MITIGATING THE CLIMATE IMPACT OF AVIATION BY OPERATIONAL MEANS - A COMPARATIVE STUDY FOR DIFFERENT WEATHER SITUATIONS

Zarah Lea Zengerling[1], Maximilian Mendiguchia Meuser[1], Alexander Lau[1] & Volker Gollnick[2]

[1]German Aerospace Center (DLR), Institute of Air Transport, Hamburg, Germany
[2]Hamburg University of Technology (TUHH), Institute of Air Transportation Systems, Hamburg, Germany

Abstract

Aviation's climate impact in terms of non-CO_2 effects can be mitigated by operational trajectory adjustments. However, their effectiveness and efficiency varies significantly for different routes as well as meteorological conditions. Therefore, this study aims for a comparable assessment of different trajectory adaptation approaches under different weather conditions. For this purpose, detailed trajectory calculations are combined with climate sensitivity grids based on algorithmic climate change functions in order to assess variations in climate mitigation potentials. Significant mitigation potentials for vertical, lateral and temporal adaptation approaches are demonstrated and varying mitigation potentials in dependence of the meteorological situation are identified. For instance, higher mitigation potentials can be observed in December compared to June and for missions of higher contrail intensity.

Keywords: non-CO2 effects, trajectory adaptation, meteorological influence, climate impact reduction

1. Reducing the Climate Impact of Aviation - Motivation & Scientific Background

Aviation emissions significantly contribute to anthropogenic global warming. Despite significant efficiency improvements of aircraft and engines, annual emissions and the resulting climate impact have increased over the last decades [1]. In contrast to other modes of transport, aviation emissions are emitted in high altitudes leading to a significant climate impact from non-CO_2 emission species such as nitrogen oxides (NO_x), water vapor (H_2O) or sulphur aerosols (SO_x) in addition to CO_2 effects. These emissions contribute to radiative forcing (RF) either via direct greenhouse effects (e.g. CO_2, H_2O), indirect greenhouse effects (e.g. NO_x via ozone production and methane depletion) as well as cloud effects (e.g. contrail-induced cirrus, CiC, or aerosol-cloud interactions) [2]. In contrast to CO_2 emissions, the climate effect induced by non-CO_2 emissions significantly depends on atmospheric boundary conditions as well as location and time of emissions. The climate impact of non-CO_2 climate forcers is estimated to contribute to about two thirds of aviation's total climate effect, but is also associated with eight times higher uncertainties compared to CO_2 [2].

Different measures are currently investigated to reduce the climate impact of aviation. Technical approaches typically aim for an increase in fuel efficiency or a reduction in emission quantities, e.g. with new engines, improved aerodynamic performance or reduced aircraft weight as well as alternative fuels. In this context, CO_2-induced climate effects can efficiently be reduced. However, non-CO_2 effects might not sufficiently be addressed by an implementation of technical innovations. For instance, new engine types can lead to the formation of more CiC due to higher overall efficiencies and increase associated climate effects [3]. Furthermore, technical innovations typically require long development times, thus are not expected to come into effect on a large scale in the near future. By contrast, operational measures can benefit from short implementation times as they can be realized with the current world fleet and reduce the climate impact of aviation especially in the next decade. Moreover, these operational improvements are suitable to target non-CO_2 climate effects by exploiting geo-temporal variations in climate sensitivity. Additionally, regulatory measures aim for facilitating

the realization of both technical and operational measures by reducing the disadvantages of their implementation (e.g. through restrictive or market-based approaches), as currently discussed based on revision of the European Emission Trading System (EU ETS) regarding non-CO_2 effects [4].
In context of operational climate mitigation measures, it is crucial to differentiate between strategic and tactical dimension (Table 1) analogous to strategic and tactical flight planning [5]. Strategic approaches require long-term planning, e.g. for an implementation of intermediate stop operations (ISO), where suitable refueling airports need to be identified and considered in the mission planning process [6, 7]. The same holds true for a strategic reduction of flight altitudes and speeds as well as airline network optimizations [8, 9], that need to be considered well in advance of the flight execution and independent of the actual weather situation along the flight. By contrast, tactical measures typically refer to trajectory adaptations in dependence of the predicted or actual weather situation along the flight. Exemplary measures are climate-optimized flight planning [10] as well as small vertical or temporal diversions to avoid highly climate-sensitive regions [11, 12].

	Strategic measures	**Tactical measures**
Planning horizon	months before flight	up to 1 day in advance
Assessment characteristics	independent of actual weather situation, climatological assessment	very dependent of weather situation, meteorological assessment
Exemplary measures	Intermediate Stop Operations Airline network optimization Reduced cruise altitudes and speeds	Trajectory optimization Small-scale lateral diversion Small-scale temporal adaptations
References	[7, 8, 9]	[10, 11, 12]

Table 1 – Comparison of strategic and tactical dimension of operational climate mitigation measures.

The current state of literature comprises a variety of different trajectory-related measures, that have been investigated individually in dependence of study-specific boundary conditions. For instance, Koch (2013), Matthes et al. (2020) and Zengerling et al. (2023) investigate effects of adjusting cruise altitudes (and partially also speeds) [8, 13, 14]. The studies show high climate mitigation potentials for reduced cruise altitudes in both strategic and tactical approaches. However, lower cruise altitudes lead to higher fuel burn and thus increase direct operating cost (DOC). Becker et al. (2022) and Kölker et al. (2023) investigate climate mitigation potentials from temporal shifts of flights to avoid especially warming night-time contrails for 12 selected days, incorporating airline network effects [12, 15]. Further studies, e.g. Lührs et al. (2021) and Meuser et al. (2022), analyze the concept of trajectory optimization in flight planning for selected weather situations and identify high mitigation potentials, especially in presence of contrails [10, 16]. The review of existing literature studies shows that although a broad set of studies exists, climate mitigation potentials are not directly comparable to each other due to differences in meteorological boundary conditions, but also regarding applied methods and assumptions. On this basis, it is difficult to identify especially effective or efficient measures to be implemented by the stakeholders of the air transport system as well as to define a suitable regulatory framework. Only very few studies systematically investigate the impact of meteorological boundary conditions. For instance, Castino et al. (2021) analyze annual variability of NO_x-optimal cruise flight altitudes [17]. The authors find both seasonal and latitudinal dependencies of NO_x-optimal flight altitudes and a minimum of mitigation potentials for NO_x-induced O_3 effects in summer. Furthermore, Yin et al. (2018) investigate the reduction of contrail effects represented by contrail distance showing a large variability over different seasons [18]. While in summer a northward and upward shift of the trajectories is preferred to avoid contrail formation, non-summer seasons show higher potential for southward and upward shifts. Furthermore, the study shows trajectory optimization to be more effective in winter compared to summer.
With limitations in the current state of research regarding overall climate mitigation potentials in dependence of meteorological conditions in general as well as an efficiency comparison of different climate mitigation measures in particular, this study aims to assess different operational climate mitigation measures in a comparable way. On this basis a quantitative comparison is targeted considering varying meteorological conditions. We build on work previously presented in Zengerling et

