Advancing the Science for Aviation and Climate

ACACIA

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1 Summary

This deliverable reports on interaction and relation between individual effects of aviation emissions as part of ACACIA Work package 2 on ‘Quantification of aviation non-CO_2 effects and associated uncertainties’ (WP2). This deliverable contributes to objective 2.4 (O2.4) which is to investigate the importance of compensation and interactions (scientific and technological trade-offs) between different aviation effects.

Between different aviation perturbations there exists compensation and interaction, which can be derived from analysing sensitivity studies on alternative flight altitudes. These are investigated with the help of simulations by state-of-the-art global climate-chemistry models comprising the effects of CO_2 and water vapour, NO_x-induced effects on ozone and methane, soot direct effect and soot indirect effect on warm clouds, contrail and contrail-cirrus effects. Similarly results from aircraft trajectory optimisation comprising the effects of CO_2, nitrogen oxides, contrails and water vapour present how individual effects vary depending on the choice of the individual trajectory. Simulations with comprehensive atmospheric models show how climate effects change when varying location of flight trajectories, specifically altitude, by flying lower or higher. Trajectory optimisation shows how avoiding specific regions reduces one effect, while increasing another one.

2 Compensation and trade-offs when flying at alternative altitudes

Results from a multi-model study exploring how individual CO_2 and non-CO_2 effects vary when aircraft fly at alternative flight altitudes have been published in an open access paper [Matthes et al., 2021]. The contents of this scientific article are summarized below, the main message is given as well as the citation and link to the publication.

2.1 Abstract of the paper 'Mitigation of non-CO₂ aviation's climate impact by changing cruise altitudes' by Matthes et al., 2021

Aviation is seeking for ways to reduce its climate impact caused by CO_2 emissions and non-CO_2 effects. Operational measures which change overall flight altitude have the potential to reduce climate impact of individual effects, comprising CO_2 but in particular non-CO_2 effects. We study the impact of changes of flight altitude, specifically aircraft flying 2000 feet higher and lower, with a set of global models comprising chemistry-transport, chemistry-climate and general circulation models integrating distinct aviation emission inventories representing such alternative flight altitudes, estimating changes in climate impact of aviation by quantifying radiative forcing and induced temperature change.

We find in our sensitivity study that flying lower leads to a reduction of radiative forcing of non-CO_2 effects together with slightly increased CO_2 emissions and impacts, in case cruise speed is not modified. Flying higher increases radiative forcing of non-CO_2 effects by about 10%, together with a slight decrease of CO_2 emissions and impacts. Overall flying lower decreases aviation-induced temperature change by about 20%, as a decrease of non-CO_2 impacts by about 30% dominates over slightly increasing CO_2 impacts assuming a sustained emissions scenario.

Those estimates are connected with a large but unquantified uncertainty. In order to improve the understanding of mechanisms controlling the aviation climate impact, we study the geographical distributions of aviation-induced modifications in the atmosphere, together with changes in global radiative forcing and suggest further efforts in order to reduce long standing uncertainties.

2.2 Selected results on compensation and trade-off of aviation effects

Here we present results and figures from the article Matthes et al. [2021] which are originating from section 3.6 of the scientific article. Figure 1 shows the radiative forcing of aviation effects for a reference case and two alternative scenarios “flying lower” and “flying higher” by 2000 feet.

- If one intends to compare non-CO_2 to CO_2 impacts it is necessary to make assumptions on the underlying temporal evolution of the emissions by defining a dedicated emission scenario. In the study presented here, we analyse an emission scenario assuming that an aircraft has always been flying at the alternative flight altitudes using temporal evolution of historic aviation emission data for the reference case.
- For the calculation of the CO_2 effects we use the linearized climate model AirClim to calculate the radiative forcing of CO_2 emissions in the reference and the alternative altitude scenarios.
- Radiative forcing caused by CO_2 emissions is equal to 21.5 mW/m^2, which increases to 21.8 mW/m^2 when an aircraft flies lower, and decreases to 21.3 mW/m^2 when an aircraft flies higher.
- Comparing non-CO_2 effects with the CO_2 effect shows the importance of non-CO_2 effects when assessing total climate impacts.
- In the **reference case** non-CO_2 effects represent about 71% of the total radiative forcing, while in the *Flying Lower* and *Flying Higher* they represent 63% and 73%, respectively, showing that non-CO_2 become more important when flying at higher altitudes.

