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CLIMATE IMPACT MITIGATION POTENTIAL OF EUROPEAN AIR TRAFFIC

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Abstract. Air traffic contributes to anthropogenic global warming by about 5% due to CO_2 emissions (about 1/3) and non-CO_2 effects (about 2/3) primarily caused by emissions of NO_x and water vapour as well as the formation of contrails. Since aviation is expected to maintain its trend to grow over the next decades, mitigation measures are required counteracting its negative effects upon the environment. One of the promising operational mitigation measures which has been subject of the EU project ATM4E, is climate-optimized flight planning using algorithmic climate change functions describing the climate sensitivity as a function of emission location and time. The methodology developed for the use of algorithmic climate change functions in trajectory optimization is described and results of its application to the planning of about 13,000 intra-European flights on one specific day are presented. The optimization problem is formulated as bi-objective continuous optimal control problem with climate impact and fuel burn being the two objectives. Results on individual flight basis indicate that there are three major classes of different routes which are characterized by different shapes of the corresponding Pareto-fronts. For the investigated scenario, results show a climate impact mitigation potential of about 73% which is related with a fuel penalty of 14.5%. However, a climate impact reduction of 50% can already be achieved with 0.75% additional fuel burn.

Keywords: climate optimization, eco-efficient trajectories, optimal control

INTRODUCTION

Global air traffic has been growing over the past decades and was able to withstand a number of global crises despite temporary declines in flight movements. In the long-term, air travel demand is expected to grow and since the fuel performance improvement rates due to a continuous development of enhanced aircraft technologies will not exceed growth rates, aviation’s impact on global gaseous emissions and hence climate is expected to increase.

Besides CO_2-emissions, air traffic causes non-CO_2 effects, due to the emission of NO_x and water vapour as well as the formation of contrails which change the concentration of radiative forcing agents in the atmosphere and influence the climate. Overall, aviation’s contribution to the anthropogenic climate change is estimated to be about 5%, of which approximately two thirds can be attributed to the non-CO_2 effects (Lee et al., 2009). Therefore, mitigation actions have to be taken as soon as possible considering both, CO_2 and non-CO_2 effects. Since the latter ones are strongly dependent on the geographic location, altitude, time of the day and the current atmospheric conditions, on the operational side the avoidance of climate sensitive regions is a very promising means. Those regions are characterized by a particularly high impact of the non-CO_2 emissions on climate, e.g. due to a high contrail formation probability. The European project ATM4E carried out in the SESAR Exploratory Research programme was dedicated to the scientific investigation of the potential of optimizing flights with respect to their climate impact already during flight planning (Matthes et al., 2017).

Prior to that, there have been several approaches to climate optimized routing, e.g. by Schumann et al. (2011), Sridhar et al. (2013), Grewe et al. (2014a, b), Hartjes et al. (2016), Zou et al. (2016), Lührs et al. (2016), Rosenow et al. (2017) and Grewe et al. (2017), which vary in the considered emission species, the geographic variability of the effects, the climate metric used and the degrees of freedom in the trajectory optimization.

At the heart of the ATM4E project was the development of algorithmic Climate Change Functions (aCCF), which allow for an efficient computation of the climate impact of different emission species purely based on available weather (forecast) data. Thanks to the aCCFs, it was possible for the first time to do fast-time flight planning for reduced climate impact for any given weather situation.

Within this study, we describe the methodology developed for the use of aCCFs in trajectory optimization for flight planning and present results for a traffic scenario which consists of about 13,000 intra-European flights on a selected day.

MODELING APPROACH

Within this section, the continuous trajectory optimization approach is illustrated. Since the climate impact prediction is mandatory for the optimization with regard to climate, the concept of aCCFs is explained in more detail.