al. (2023) investigating a set of operational improvements for four selected flight missions on one representative summer day [14]. In the following, we extend these results to a broader scope and increase significance by both looking into a representative amount of origin-destination combinations as well as by taking different weather situations into account. For this purpose, we rely on climate sensitivity grids [19] enabling an efficient climate assessment of flight trajectories. Therefore, we contribute to current state of research by (1) establishing an efficient method to assess and compare different trajectory-related climate mitigation measures in dependence of meteorological conditions, (2) identifying parameters influencing effectiveness of different climate mitigation measures, and (3) relating results from tactical trajectory adaptations to strategic approaches. To this end, this paper is structured as follows: Subsequent to this introduction, we introduce method and data applied to simulate operational climate mitigation measures considering meteorological variability in section 2 before we present the results in section 3. Significance of results and operational implementability of different measures are discussed in section 4 and we conclude this paper with a final summary and outlook in section 5.

2. Simulating Operational Climate Mitigation Measures - Method & Data

The assessment method to evaluate and compare different climate mitigation measures is illustrated in Figure 1. The reference case is assessed in a business-as-usual (BAU) scenario before the implementation of different operational measure is investigated in different scenarios. First, trajectories are simulated with DLR's Trajectory Calculation Module (TCM) [20, 14] before emission quantities are assessed with Boeing Fuel Flow Method 2 (BFFM2) [21]. The climate impact assessment is performed with algorithmic climate change functions (aCCFs) Version 1.0A determining the climate sensitivity of non-CO_2 effects in dependence of atmospheric parameters such as temperature, humidity and potential vorticity [22, 23, 24]. In this context, we apply a newly developed set of climate sensitivity grids for an efficient climate assessment of a large sample of trajectories [19]. The climate impact is assessed in average temperature response over 50 years (ATR50) based on a future emission scenario development. Finally, we can estimate the impact on aviation stakeholders based on resulting flight time, distance, fuel burn and resulting DOC. The individual assessment of different routes and weather situations generates a broad data basis for addressing the comparison of different measures under varying meteorological conditions.

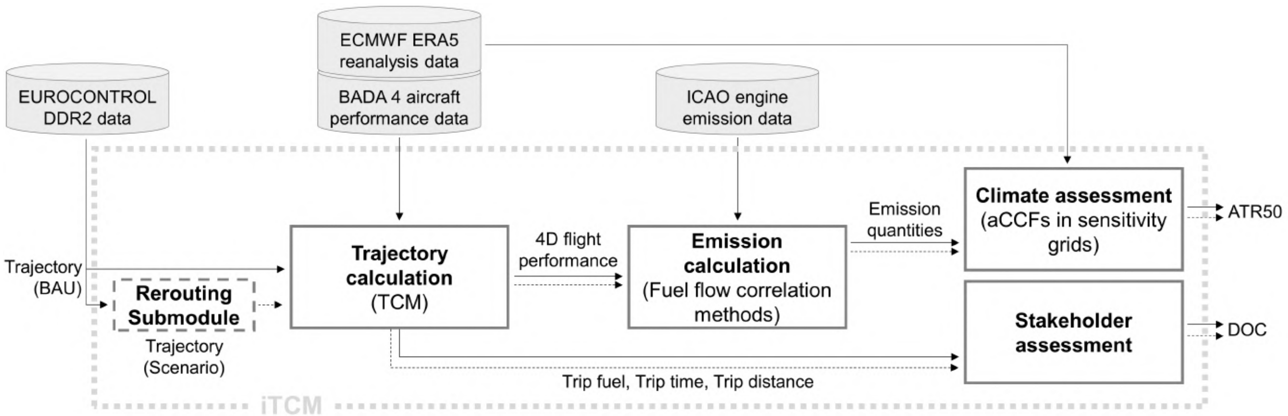


Figure 1 – Workflow for assessment and comparison of climate mitigation measures (solid line represents BAU, dashed line represents adaptation scenarios)

2.1 Trajectory Simulation and Emission Calculation

Trajectory calculation is based on the Trajectory Calculation Module (TCM), which has been developed at DLR Institute of Air Transport [20, 25]. Modelling capabilities have been extended in the new integrated TCM (iTCM). Based on route information, where different levels of granularity are possible, and flight performance parameters, e.g. as provided by Base of Aircraft data (BADA) in version 3 or 4, a total-energy-model (TEM) approach is applied for a step-wise forward integration of aircraft state along the respective flight mission [26]. On this basis, flight performance parameters such as speeds, forces, and fuel burn can be estimated. Boundary conditions for TEM equations are set based on a standardized flight phase description in dependence of mission and aircraft type. Moreover, meteorological information such as pressure, temperature, relative humidity and wind can be considered. Furthermore, different vertical navigation options are possible, ranging from optimization in terms of fuel-optimal step climbs to the re-modelling of actually flown altitude profiles [20, 14]. The iTCM has additionally been extended by a set of submodules, that allow a comparable assessment of different operational measures in a pre-processing step for route definition. This incorporates a Rerouting submodule considering lateral, temporal and vertical trajectory changes as well as small scale trajectory optimizations. Furthermore, new post-processing submodules facilitate the assessment of stakeholder effects, for instance regarding operating cost for airlines or air-traffic management related indicators.