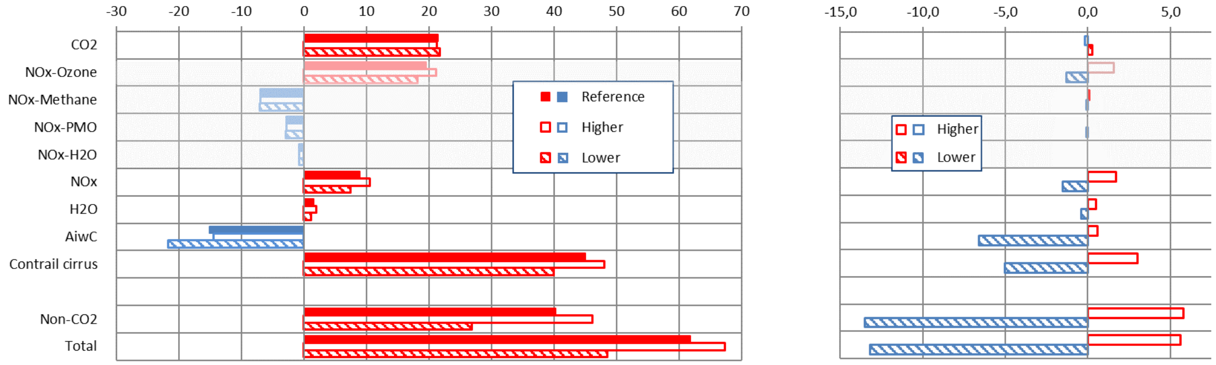


Figure 1. Global radiative forcing [mW/m^2] of aviation emissions for different scenarios: reference case (filled), *Flying Higher* (not filled) and *Flying Lower* (stripes) as absolute radiative forcings (left) and as changes for alternative flight altitudes scenarios compared to reference case (right) *(Figure originating from Matthes et al. [2021], figure 7)*.

- In order to go beyond radiative forcing in terms of metrics it was calculated how large the aviation-induced temperature change due to CO_2 and non-CO_2 would be in the year 2006 (Figure 2) assuming similar temporal evolution of (historic) aviation emissions.
- Comparing the climate impact of the **Flying Lower** scenario given as temperature change to the reference case shows that in our simplified alternative routing study, total impact would be about 4 mK lower, while in the **Flying Higher** scenario total climate impact would be about 2 mK higher, noting that large uncertainties remain.
- In the **Flying Lower** scenario, we find that for both radiative forcing and temperature change, the CO_2 climate impacts slightly increase, while decreasing non-CO_2 effects compensate this effect, resulting in an overall lower climate impact of the Flying Lower scenario.
- In the **Flying Higher** scenario both effects go into opposite directions in a similar way, however, now non-CO_2 effects increase, resulting in an overall increase of climate impact.
- Overall, the aviation-induced temperature change increases by about 10% when aircrafts are flying higher, while total temperature change decreases by 20% when aircrafts are flying lower. The uncertainty in those changes is very large in particular because they are connected with the cloud related aviation effects that also have a very large uncertainty.

In the analysis with AirClim in Matthes et al. [2021] the following methodology is chosen: No internal variability was simulated which avoids detection problems or the necessity of scaling as applied in [7], as we are similarly considering relatively small component forcings and responses. In the sensitivity study presented therein no uncertainty of results is shown because it is for some of the components not known or can be only very roughly estimated, which is in particular true for the cloud related radiation forcing components.

