*left*), Helsinki-Gran Canaria (*middle*), Baku-Luxembourg (*right*): great circle (blue), fuel-optimized trajectory (black). Altitude profile: fuel optimal case (*middle row*) and climate optimized case with 0.5% cost (*bottom row*), indicating algorithmic climate change functions warming (red) and cooling impacts (blue).

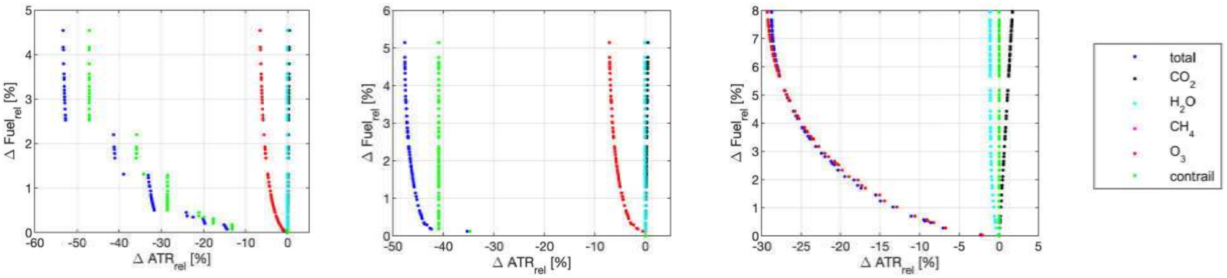

Figure 2. Pareto fronts for aircraft trajectory optimisation showing average temperature response (ATR_{20}) vs. fuel increase Lulea-Gran Canaria (*left*), Helsinki-Gran Canaria (*middle*), Baku-Luxembourg (*right*) and individual effects. For given fuel increase, dark blue dots show the optimal climate change impact from the possible routes available. Other individual dot colours indicate the CO_2 and non-CO_2 climate impacts for that alternative route.

In order to identify the role and importance of individual aviation emission effects as well as their importance in mitigation solutions, we present individual components of total climate impact (CO_2 and non-CO_2 effects) of the climate-optimal trajectories for a given fuel penalty compared to (theoretical) fuel optimum (Fig. 3). Due to climate-optimisation, the relative contributions from non-CO_2 effects to total climate impact decreases as the fuel use increases; depending on the particular route and meteorological conditions along the trajectory, reductions are dominated by either contrail cirrus avoidance or reduction in nitrogen oxides effects. On the route between Baku and Luxembourg (Figure 3, right) on the specific day no contrails can form along the trajectory and hence the climate impact from aviation induced cloudiness is zero. On the fuel optimal trajectory, the climate impact of CO_2 emissions account for 23% of total climate impact, hence non-CO_2 effects contribute 77%. Specifically, impacts of nitrogen oxides contribute 74% and direct water vapour emissions 3%. On the climate-optimised trajectories, these relative contributions change: contributions due to non-CO_2 effects decrease to 74%, 73%, 70%, and 65% for climate-optimised cases considered, respectively for the 0.5%, 1%, 2% and 5% fuel increase that results from climate-optimisation. This additional fuel enables a reduction in total climate impact calculated to be equal to 9%, 15%, 20%, and 30%, respectively. On the route *Helsinki-Gran Canaria* (Figure 3, middle) contrails can form over France (Fig. 1). On the fuel optimal trajectory CO_2 impacts contribute 11% while non-CO_2 effects contribute 89%, with impacts from nitrogen oxides and contrail cirrus contributing about the same order of magnitude, 45% and 43% respectively, and water vapour 1%. Following climate-optimisation, relative CO_2 contributions increase while non-CO_2 contributions decrease. Specifically with a fuel increase of 0.5%, climate impacts due to contrail cirrus can be completely avoided resulting in a reduction of total climate impact by 47% (individual contributions: CO_2 20%, NO_x 78%, water vapour 2%).