Estimation of emission quantities is performed with BFFM2, which is integrated in the Emissions submodule of the iTCM. While emission quantities of direct combustion products H_2O and CO_2 can directly be derived from their proportional relation to fuel flow, fuel-flow correlation methods are required for by-product emissions such as NO_x. BFFM2 relies on a correlation between flight conditions, fuel flow and emission index. In this context, first, in-flight fuel flow is reduced to reference conditions at sea level, for which reference emission indices have been obtained. Finally, this reference EI can be translated back to in-flight conditions in dependence of ambient pressure, temperature, relative humidity as well as flight speed [27, 21].

2.2 Climate Impact Assessment

Recently, effects induced by non-CO_2 emissions have been in focus of research and regulatory bodies due to the inherent high mitigation potential by operational measures. This is due to high sensitivity to time and location of emission. A fast quantification of such effects has been made possible by the development of algorithmic climate change functions (aCCFs), which provide the climate impact of aviation emission per flown kilometer and per emitted quantity of each emission species as a multi-dimensional response (i.e. longitude, latitude, altitude, time and species) [23, 24]. Exemplary results for the merged aCCF considering NO_x, direct H_2O and CiC effects are depicted in Figure 2. The aCCFs are especially suited for studies on operational mitigation measures due to their fast computation. Based on a reduced number of meteorological parameters and aircraft information, they provide estimates on effects induced by NO_x, H_2O and CiC [22]. In the scope of this study we evaluate climate sensitivity by means of aCCFs for the North Atlantic applying future-emission-scenario-based ATR50 (F-ATR50) as a suitable climate metric. By selecting F-ATR50, we try to put equal weight on both long- and short-lived, i.e. CO_2 and non-CO_2 species, while one of the two is focused when looking at other time horizons (e.g. 20 or 100 years) or a pulse-emission scenario.

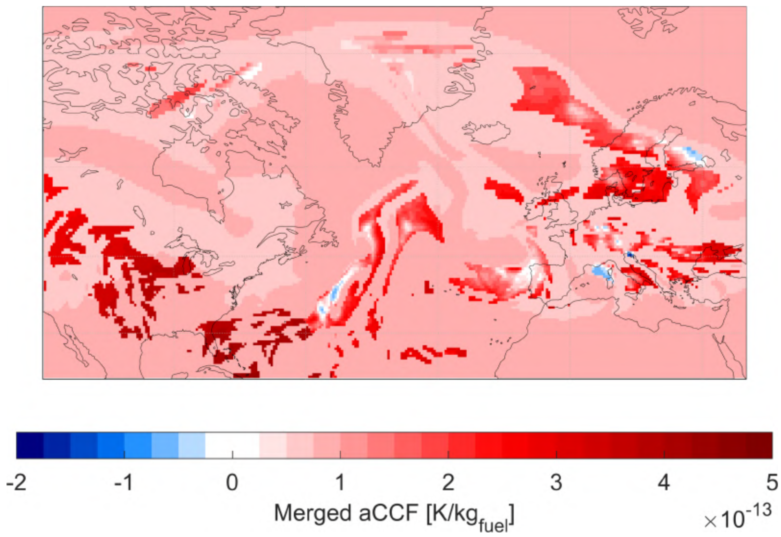
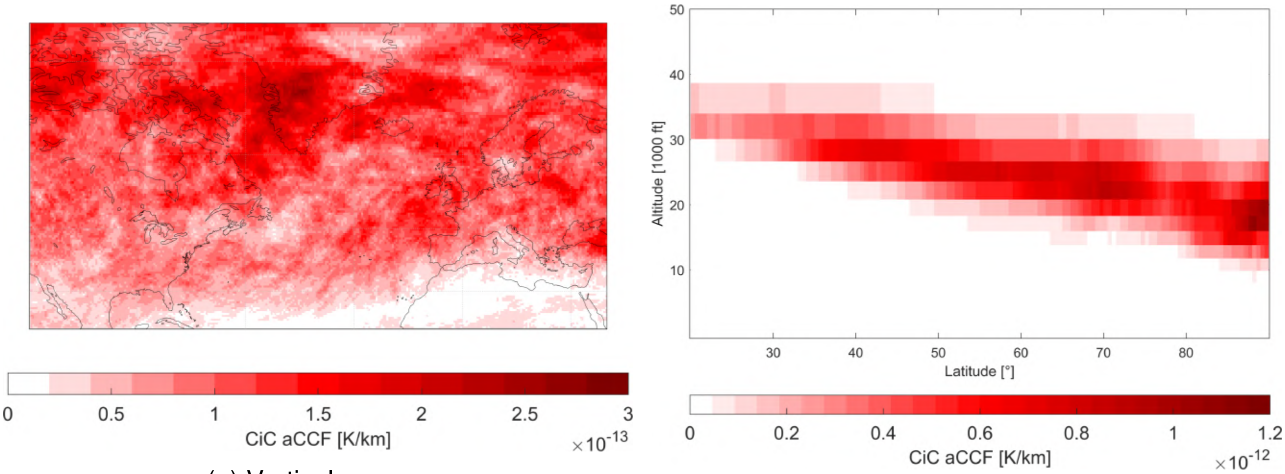


Figure 2 – Exemplary results of merged aCCF in ATR20 (pulse) at pressure level 250 hPa in the North Atlantic region at 12:00 UTC for June 26th, 2018.

Besides detailed information regarding climate sensitivity at a specific time, we evaluate mean sensitivities of each species per time of day across monthly periods for the selected months leading to extensive climate sensitivity grids [19] as illustrated in Figure 3. These can be generated as four-dimensional response surfaces that can be interpolated along the previously calculated flight trajectories.



(a) Vertical average.

(b) Longitudinal average.

Figure 3 – Average contrail aCCF in ATR20 (pulse) in the North Atlantic region at 03:00 UTC for December 2018.