Trajectory Optimization

In order to determine continuous climate optimized trajectories, the Trajectory Optimization Module (TOM) is used (Lührs et al., 2016, 2018). Following an optimal control approach, aircraft's motion is described as temporal evolution of state variables $\boldsymbol{x}(t)$ (e.g. location, speed, emission flows) and control variables $\boldsymbol{u}(t)$ (e.g. thrust, heading, acceleration). Optimal trajectories are obtained by identifying the control input $\boldsymbol{u}(t)$ which minimizes the cost functional J while satisfying dynamic constraints (e.g. equations of motion) as well as control (e.g. maximum thrust), state (e.g. maximum speed), and path limitations (e.g. maximum pressure altitude). The resulting continuous optimal control problem is converted into a discrete non-linear programming problem (NLP) with the MATLAB optimal control toolbox GPOPS-II (Patterson and Rao, 2014) and solved with the NLP-solver IPOPT (Wächter and Biegler, 2006).

Cost functional

In order to determine trajectories which are Pareto-optimal with respect to fuel burn and climate impact, the cost functional is expressed as the weighted sum of climate impact (curly brackets) and fuel burn (squared brackets). Both, climate impact and fuel burn are normalized with respect to the corresponding reference values of the minimum fuel burn trajectory ($\mathrm{ATR_{ref}}$, $m_{\mathrm{fuel,ref}}$). The climate impact is obtained as temporal integral of the product of the aCCF and the associated emission flow $\dot{m}_i$ for CO_2, NO_x and H_2O or the true airspeed v_{TAS} in the case of contrail induced cirrus cloudiness (CIC).

$$J = c_{\mathrm{clim}} \cdot \left\{ \sum_i \int_{t_0}^{t_f} \mathrm{aCCF}_i(\boldsymbol{x},t) \cdot \dot{m}_i(t)\,\mathrm{d}t + \int_{t_0}^{t_f} \mathrm{aCCF_{CIC}}(\boldsymbol{x},t) \cdot v_{\mathrm{TAS}}(t)\,\mathrm{d}t \right\} \cdot \mathrm{ATR_{ref}^{-1}}$$

$$+ c_{\mathrm{fuel}} \cdot \left[m_0 - m_f\right] \cdot m_{\mathrm{fuel,ref}}^{-1} \;; \quad i \in \{\mathrm{CO_2}, \mathrm{NO_x}, \mathrm{H_2O}\} \tag{1}$$

$$c_{\mathrm{clim}} + c_{\mathrm{fuel}} = 1 \quad \text{with} \quad c_{\mathrm{clim}}, c_{\mathrm{fuel}} \in [0,1] \tag{2}$$

Varying the weights of climate impact and fuel burn (c_{clim} and c_{fuel}) yields Pareto-optimal trajectories. Minimum climate impact trajectories are determined with $c_{\mathrm{clim}} = 1$ and minimum fuel burn trajectories with $c_{\mathrm{fuel}} = 1$.

Dynamic constraints

The dynamic constraints are formulated based on the equations of motion given by Eurocontrol's Base of Aircraft Data (BADA) 4.0 performance models which assume a point-mass model with three degrees of freedom and variable aircraft mass (Nuic and Mouillet, 2012). In order to estimate aircraft's emissions, the Eurocontrol modified Boeing Fuel method 2 is used (Jelinek et al., 2004; DuBois and Paynter, 2006).

Control, state and path limitations

In order to avoid violations of the aircraft's flight envelope, control, state and path limitations are introduced. The limitations are extracted from the BADA 4.0 dataset and cover aircraft mass, fuel capacity, pressure altitude, calibrated airspeed, Mach number and maximum lift coefficient. Additional geographic boundaries are set up to reduce the solution space, and hence the computational effort.

Algorithmic Climate Change Functions

Climate Change Functions (CCFs) allow for the quantification of the global climate impact of local aircraft emissions as a function of emission location and time (Grewe et al., 2014; Frömming et al. 2020). Since the calculation of CCFs using complex climate-chemistry models is computationally expensive and hence cannot be performed in real-time, algorithmic Climate Change Functions (aCCFs) were developed in the course of the project ATM4E. These aCCFs consider both CO_2 and non-CO_2 effects and measure global climate impact using the average temperature response integrated over a 20-year period (ATR_{20}). The robustness of climate optimized trajectories with regard to different metrics is discussed by Matthes et al. (2020). By design, aCCFs allow for a fast-time calculation of the climate impact of ozone and methane changes resulting from NO_x emissions, water vapour emissions and persistent contrail formation using standard weather forecast data which is available for flight planning (Van Manen and Grewe, 2019; Yin et al., 2018, 2020; Yamashita et al., 2020).