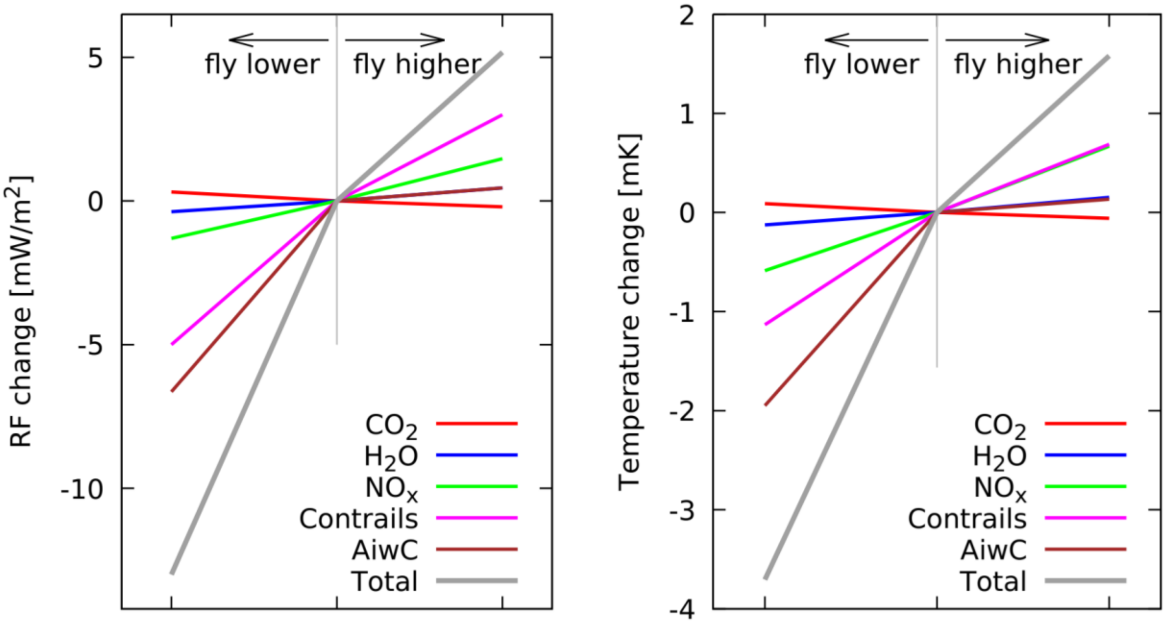


Figure 2. Change in radiative forcing [mW/m^2] (left) and change in temperature [mK] (right) assuming aircraft has always been *Flying Lower* or *Flying Higher* by 2000 ft compared to a reference (base) case comprising direct water vapor (H_2O), net nitrogen oxide induced impact (NO_x), contrail cirrus (contrails), aerosol indirect effect on warm clouds (AiwC) *(Figure originating from Matthes et al. [2021], figure 8).*

3 CO_2 and non-CO_2 effects on climate-optimized trajectories

Results from a comprehensive modelling approach aiming to identify climate-optimized aircraft trajectories have been published in an open access paper [Matthes et al., 2020]. The contents of this scientific article are summarized below, the main message is given as well as the citation and link to the publication.

3.1 Abstract of the paper 'Climate-optimized trajectories and robust mitigation potential: flying ATM4E' by Matthes et al. [2020]

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 when aiming to identify such climate-optimized aircraft trajectories. The overall concept relies on a multi-dimensional environmental change function concept, which is capable of providing climate impact information to air traffic management (ATM). Estimates on overall climate impact reduction from a one-day case study are presented relying on best estimate for climate impact information. Specific weather situation that day, containing regions with high contrail impact, results in a potential reduction of total climate impact, by more than 40%, considering CO_2 and non-CO_2 effects, associated with an increase of fuel by about 0.5%. The climate impact reduction per individual alternative trajectory shows a strong variation and hence also the mitigation potential for an analyzed city pair, depending on atmospheric characteristics along the flight corridor as well as flight altitude. By using a range of different climate metrics, the robustness of proposed climate-optimized trajectories is assessed. A more sustainable ATM needs to integrate comprehensive environmental impacts and associated forecast uncertainties into route optimization in order to identify robust eco-efficient trajectories.