2.3 Study Set-up and Data

We limit our consideration of operational improvements to measures that affect in-flight operations in general and cruise flight phase in particular because the associated climate impact is expected to be significantly higher compared to ground operations and lower flight phases [28]. Furthermore, we focus on mitigation measures that can directly be related to the trajectory itself, i.e. lateral, vertical, or temporal adaptations. Other, especially strategic, operational measures, such as formation flight or intermediate stop operations also show significant climate mitigation potentials [29, 7], but typically require significant changes to the infrastructure (e.g. in the form of rendezvous points or an upgrade of airport infrastructures for refueling). Therefore, we investigate the following trajectory-related climate mitigation approaches:

- Vertical changes to flight trajectories to avoid especially climate sensitive altitudes, which is represented in cruise altitude shifts of +/- 2000 ft as well as a constant cruise flight altitude,
- Lateral changes to flight trajectories to avoid climate sensitive regions modelled with five degrees upward and downward shifts, and
- Temporal changes to flight trajectories to take advantage of varying climate effects depending on the time of day (especially regarding CiC) considering shifts of take-off time by +/- three hours.

Moreover, we restrict our analysis to the North Atlantic as a highly relevant region in terms of air traffic as well as the region where aCCFs have been validated for [23]. The selection of representative flights crossing the North Atlantic is restricted to those performed with representative wide-body aircraft. To maximize comparability over the different investigated days, we limit our considerations to those missions characterized by origin, destination and aircraft type, that have all been performed on the considered case study days.
Temporally, we look into different representative summer and winter days in June and December of 2018. This allows us to exclude COVID-19 effects and to restrict the temporal analysis to seasons of the year for which the aCCFs have been validated [23]. We consider three case study days per month in detail, where we incorporate actually flown flight trajectories into our analysis, namely June

6th, 16th and 26th as well as December 1st, 11th and 21st. In addition, we investigate meteorological data over the entire considered case study months June and December.
Reference (BAU) trajectories are described as realistically as possible according to the actually performed trajectory on the respective day. Therefore, we apply flight plan data from EUROCONTROL, which is originally provided by airspace users to air traffic control (ATC) and the Network Manager. Trajectories are derived from agreed flight plans corrected for large deviations with respect to the actual flights based on correlated position reports (model3) [30]. Moreover, we utilize BADA4 aircraft performance data [26] to model flight performance and fuel consumption along individual flight missions. For emissions calculation, we apply reference emission indices from ICAO Engine Emissions Databank (EEDB) [31]. Meteorological information is derived from ECMWF ERA5 reanalysis data [32].

3. Comparing Different Climate Mitigation Measures - Study Results

The combination of detailed trajectory calculation and efficient evaluation of climate impact with aCCF-based climate sensitivity grids allows us to evaluate mitigation potentials of trajectory adaptations in context of different meteorological conditions addressing different research questions. To this end, this section presents the study results in the following structure: First, section 3.1 illustrates changes in climate and non-climate indicators for selected case studies to demonstrate application of the above described method and general suitability of the selected trajectory adaptation strategies. On this basis, we demonstrate influence of weather on the efficiency of different measures in section 3.2, also considering differences in mission characteristics. Finally, we analyze the efficiency of the selected climate mitigation measures and their robustness over different weather situations as well as differences for tactical and strategic approaches in section 3.3.

3.1 Mitigation Potentials in Single-mission Case Studies

With non-CO_2 climate effects of flight missions depending on both emission location and time as well as meteorological boundary conditions, climate impact along those trajectories can be changed by adjusting these trajectories in vertical, lateral and temporal dimension. However, trade-offs between CO_2 and non-CO_2 effects need to be considered when selecting the most promising adaptation strategy per mission.
Figure 4 exemplarily illustrates the reference trajectory as well as the resulting vertically and laterally adapted trajectories for a case study mission from New York (KJFK) to Lisbon (LPPT) on December 1st (take-off time 04:25 UTC). Both reference and mission of constant cruise altitude cross areas of significant warming contrail impact in the second half of the trajectory (Figure 4), while the first half is dominated by NO_x effects. These effects are characterized by an optimal altitude corridor with minimum climate impact. In this case, both increasing and decreasing flight altitudes lead to a reduction in non-CO_2 climate impact primarily driven by CiC and secondary by NO_x effects (Figure 5, left; Table 2). As indicated in Table 2, flying 2000ft lower compared to the reference flight level reduces the overall climate impact in terms of ATR50 by approximately 17% while higher flight altitudes lead to a decrease of approximately 13%. While total fuel burn and DOC increase for a higher flight altitude, these parameters are reduced for the mission of lower flight altitude mainly due to fuel efficiency gains.
Furthermore, lateral changes to the trajectory are also suitable to reduce climate impact when shifting the route to higher latitudes. In this case, climate impact can be reduced by approximately 12%. However, this measure appears inferior to lateral adaptations due to a rise in DOC by approximately 4% (Table 2) . Flying at lower latitudes does not only reduce CiC effects by 18% but also effects from NO_x by almost 5% (Figure 5, left).
Finally, temporal adaptations address time-dependent effects of CiC with a focus on avoiding warming night-time contrails. In this example, a later take-off shifts the mission towards day-time and a lower effect from CiC can be observed leading to a reduction in climate effects by approximately 3% without major influence on the considered non-climate indicators.
The considered flight trajectory is characterized by a large contrail impact dominating non-CO_2 climate effects along the mission (see Figure 5, left). 60.5% of the entire climate impact in terms of ATR50 is caused by CiC, while NO_x effects account for 28% of overall effects. The remaining climate