The water vapour and nitrogen oxide aCCFs were created by applying correlation analyses using the CCFs estimated by Grewe et al. (2014) and are based on four meteorological parameters which show a reasonable statistical significance. While for water vapour, the potential vorticity is best suited to correlate the effects, the warming effect of ozone caused by NO_x is modeled as a function of the local temperature and the geopotential. The cooling effects of the methane reductions were captured by a relationship which includes the geopotential and the amount of incoming solar radiation at the top of the atmosphere.

Contrail-aCCFs were derived separately for night-time contrails and day-time contrails since the net contrail climate effect is hugely influenced by the time of the day. It was found that temperature (which strongly determines the amount of contrail ice content) and the outgoing infrared radiation provide reasonable approximations to the climate effect in regions were the Schmidt-Appleman criterion predicts persistent contrails to form (Appleman, 1953).

RESULTS

Below, the chosen reference day for the case study is characterized. Then, Pareto-fronts for exemplary routes are presented. Finally, the individual Pareto-fronts are consolidated in order to formulate more general statements.

One-day Case Study of European Air Traffic

Using the modelling approach described above, en-route climate optimized trajectories within Europe are estimated and evaluated with respect to fuel burn and climate impact of CO_2 and non-CO_2 effects for the 18th December 2015. This day is characterized by a high traffic volume with unaffected traffic flows indicated by a low number of weather-, ATC-, and aerodrome related regulations. Additionally, the weather situation shows persistent contrail formation areas over central Europe.

The corresponding traffic inventory is extracted from Eurocontrol's Demand Data Repository 2 (DDR2) database and contains 28,337 flights. After filtering by restricting to intra-ECAC (European Civil Aviation Conference) flights only and by restricting to flights covered by Eurocontrol's BADA 4.0 models, a traffic sample containing 13,276 flights is generated. Although this seems to be a large reduction of flights, the amount of considered available seat kilometres only decreases by about 9% since especially large Airbus and Boeing aircraft are part of BADA.

Meteorological parameters which are required for both the aircraft performance calculations as well as the aCCF evaluation are determined based on ECMWF ERA-Interim reanalysis data (Dee et al., 2011).

Results for individual routes

Assuming that climate impact is considered along with economical aspects in the trajectory planning process, approximately 100 Pareto-optimal trajectory options for each route within the traffic sample have been calculated by systematically varying the weighting factors c_{clim} and c_{fuel} according to Eq. (2). During the analysis of the results, three characteristic shapes have been identified including smooth curves and discontinuous Pareto-fronts (see figure 1).
The first shape is characterized by a smooth overall Pareto-front which has no contrail impact and is dominated by the climate impact reduction of NO_x (see figure 1, left). Caused by detours compared to the minimum fuel solution, the fuel burn and hence the climate impact of CO_2 is increasing. In the second case, various contrail areas along the route are involved. Only minor trajectory changes lead to the avoidance of contrail sensitive areas and hence lead to large climate impact reductions (see figure 1, middle). In the third case, the minimum fuel trajectory passes a contrail sensitive region at its edge. Small trajectory changes causing only low amounts of additional fuel lead to a full avoidance of contrails. Further climate impact reduction is possible by deviating to regions with lower climate sensitivities with respect to NO_x emissions (see figure 1, right).