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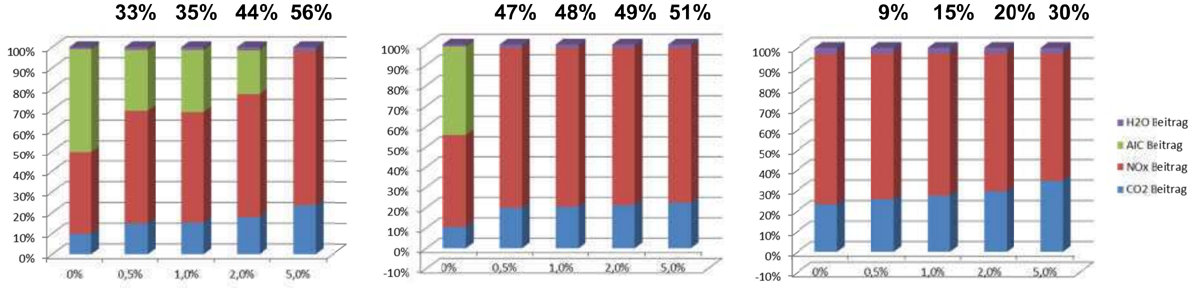

Figure 3. Individual contributions to total climate impact (ATR20) Lulea-Gran Canaria (*left*), Helsinki-Gran Canaria (*middle*), Baku-Luxembourg (*right*); shown for individual mitigation trajectories allowing fuel increase by 0.5%, 1%, 2% and 5% and fuel optimal (0%). Numbers on top indicating decrease of total climate impact for respective alternative trajectory.

During climate optimisation relative contributions from non-CO_2 effects decrease from 89% to 80%, 79%, and 78%, for fuel increases by 0.5%, 2%, and 5%.

Similarly, on the route *Lulea-Gran Canaria* on that day fuel optimal trajectory CO_2 contributes only 10% (Fig 3, left), while non-CO_2 impacts contribute 90%; nitrogen effects 40% and contrail cirrus 50%, respectively. Following climate optimisation these non-CO_2 contributions drop to 85%, 82% and 77%, respectively, associated with reductions of climate impact by 33% of up 56%, for increases in fuel burn between 0.5% and 5%.

On this route it is most efficient to mitigation contrail cirrus effects. On the Helsinki to Gran Canaria route our analysis shows, initially efficient mitigation originates from contrail cirrus effects. Once contrail cirrus impacts are avoided, further reductions at higher costs, can be achieved due to mitigation of the nitrogen oxide effect. In our feasibility study using aCCFs initial mitigation gains of up to 18 pK/(kg fuel), an alternative trajectory is calculated with small fuel penalties here, avoiding more than 40% climate impact. Later mitigation associated to nitrogen oxide effects show considerably lower gains of only up to 8 pK/(kg fuel), which then decrease down with 1-2 pK/(kg fuel). On the connection Baku-Luxembourg our analysis calculates lower values of mitigation gains starting from values of about 1 pK/(kg fuel), followed by smaller values, by an order of magnitude.

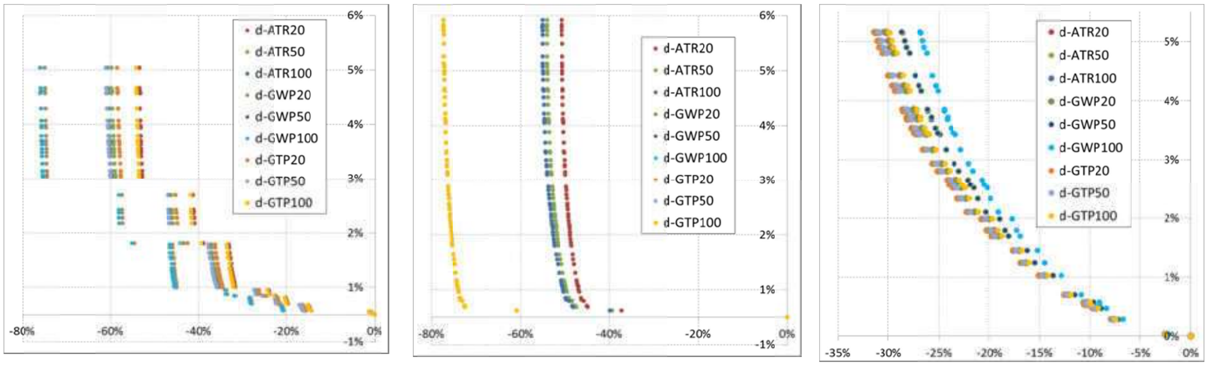

Figure 4. Pareto front on climate impact reduction vs. fuel change [%] for different climate metrics: Lulea-Gran Canaria (*left*), Helsinki-Gran Canaria (*middle*), Baku-Luxembourg (*right*);