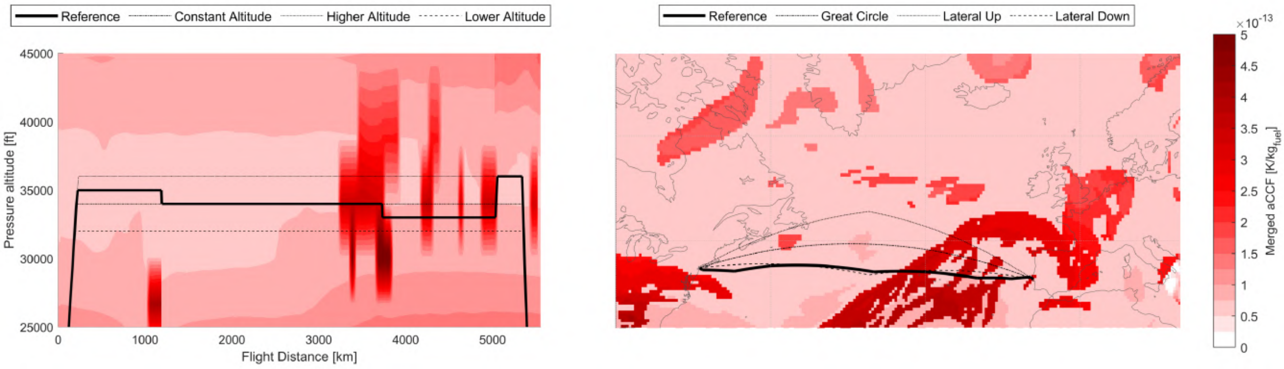


Figure 4 – Vertical (left) and lateral (right) trajectory adaptations for exemplary mission from KJFK to LPPT in relation to climate impact sensitivity in ATR20 (pulse) over fuel consumption

	ATR50	Fuel burn	Distance	Flight time	DOC
Reference	$7.05 \cdot 10^{-9}$ K	19,300 kg	5,550 km	05:51	59,804 USD
Constant Altitude	+ 2.92%	- 0.37%	0.0%	- 0.01%	- 0.07%
Lower Altitude	- 17.1%	- 5.25%	0.0%	- 0.25%	- 1.16%
Higher Altitude	- 13.3%	+ 6.05%	0.0%	- 0.19%	+ 1.44%
Great circle	+ 1.14%	- 1.37%	- 2.71%	- 0.84%	- 0.80%
Lower Latitudes	- 11.6%	+ 4.66%	- 0.79%	+ 5.40%	+ 4.17%
Higher Latitudes	+ 14.7%	- 1.41%	- 0.79%	- 0.99%	- 0.88%
Temporal Advance	+ 1.27%	+ 0.48%	0.0%	+ 0.38%	+0.33%
Temporal Delay	- 3.08%	- 0.24%	0.0%	- 0.22%	-0.18%

Table 2 – Change in climate and non-climate indicators for different trajectory adaptation strategies in relation to reference mission for an exemplary mission from EGKK to KJFK.

effect is caused by H_2O and CO_2. Consequently, there is a large mitigation potential through contrail avoidance with trajectory adaptation. By contrast, Figure 5 (right) illustrates the contribution of different species for a mission from London Heathrow (EGLL) to Atlanta (KATL) as performed on June 6th, 2018, where the climate impact from CiC is negligible (0.6% of the total climate impact). In this case, climate mitigation potentials are mainly influenced by NO_x effects which account for more than 80%. For instance, the total climate impact can be reduced by 6.1% caused by a reduction of 8% in NO_x and 12% in H_2O effects. While the CiC-intensive example shows mitigation potentials of up to 17%, mitigation potentials are significantly lower in this case.

3.2 Efficiency of Different Measures in Dependence of Meteorological Situation

Based on the results obtained in section 3.1, we investigate climate mitigation potentials and associated change in DOC from different trajectory adaptations in dependence of the weather situation for the North Atlantic flight sample in the following. Reference climate impact and mitigation potentials for the different adaptation measures do not only vary for different origin-destination combinations and aircraft types defining the mission, but also due to differences in:

- Vertical and lateral route characteristics (as indicated in Figure 6)
- Temporal aspects, such as take-off and landing-times as well as flight speed
- Meteorological boundary conditions in dependence of the selected day

To investigate these influencing factors, we analyze variations in mitigation potentials on different days (Subsection 3.2.1) considering differences in the reference mission regarding lateral, vertical and temporal routing. In a second step, we aim to exclude effects from different route configurations to focus on effects from different meteorological conditions which is described in subsection 3.2.2.

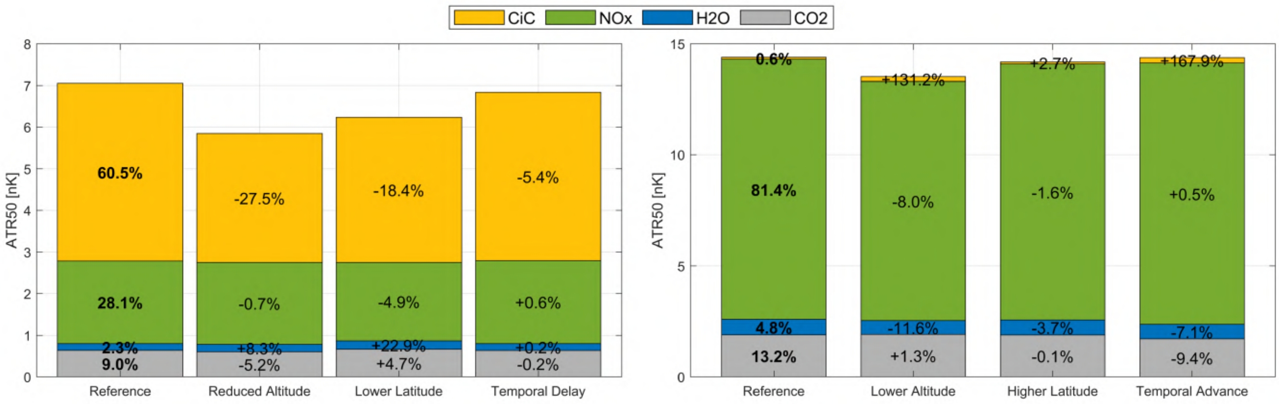


Figure 5 – Change in climate impact due to selected trajectory adaptations for an exemplary mission with high contrail intensity from KJFK to LPPT (left) and an exemplary mission with low CiC intensity from EGLL to KATL (right). Numbers in reference bar indicate share of different climate forcers, numbers in other bars indicate change in climate impact relative to reference.