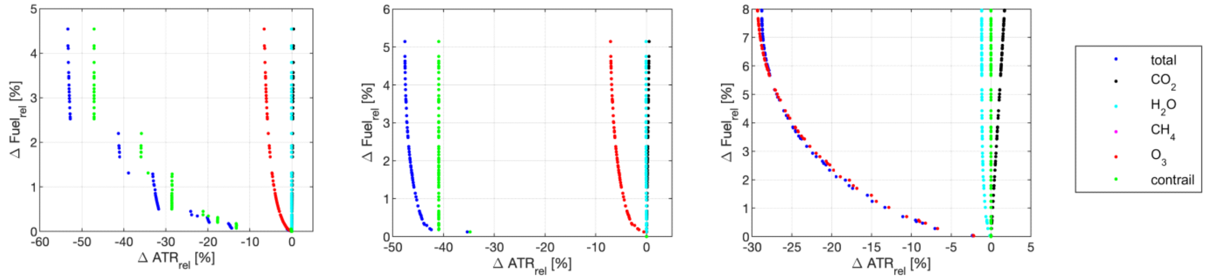
3.2 *Selected results on individual aviation effects*

From aircraft trajectory optimisation it becomes clear how individual components of total climate effects are mitigated when identifying trajectories which have a lower climate impact. In the one-day case study presented in Matthes et al. [2020] the effects of four effects have been explored: CO_2 emissions, NO_x-induced effects on ozone and methane, water vapour effects and aviation induced cloudiness (AIC).

In order to identify the role and importance of individual aviation emission effects as well as their importance in mitigation solutions, the paper presents 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). It is shown that due to climate-optimization, the relative contributions from non-CO_2 effects to total climate impact decreases as the fuel consumption 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. Specifically, in the scientific paper results for three example trajectories are presented:

Specific results for the route Lulea-Gran Canaria (Fig 3a, Fig. 4 *left*) are:

- Optimization shows that on this route it is most efficient to mitigate contrail cirrus effects, with several alternative trajectories appearing in the pareto front (Fig. 3a).
- On that day the fuel optimal trajectory CO_2 contributes only 10%, while non-CO_2 impacts contribute 90%; nitrogen oxides effects 40% and contrail cirrus 50%, respectively.
- Following climate optimization these non-CO_2 contributions drop to 85%, 82% and 77%, respectively, associated with reductions of total climate impact by 33% of up 56%, for increases in fuel burn between 0.5% and 5%.



(a) **(b)** **(c)**

Figure 3. Pareto fronts for aircraft trajectory optimization showing average temperature response (ATR_{20}) vs. fuel increase for 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 *(figure originating from Matthes et al. [2020], figure 2)*.

Specific results for the route Helsinki-Gran Canaria (Fig. 3b, Fig. 4 *middle*) are:

- On the route Helsinki-Gran Canaria contrails can form over France. Assuming sustained emissions and an ATR_{20}, 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 degree, 45% and 43% respectively, and water vapor 1%.
- Following climate-optimization, 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 considerable reduction in total climate impact by 47% (individual contributions: CO_2 20%, NO_x 78%, water vapor 2%), at nearly no fuel penalty representing clear jumps in the associated Pareto front.
- Climate-optimization on this connection identifies alternative trajectories with a lower overall climate impact, e.g. with 48% of impact of fuel optimal trajectory by avoiding contrail cirrus climate effects.
- For NO_x absolute contributions remain more or less constant, while relative contributions to total climate impact of trajectory increase.
- On the Helsinki to Gran Canaria route the presented analysis also 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 oxides effect.
- During climate optimization on the route Helsinki-Gran Canaria relative contributions from non-CO_2 effects decrease from 89% to 80%, 79%, and 78%, for fuel increases by 0.5%, 2%, and 5%.
- When comparing climate-optimized trajectory solutions in terms of their individual effects, e.g. related to nitrogen oxide emissions, one finds that while their relative contributions to total climate impact increase (e.g. from 23% to 26%, or from 40% to 50%, Fig. 3), associated absolute climate impact of NO_x emissions in general still decreases, due to lower total climate impacts (Fig. 4).

Specific results on the route between Baku and Luxembourg (Fig. 3c, Fig. 4 *right*) are:

- No contrails can form along the trajectory on this specific day and hence the climate impact from aviation induced cloudiness is zero.
- On the **fuel optimal trajectory**, the climate impact of CO_2 emissions accounts for 23% of total climate impact, non-CO_2 effects contribute 77%. Nitrogen oxides contribute 74% and direct water vapor emissions only 3% to the total climate impact on the fuel optimal trajectory.
- Climate impact of nitrogen oxides depends on both the height and geographic location of the aircraft; hence changing the aircraft trajectory has the potential to reduce climate impact of NO_x emissions. This causes changes in NO_x-induced climate impacts not correlating with changes in fuel composition.