In order to investigate robustness of identified alternative trajectories we calculate associated climate impact using a set of different climate impact metrics (Fig. 4). We calculate three different climate impact metrics using ATR, GWP, and GTP, over three distinct time horizon, leading to nine different climate impacts metrics, and evaluate associated change in climate impact. Identified trajectories show positive mitigation gains, hence they are robust under different climate impact metrics. On the Lulea-Gran Canaria range of climate impact reduction for a fuel penalty of 0.5% is equal to 8-10% using different climate metrics, and 13-15% for 1% fuel penalty. We propose to use this range of climate impact reduction as robustness parameter, testing sign of climate impact changes calculated. Overall robustness analysis on our presented alternative trajectories shows that identified alternative trajectories are robust under the selected set of climate impact metrics.

The decrease of non-CO_2 impacts due to climate optimization can also be illustrated in the concept of calculating total impacts, CO_2 and non-CO_2, with a simple multiplication factor based on CO_2 impacts, a weighting factor to obtain equivalent CO_2 (Table 1). We calculate on the Baku-Luxembourg in the fuel optimal case that CO_2 impacts have to be multiplied by a factor of 4.3 in order to quantify total climate impacts, but only with a lower value of 2.9 in the climate-optimised case. On the Helsinki-Gran Canaria route this factor reduces from 9.5 down to 4.5, and on the Lulea-Gran Canaria route drops from 10.2 down to 4.3. Our analysis shows that with climate optimisation, we find a clear reduction in the multiplication factor, from values of up to 10 down to about 3, hence a reduction of non-CO_2 impacts.

Table 1. Multiplier to CO_2 emissions in order to represent the total CO_2 and non-CO_2 climate impact for individual city pairs for relative fuel increases up to 5%.

Route / Fuel increase	0%	0.5%	1%	2%	5%
EFHK-GCLP	9.5	5.0	4.9	4.7	4.5
UBBB-ELLX	4.3	3.9	3.7	3.4	2.9
ESPA-GCLP	10.2	6.8	6.6	5.6	4.3

Our feasibility study provides initial estimates for European air traffic, involving intra-ECAC flights, applying a bottom-up approach. An assessment of the top-2000 routes shows (Lührs et al., 2020) on that specific day climate impact can be mitigated by 46% for an increase of 0.5% fuel. Climate impact in the fuel optimal case is dominated by non-CO_2 effects (90%), getting lower flying on alternative trajectories (down to 83% for 0.5% fuel increase).

DISCUSSION

This study demonstrates the feasibility of an approach to optimize aircraft trajectories by using spatially and temporally resolved aCCFs in order to reduce their environmental impact, while providing parameters on robustness of identified mitigation solutions. We have applied this approach for a full traffic sample for a single day in Europe, showing results in more detail for three European city-pairs. Analysis shows the clear potential to optimize for environment and economic aspects simultaneously, by avoiding non-CO_2 effects in particular from nitrogen oxides, and contrails, while also assessing the robustness of these optimised trajectories to the choice of climate metric. A sensitivity analysis shows clearly a small impact of the choice of the climate metric if they all follow a given political objective (here: climate impact evaluation of a strategic and durable change in routing).

As part of our analysis in this feasibility study we have the ability to identify routes and associated trajectories which offer a large mitigation potential with high mitigation gains. Specifically, we presented alternative routes which showed a strong mitigation gain due to contrail avoidance in our feasibility study in that specific meteorological situation that day over Europe. Our full paper will comprise a more comprehensive evaluation on total impacts for full traffic sample and on strong forcing calculated for contrail cirrus, in order to assess to what extend our estimates can be confirmed from, e.g. considerations of radiative transfer in the atmosphere and satellite images. In our feasibility study they appear as big hits, in terms of offering a large mitigation gain, and hence merit further investigation.

Comparing our estimates of climate impact from European Air Traffic on that specific one-day case study with estimates on global climate impact, we find that our analysis covers about 3% of global fuel consumption. Comparing total climate impacts of our top-2000 routes with impact of a global fleet (e.g. Matthes et al., 2020) we find that our estimates on total climate impact are about 6% higher, and contributions from non-CO_2 differ slightly.