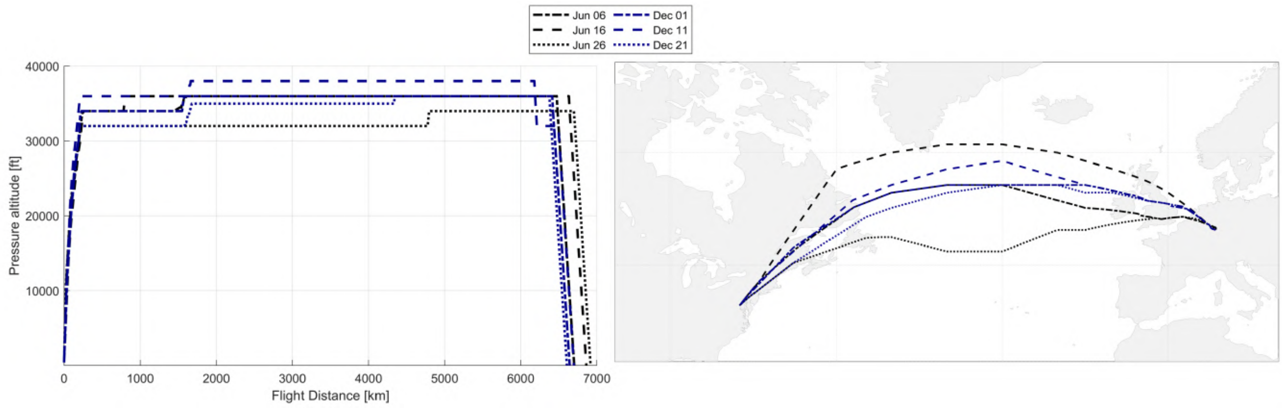


Figure 6 – Vertical (left) and lateral (right) differences in reference trajectory for selected case study days in June and December for exemplary mission EDDF - KIAD

3.2.1 Selected Case Study Days

Figure 7 illustrates possible climate mitigation potentials in relation to resulting changes in DOC. Different colors in these figures represent different analysis days, thus different reference route configurations in spatial and temporal domain. The variability of mitigation potentials and efficiencies is influenced by both differences in reference route as well as meteorological conditions. As illustrated in Figure 6 for an exemplary mission from Frankfurt (EDDF) to Washington D.C. (KIAD) both lateral and vertical routing vary significantly over the selected case study days. Cruise flight altitudes range between FL320 and 380 while lateral expansion in the North Atlantic flight corridor varies between maximum latitudes of 54 and 62 degrees. In relation to spatial variations of average climate sensitivities (Figure 3), these route variations already lead to significant reference climate impact variations. In combination with changing meteorological conditions, we find differences in reference climate impact of up to 33.4% in total and even larger variations in NO_x effects (up to 43.9% compared to the mission with lowest NO_x impact) and CiC effects (up to 600% compared to the mission with lowest contrail intensity).

This leads to significant variations in mitigation potentials. For the selected exemplary mission from EDDF to KIAD, benefits from vertical trajectory adaptations can only be identified for three of the analyzed case study days (see Figure 7, left). For instance, on June 26th, climate impact can be mitigated with both lower and constant altitude, while it is increased for higher altitudes. Up to 12% of climate impact can be mitigated with lateral adaptations over the different considered case study days. Nevertheless, we observe that many adaptation strategies do not reduce the climate impact as it is the case for higher flight altitudes for 4 of the 6 selected days. This varies significantly with the

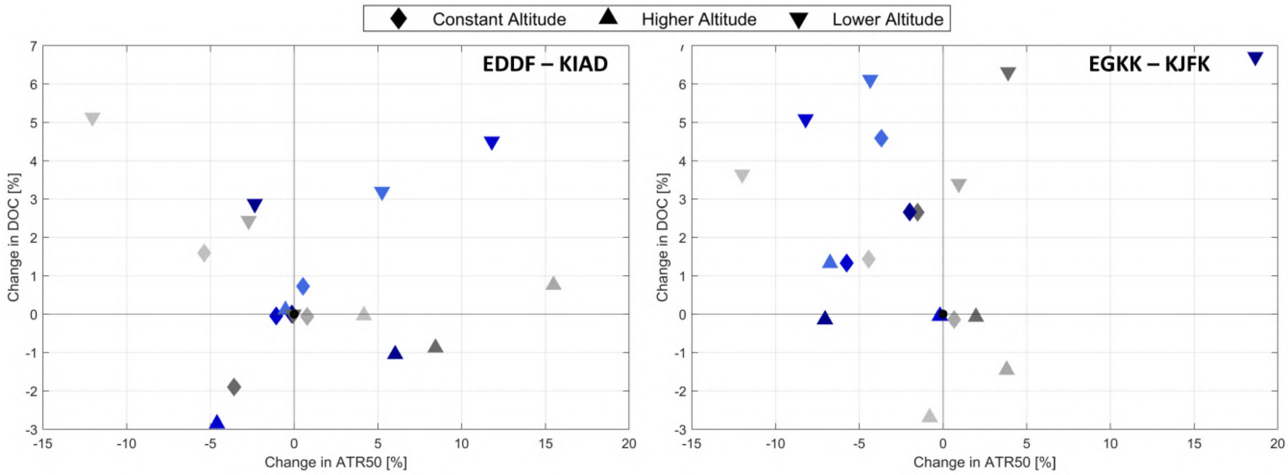


Figure 7 – Changes in mitigation potentials from vertical adaptations related to DOC changes for an exemplary mission from EDDF to KIAD (left) and EGKK to KJFK (right) on investigated case study days in June and December. Different analysis days are indicated by different colors.

considered route as we see generally higher climate mitigation potentials of the considered vertical trajectory adaptations for the mission from London Gatwick (EGKK) to New York (KJFK), as indicated in Figure 7 (right).

Generalizing the obtained individual mission results to the scope of North Atlantic missions considered in this study, we find no superior adaptation strategy in general. Rather, the selection of especially effective or efficient measures depends on both reference route configurations, such as reference flight altitude or lateral dimension, as well as meteorological conditions. Figure 8 highlights the dependencies of climate mitigation potentials from different adaptation measures and reference mission parameters. It shows on average higher climate mitigation potentials for a higher share of CiC effects related to the total climate impact. Analogously, mitigation potentials decrease with a higher NO_x share (Figure 8, top left). Since CiC effects can be both warming and cooling, the analysis of relative contrail distance (i.e. distance of a mission with contrail formation related to total mission distance) generalizes these effects and shows higher mitigation potentials from trajectory adaptations for missions with longer relative contrail distance (Figure 8, top right). We also observe higher mitigation potentials in December compared to June.