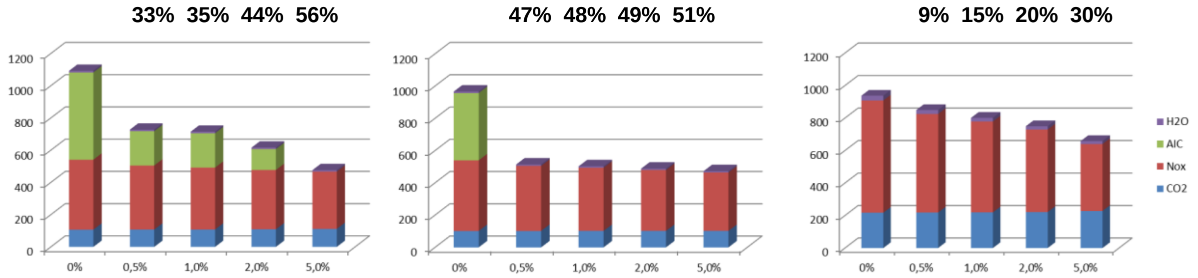


Figure 4. Individual contributions to total climate impact (ATR_{20}, pK) on Lulea-Gran Canaria (*left*), Helsinki-Gran Canaria (*middle*), Baku-Luxembourg (*right*); shown for individual mitigation trajectories allowing fuel increase by 0.5%, 1%, 2% and 5% and fuel optimal (0%). Numbers on top indicating decrease of total climate impact for respective alternative trajectory. *(figure originating from Matthes et al. [2020], figure 3).*

- For the **climate-optimized trajectories**, these relative contributions change: contributions due to non-CO_2 effects decrease to 74%, 73%, 70%, and 65% for the climate-optimized cases considered, respectively for the 0.5%, 1%, 2% and 5% fuel increase or fuel penalty that results from climate-optimization. This additional fuel enables a reduction in total climate impact calculated to be equal to 9%, 15%, 20%, and 30%, respectively.

3.3 Selected results on limitations of a concept relying on a uniform multiplier

Based on the results from individual trajectory optimisation limited applicability of a multiplier approach is shown in Matthes et al. [2020]. The paper emphasised the large variation that such a multiplier shows, which demonstrates how a unified multiplier is not able to represent non-CO_2 effects realistically.

For the three example trajectories the variation of the multiplier approach is presented for alternative, climate-optimized aircraft trajectories. The values listed in Table 1 represent the relation of the total effects (comprising CO_2 and non-CO_2 effects) divided by the CO_2 effect, resulting in the corresponding multiplier.

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

This analysis presented in Matthes et al. [2020] shows that an approach which applies a uniform multiplier to account for non-CO_2 effects is not able to provide a realistic estimate of these effects, as the relative importance of non-CO_2 effects varies strongly with the considered aircraft trajectories. Hence, the application of such a multiplier approach is not recommended, but more sophisticated measures need to be applied.

4 Conclusions

Results from a multi-model study relying on state-of-the-art chemistry climate modelling published in Matthes et al. [2021] shows the importance of individuals effects, as well as their opposite signs but also their varying strength. Results show that for the alternative flight altitudes in the “flying lower” scenario the non-CO2 effects are acting in the same way, resulting in an overall lower climate effect, while the CO_2 effect has an opposite sign and is increasing. As a consequence, we want to stress here in this ACACIA deliverable, that it is necessary when aiming for estimating the total climate effect or possible mitigation gains the full set of individual effects has to be analysed and quantified, in order to identify such compensation and trade-off mechanisms.

The analysis of the results of trajectory optimisation published in Matthes et al. [2020] shows the strong variation of non-CO_2 effects. Presented are relative contributions of individual non-CO_2 effects to the total climate effect for the fuel optimal trajectory, as well as for the alternative aircraft trajectories, which are climate-optimized. Hence, they are having a lower climate effect. In the summary, we again stress, that a multiplier approach is not able to realistically estimate the non-CO_2 effects of aviation.

5 References

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