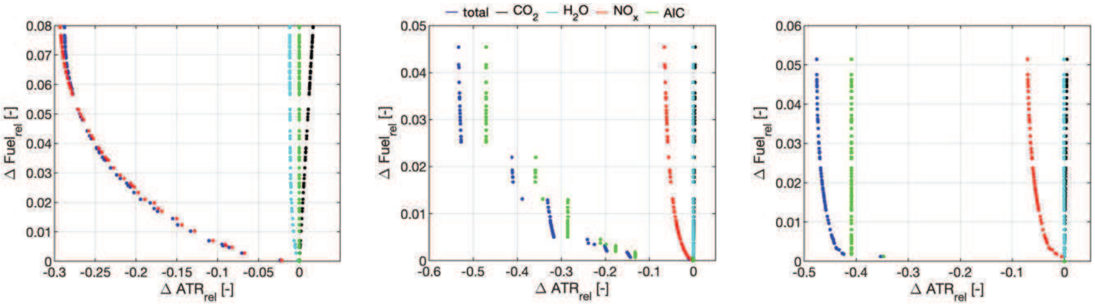

Figure 1. Pareto-fronts for Baku-Luxembourg (left) Lulea-Gran Canaria (middle) Helsinki-Gran Canaria (right). The coloured dots indicate the individual contribution of CO_2 (black), H_2O (cyan) NO_x (red) and contrails (green) to the overall climate impact reduction (blue) for a given fuel increase. Results are expressed relative to the minimum fuel case.

Consolidated Results

The individual Pareto-fronts are estimated for all 13,276 routes of the traffic scenario. Based on these, an average Pareto-front is created, where one point on each individual Pareto-front (index *i*) is selected such, that a given overall fuel penalty for all routes is not exceeded and the total climate impact of all routes is minimized according to Eq. (3). Finally, the average Pareto-front is obtained by varying the accepted fuel penalty.

$$\begin{aligned} &\min \textstyle\sum_i \mathrm{ATR}_{20,i} \\ &\text{subject to } \textstyle\sum_i \mathrm{m}_{\mathrm{fuel},i} < \mathrm{m}_{\mathrm{fuel,penalty}} \end{aligned} \qquad (3)$$

Figure 2 (left) shows the individual Pareto-fronts of the top 10 routes (coloured) of the traffic scenario in terms of available seat kilometers as well as the resulting average Pareto-front (black curve). The black circle indicates the +5% fuel burn point on the average Pareto-front which corresponds to a total climate impact reduction of about 42% for these routes. The red circles highlight the points which are chosen on each route's Pareto-front in order to achieve an overall +5% fuel burn increase while minimizing the total climate impact. Depending on the shape and slope of each individual Pareto-front, climate impact mitigation and additional fuel burn may vary strongly between the routes.
Moreover, figure 2 (right) shows the Pareto-front for the top 2,000 routes. A maximum climate impact reduction of about 73% can be achieved if a fuel penalty of 14.5% was

accepted. Higher climate impact mitigation efficiencies (climate impact reduction per fuel increase) are obtained at low fuel penalties, e.g. a fuel penalty of 0.75% may already lead to a climate impact reduction of about 50%. The individual contribution of the species indicates that the climate impact reduction is dominated by the reduction of the contrail climate impact shown in green. Because of the importance of the contrail impact, a more comprehensive evaluation of contrail radiative forcing will be included in Matthes et al. (2020). However, for this study, a weather situation with high contrail formation probabilities over central Europe has been chosen. Consequently, mitigation potentials and efficiencies may look very different for other weather situations.

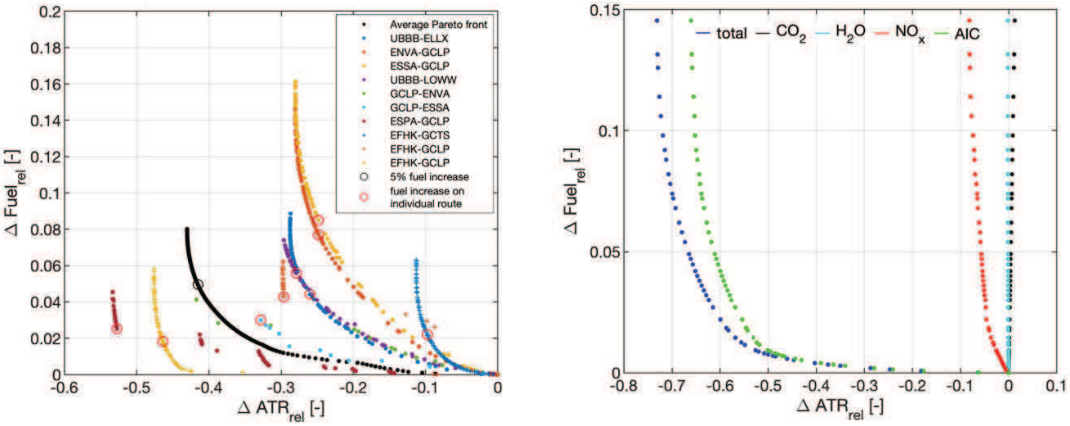

Figure 2. Top 10 single route Pareto-fronts and corresponding average Pareto-front (left) and average Pareto-front (right) for the top 2000 routes with individual contribution of the species CO_2 (black), H_2O (cyan), NO_x (red) and AIC (green) to the overall climate impact reduction (blue) for a given fuel increase. Results are expressed relative to the minimum fuel case.