Looking into routing characteristics of the reference mission, Figure 8 (bottom, left) illustrates changes in ATR50 for the three considered vertical adaptation methods and shows a small dependency from the cruise altitude of the reference mission. While missions with a high average reference flight altitude benefit from reduced altitudes, missions with lower reference altitude benefit from higher altitudes. A restriction to the constant cruise flight level also appears beneficial for higher flight altitudes. Furthermore, Figure 8 (bottom, center) shows dependencies of lateral route adaptions of the average latitude per reference mission. In general, we observe a higher effectiveness of lateral upward shifts for lower average altitudes while downward shifts on average do not increase mitigation potentials. Figure 8 (bottom, right) displays the variability of temporal mitigation potential in relation to the average time of day per considered mission. For this flight sample of North Atlantic missions, we observe benefits from later take-off times (temporal delay) for flights with average flight times in the morning and from earlier take-off times (temporal advance) for flights with average flight times in the evening. This can be explained by the fact that during day CiC climate effects can be both warming and cooling while they are limited to warming effects during night. Therefore, both approaches represent a shift of trajectories more towards the day. Nevertheless, Figure 8 shows significant higher variations in mitigation potentials considering route parameters while reference climate impact of contrails represents gives a more stable indication.

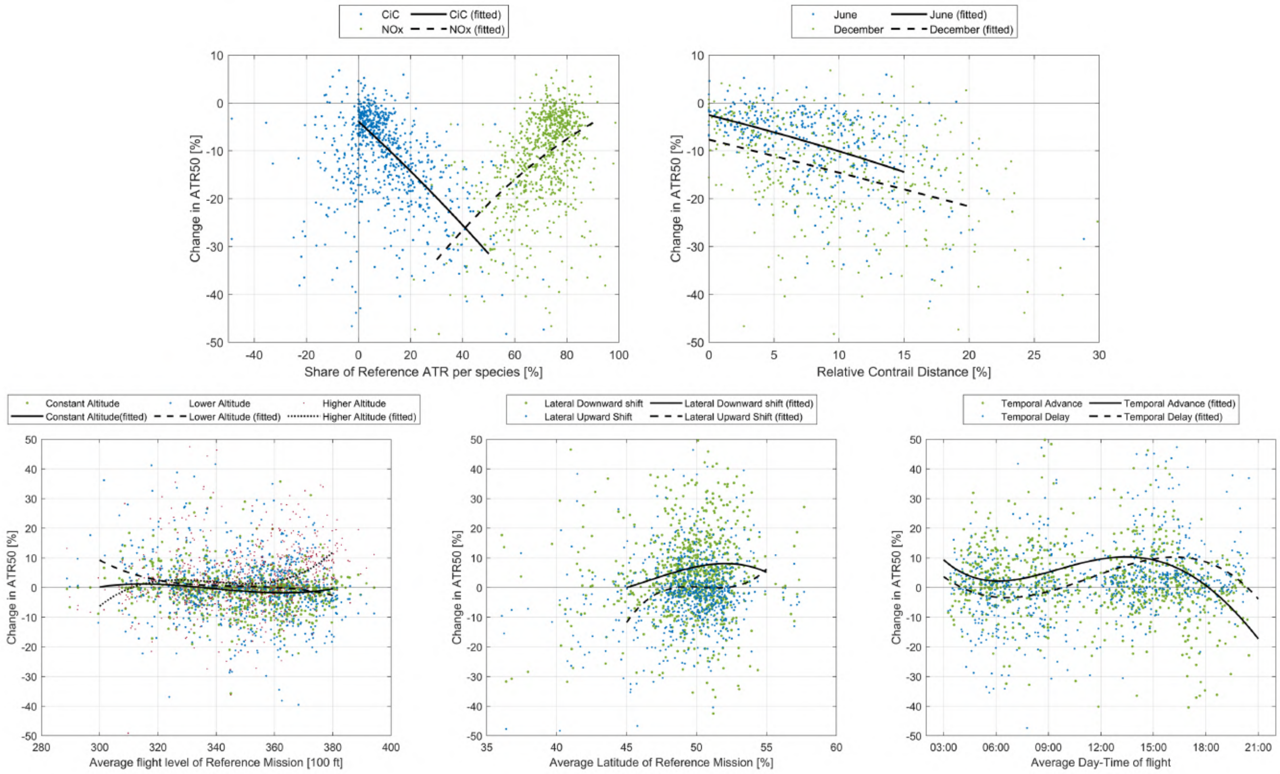


Figure 8 – Dependencies of climate impact mitigation for different measures from reference route characteristics.

3.2.2 Monthly Variance of Mission-related Climate Effects

To exclude effects from varying reference route configurations, this chapter analyzes one reference trajectory over the course of all daily meteorological situations in June and December of 2018. In this course, we can reduce variations in mitigation potentials to the variations in meteorological conditions. Figure 9 (top) shows the variance in climate impact for an exemplary route from EGKK to KJFK over all days of the considered months June and December. We observe a strongly varying climate impact of CiC effects in both month represented by days without or negligible contrail formation (e.g. June 7th, June 28th, December 8th and 9th) and days of strong contrail climate impact (e.g. June 13th, June 23rd, December 22nd). Due to longer days in the northern hemisphere in summer, we also find two days with cooling CiC effects in summer (June 18th and 29th), which is not the case for this night-time flight in winter. By contrast, we observe a small variation of NO_x effects in June, while we find higher variation for the selected route in December 2018. Water vapor effects also vary in dependence of the meteorological situation, but their influence remains limited due to their small overall contribution to the entire climate effect. CO_2 effects do not change based on constant route and wind assumptions over all considered days.