The presented study considers aircraft performance, realistic meteorological conditions from reanalysis, and algorithmic climate change functions (aCCF) originating from complex chemistry-climate model simulations which were derived by van Manen and Grewe (2019) and Yin et al. (2020). However, the analysis presented does not take into account airspace structure, e.g. ATC sectors, route charges. It also does not account for other environmental impacts beyond climate change, or the ability to accurately forecast the weather conditions sufficiently far ahead for flight planning; this would be a necessity for optimisation to be effective.

We suggest that integration of such an advanced MET service should be done via the meteorological information interface to flight-planning processes, due to the fact that aCCF are calculated as a function of specific weather forecast meteorological information (ATM4E final report, 2017) Combination of environmental and climate impact services can be done in conjunction with other services for the purpose of safety relating to weather events, e.g. thunderstorm and convective hazards (Matthes et al., 2018).

Depending on the atmospheric region where aircraft fly, overall climate impact of trajectories is dominated by individual non-CO_2 impacts. This becomes also apparent when identifying from which effect mitigation gains originate. On the city pair between Lulea and Gran Canaria, a considerable reduction in overall climate impact can be achieved by avoiding regions which are sensitive to contrail formation. By contrast, on the connection between Baku and Luxembourg, mitigation gain originates from lowering the flight altitude and avoiding warming effects of nitrogen oxides emissions. We have applied a climate metric which assumes sustained emissions, as we assume that a respective routing strategy would be flown on every day of the year, leading to sustained impacts.

CONCLUSION AND OUTLOOK

The overall approach of climate-optimisation of aircraft trajectories has been successfully applied within this feasibility study for Europe using algorithmic climate change functions and optimizing a one day full traffic sample of European air traffic. This extends previous work on trans-Atlantic flights (Grewe et al. 2017). As a result of this analysis, climate-optimized trajectories have been identified and characterised by their potential mitigation gain and their non-CO_2 associated contributions, as well by demonstrating their robustness to different climate impact metrics, within the prototypic aCCFs adopted.

We conclude that climate 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 climate change functions is to use algorithms which calculate impact from standard meteorological parameters that are available in a weather forecast system. For this we introduced the aCCFs which enable providing climate impact information directly from standard meteorological parameters at each 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 mitigation options which are robust under different climate impact metrics. 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 in particular contrail cirrus, nitrogen oxides (ozone, methane) as well as, potentially, indirect aerosol effects, once these aerosol effects are better understood.

The implementation of such environmental optimized routing would need quantitative performance indicators to be able to demonstrate benefits for the environment and more specifically to climate impacts relating to the key performance area environment (KP05), in order to gain the confidence of the stakeholder community.

This concept lays the basis for performing route optimizations in the European airspace using advanced MET information in the light of climate impact assessment and optimization of aircraft movements in Europe. To further advance efficient implementation of eco-efficient (green) trajectories, a strategic roadmap has been defined (ATM4E, 2018b). This proposes a route 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 algorithmic ECFs allows efficient implementation of environmental optimization in an overall information infrastructure. Ignoring the representation of relevant non-CO_2 impacts in an overall assessment framework, e.g. because they are considered negligible (or too uncertain), can lead to wrong estimates of total climate impact, and even create misleading incentives, if trade-offs are not adequately taken into account.

With this study an important step towards assessment of robustness information was made, while further research should address the incorporation of information on robustness of the environmental aircraft trajectories, considering uncertainties from weather and climate impact data, as well as representations of aircraft/engine dependence. An adequate implementation of individual sources of uncertainty should help to identify robust climate impact mitigation solutions and trajectories.

However, as estimated by climate impact assessment studies, e.g. Lee et al. (2010), Grewe et al. (2017), there still exists uncertainties in the quantitative estimates of climate impact of aviation using radiative forcing as a metric. Here, our approach introduced could also be applied in order to estimate parameters of robustness of identified alternative, climate-optimized trajectories with regard to its environmental impact. 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 environmental impacts comprising climate impact, air quality and noise, which enables identification and environmental optimization of aircraft trajectories. Eventually, such a framework will allow the quantification of the climate impact mitigation potential, studying and characterizing changes in traffic flows due to environmental optimization, as well as studying trade-offs between distinct strategic measures.

ACKNOWLEDGEMENTS

The project leading to this study has received funding from the SESAR Joint Undertaking under grant agreement No 699395 under European Union’s Horizon 2020 research and innovation programme” within the Exploratory Research project ATM4E. Part of the work has Individual authors of this study receive funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 875503 (ClimOP). Work in this article was supported by DLR project Eco2Fly (2018-2022). High performance supercomputing resources were used from the German DKRZ Deutsches Klimarechenzentrum Hamburg.