Figure 3 shows the cumulative climate impact reduction as a function of the number of changed routes for different fuel penalties. The routes have been sorted according to their absolute climate impact reduction. At a fuel penalty of 1% which is related to a climate impact reduction of approximately 53% (see figure 2), the adaption of only 500 of the total 2,000 routes would already yield more than 85% of the potential for all routes (left). This effect slightly decreases for increasing fuel penalties: at 14.5% fuel penalty, 500 routes are related with about 75% of the overall potential (right). Since the slope of the individual contribution of contrails tends towards zero after about 1,000 changed routes in all three cases, it can be concluded that routes which allow the avoidance of contrails areas are characterized by high climate impact mitigation potentials and hence should be changed first.

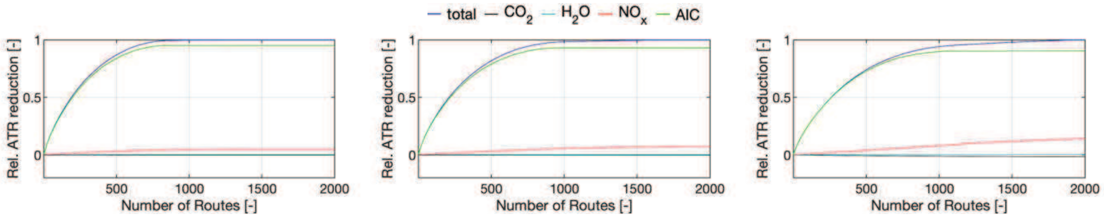

Figure 3. Cumulative ATR reduction as a function of the number of changed routes for 1% (left), 2% (middle) and 14.5% (maximum) increase in fuel burn (right) for the top 2,000 routes. Individual contributions to the total ATR reduction (blue) are shown for CO_2 (black), H_2O (cyan), NO_x (red) and contrails (green).

CONCLUSION AND OUTLOOK

Within this study, the climate impact mitigation potential of intra-European air traffic is estimated for a one-day case study. For this purpose, aircraft trajectories are optimized with regard to climate impact by avoiding regions in which the atmosphere shows a high climate impact sensitivity with regard to non-CO_2 emissions. Climate impact sensitivities are determined based on algorithmic Climate Change Functions measuring the climate impact per unit emission based on meteorological parameters which can be obtained from weather forecasts.

Results of the top 2000 routes (in terms of available seat kilometres) show a maximum climate impact mitigation potential of up to 73% related with additional fuel burn of about 14.5% compared to the minimum fuel solution. However, a climate impact reduction of 50% can already be achieved with only 0.75% additional fuel burn. Since a case study day with high persistent contrail formation probability was chosen, the climate impact reduction is dominated by a reduction of the contrail impact. Therefore, in following studies different weather situations will be evaluated with regard to potential climate impact savings. Additionally, results indicate, that a large fraction of the overall climate impact mitigation potential can already be achieved with the modification of a comparably low number of routes with particularly high climate impact reduction potential. This finding will be addressed in more detail in upcoming studies.

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REFERENCES

Appleman, H., 1953: The Formation of Exhaust Condensation Trails by Jet Aircraft. Bull. Amer. Meteor. Soc., 34, 14–20, https://doi.org/10.1175/1520-0477-34.1.14

Dee, D.P. et al..: The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society (2011), April, pp. 553–597.

DuBois, D.; Paynter, G.: 'Fuel Flow Method 2' for Estimating Aircraft Emissions. Society of Automotive Engineers (SAE), SAE Technical Paper 2006-01-1987, 2006.

Frömming, C., Grewe, V., Matthes, S., Brinkop, S., Haslerud, A.S., Irvine, E.A., Rosanka, S., van Manen, J., 2020. Influence of weather situation on aviation emission effects: The REACT4C climate change functions (in preparation).

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. 2014*, 94, 616–625, 2014a.

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

Grewe, V., Matthes, S., Frömming, C., Brinkop, S., Jöckel, P., Gierens, K., Champougny, T., Fuglestvedt, J., Haslerud, A., Irvine, E., Shine, K.: Feasibility of climate-optimized air traffic routing for trans-atlantic flights. Environ. Res. Lett. 12, 034003. https://doi.org/10.1088/1748-9326/aa5ba0, 2017.

Hartjes, S., Hendriks, T., Visser, H.G.: Contrail mitigation through 3D aircraft trajectory optimization. In: 16th AIAA Aviation Technology, Integration, and Operations Conference, American Institute of Aeronautics and Astronautics. doi:https://doi.org/10.2514/6.2016-3908, 2016.

Jelinek et al.: Advanced Emission Model (AEM3) v1.5 - Validation Report. EEC Report EEC/SEE/2004/004, 2004.

Lee, D. S. et al.: Aviation and global climate change in the 21st century, Atmospheric Environment journal, Volume 43, 2009, pp.3520-3537.

Lührs, B.; Niklaß, M.; Frömming, C.; Grewe, V.; Gollnick, V.: Cost-Benefit Assessment of 2D- and 3D Climate and Weather Optimized Trajectories. 16th ATIO conference, 2016.

Lührs, B.; Niklaß, M.; Frömming, C.; Grewe, V.; Gollnick, V.: Cost-Benefit Assessment of Climate and Weather Optimized Trajectories for different North Atlantic Weather Patterns. 31st Congress of the International Council of the Aeronautical Sciences (ICAS), 2018.

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. Lührs, B., Dahlmann, K., Linke, F., Grewe, V. Yin, F., Shine, K., Robustness of climate-optimized trajectories and mitigation potential: Flying ATM4E, in in "Making Aviation environmentally sustainable", Vol 1, ECATS 3rd Conference 2020.

Nuic, A.; Mouillet, V.: User Manual for the Base of Aircraft Data (BADA) Family 4. ECC Technical/Scientific Report No. 12/11/22-58, 2012.

Patterson, M.A.; Rao, A.V.: GPOPS-II: A MATLAB Software for Solving Multiple-Phase Optimal Control Problems Using hp-Adaptive Gaussian Quadrature Collocation Methods and Sparse Nonlinear Programming. ACM Transactions on Mathematical Software, Vol. 1, No. 1, Article 1, 2014.

Rosenow, J., Lindner, M., Fricke, H.: Impact of climate costs on airline network and trajectory optimization: a parametric study. CEAS Aeronaut. J. 8, 371–384. https://doi.org/10.1007/s13272-017-0239-2, 2017.

Schumann, U., Graf, K., Mannstein, H.: Potential to reduce the climate impact of aviation by ight level changes. 3rd AIAA Atmospheric Space Environments Conference. AIAA paper 2011-3376, 2011.

Sridhar, B., Chen, N.Y., Ng, H.K.: Energy efficient contrail mitigation strategies for reducing the environmental impact of aviation. 10th USA/Europe Air Traffic Management Research and Development Seminar, 2013.

Van Manen, J.; Grewe, V.: Algorithmic climate change functions for the use in eco-efficient flight planning. Transportation Research Part D: Transport and Environment, Vol. 67, pp. 388-405, https://doi.org/10.1016/j.trd.2018.12.016, 2019.

Wächter, A.; Biegler, L. T.: On the implementation of an interior-point filter line-search algorithm for large-scale nonlinear programming. Mathematical Programming. Vol. 106, pp. 25-57, 2006.

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 NOx 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.

Zou, B., Buxi, G.S., Hansen, M.: Optimal 4D aircraft trajectories in a contrail-sensitive environment. Networks Spat. Econ. 16, 415–446. https://doi.org/10.1007/s11067-013-9210-x, 2016.