REFERENCES

Allen, M., Fuglestvedt, J., Shine, K., Reisinger, A., Raymond T., Pierrehumbert, R.T., Forster P.M., New use of global warming potentials to compare cumulative and short-lived climate pollutants. Nature Clim Change 6, 773–776. https://doi.org/10.1038/nclimate2998, 2016.

ATM4E, Conceptual Roadmap, D4.3, June 2018, deliverable available under www.atm4e.eu/workpackages/pdfs, Exploratory Project, SESAR-04-2015, Grant No. 699395, 2018.

Frömming, C., Grewe, V., Brinkop, S., Haslerud, A.S., Rosanka, S., van Manen, J., and Matthes, S., The REACT4C Climate Change Functions: Impact of the actual weather situation on aviation climate effects, in preparation, 2020.

Green, J. Air Travel-Greener by Design. Mitigating the environmental impact of aviation: Opportunities and priorities. Aeronaut. J. 2005, 109, 361–418

Grewe, V., Matthes, S., Dahlmann, K., The contribution of aviation NO_x emissions to climate change: are we ignoring methodological flaws, Environ. Res. Lett., 14, 121003, 2019.

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

Grewe, V.; Champougny, T.; Matthes, S.; Frömming, C.; Brinkop, S.; Søvde, O.; Irvine, E.; Halscheidt, L. Reduction of the air traffic’s contribution to climate change: A REACT4C case study. Atmos. Environ.,94, 616–625, 2014b.

Lee, D.; Pitari, G.; Grewe, V.; Gierens, K.; Penner, J.; Petzold, A.; Prather, M.; Schumann, U.; Bais, A.; Berntsen, T.; et al. Transport impacts on atmosphere and climate: Aviation. Atmos. Environ. 2010, 44, 4678–4734.

Lührs, B., Linke, F., Matthes, S., Grewe, V., Yin, F. Shine, K.P. Climate optimized trajectories in Europe, in "Making Aviation environmentally sustainable", Vol 1, 3rd ECATS Conference 2020.

Matthes, S., Ling, L., et al., Mitigation of aviation's non-CO2 climate impact by changing cruise altitudes, in in "Making Aviation environmentally sustainable", Vol 1, ECATS 3rd Conference, 2020.

Matthes S, Grewe, V, Dahlmann, K, Frömming, C, Irvine E; Lim L, Linke F, Lührs B, Owen B, Shine K P, Stromatas S, Yamashita H, and Yin F, 2017. A Concept for Multi-Criteria Environmental Assessment of Aircraft Trajectories, Aerospace 2017, 4, pp. 42; doi:10.3390/aerospace4030042.

Matthes, S.; Schumann, U.; Grewe, V.; Frömming, C.; Dahlmann, K.; Koch, A.; Mannstein, H. Climate optimized air transport. In Atmospheric Physics: Background-Methods Trends; Schumann, U., Ed.; Springer: Berlin/Heidelberg, Germany, 2012; pp. 727–746, doi: 10.1007/978-3-642-30183-4_44.

van Manen, J., and Grewe, V., Algorithmic climate change functions for the use in eco-efficient flight planning, Transp. Res. Part D 67, 388-405, doi:10.1016/j.trd.2018.12.016, 2019.

Yamashita, H., Yin, F., Grewe, V., Jöckel, P., Matthes, S., Kern, B., Dahlmann, K., and Frömming, C. Various aircraft routing options for air traffic simulation in the chemistry-climate model EMAC 2.53: AirTraf 2.0, Geosci. Model Dev. Discuss., https://doi.org/10.5194/gmd-2019-331, in review, 2019.

Yin, F., Grewe, V., van Manen, J., Matthes, S., Yamashita, H., Irvine, E., Shine, K.P. Lührs, B., Linke, F., Verification of the ozone algorithmic climate change functions for predicting the short-term NO_x effects from aviation en-route, 8th international conference on air transportation (ICRAT), Barcelona, Spain, 2018.

Yin, F., Grewe, V., Matthes, S., Yamashita, H., Irvine, E., Shine, K.P. Lührs, B., Linke, F., Predicting the climate impact of aviation for en-route emissions: The algorithmic climate change function sub model ACCF 1.0 of EMAC 2.53, GMDD in preparation, 2020.