The average climate impact in June is slightly higher compared to December, also associated with slightly lower standard deviations (Table 3). As indicated in Figure 9, Table 3 confirms a lower mean climate effect and a higher variance for NO_x emissions in December. Moreover, absolute CiC effects for this example are slightly smaller in December, but the relative contribution of CiC is higher (18.5% of total impact in December and 17.4% in June). Figure 9 (bottom) relates the mitigation potentials from vertical trajectory adaptations to the reference climate impact. We observe especially high mitigation potentials on days with a high CiC climate impact. In general, results indicate a higher average mitigation potential of 4.5% in December compared to June (4.1%). During both months, reduced cruise altitudes represent the preferred trajectory adaptation measure.

Generalizing the results illustrated for an exemplary flight mission to the entire sample of North Atlantic flights of this study, we confirm a higher reference climate impact in June compared to December (Table 3), as well as a lower NO_x impact in December compared to June. The climate impact of CiC is significantly higher during night time and also varies significantly between June and December.

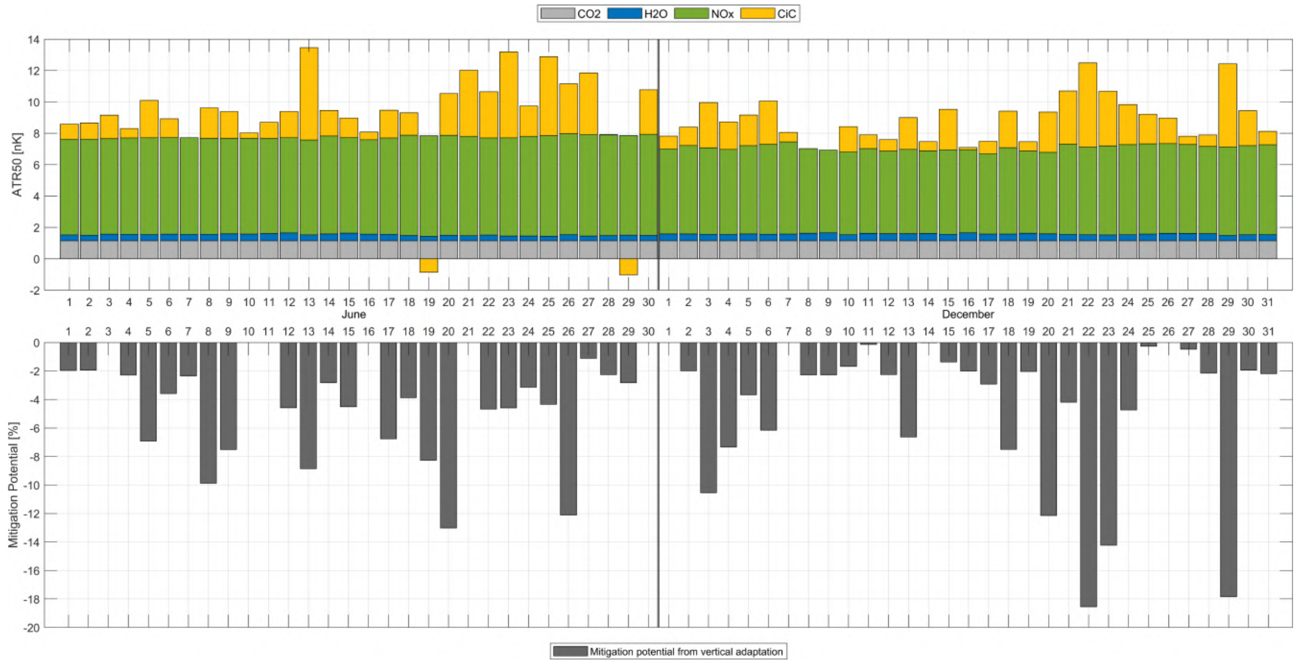


Figure 9 – Variation of climate impact from different species for representative route (top) and mitigation potentials from vertical adaptations (bottom) for an exemplary mission from EGKK to KJFK.

	EGKK - KJFK		North-Atlantic flight sample			
	Night-time		Day-time		Night-time	
	Jun	Dec	Jun	Dec	Jun	Dec
Total ATR50 [nK]	9.7 (1.7)	8.9 (1.4)	12.8 (0.6)	10.9 (0.9)	14.1 (0.9)	13.3 (1.1)
ATR50 of CO_2 [nK]	1.1 (0.0)	1.1 (0.0)	1.7 (0.0)	1.7 (0.0)	1.7 (0.0)	1.7 (0.0)
ATR50 of H_2O [nK]	0.4 (0.1)	0.4 (0.04)	0.5 (0.04)	0.6 (0.03)	0.5 (0.04)	0.6 (0.03)
ATR50 of NO_x [nK]	6.2 (0.1)	5.5 (0.2)	9.3 (0.2)	8.1 (0.2)	9.4 (0.1)	8.1 (0.2)
ATR50 of CiC [nK]	1.9 (1.7)	1.8 (1.3)	1.2 (0.5)	0.4 (0.9)	2.5 (0.9)	2.8 (1.0)

Table 3 – Mean climate impact and standard deviation (in brackets) for different species over different flight samples.

3.3 Efficiency Comparison from Tactical and Strategic Perspective

Sections 3.1 and 3.2 analyze climate mitigation potentials from different trajectory adaptation mechanisms. In this context, we confirm a high dependency of mitigation potentials from both meteorological and routing characteristics. It appears that the most suitable adaptation approach per trajectory needs to be selected in consideration of the reference route and its climate impact under the specific atmospheric constraints in a tactical set-up. Consequently, the tactical selection of the best trajectory adaptation per route leads to a climate mitigation potential between 8.8 and 11.4% (9.5% on average) for the June case study days and 13.6 and 16.2% (15.1% on average) for the December case study days. This is associated with cost changes of up to 1%. Moreover, the preferred adoption mechanism varies over the different case study days. In June, a lateral shift of trajectories leads to the highest mitigation potentials in 24% of the cases, whereas reduced cruise altitudes are most effective for 17% of all flights. For the selected December days, a reduction of cruise altitude is preferred in 25% and a temporal delay of take-off times in 15.4% of the cases.

In contrast to a strategic perspective, the effectiveness of each measure varies significantly with the actual weather situation when consistently applied to the entire flight plan. While, for instance, lower cruise altitudes in general reduce the climate impact by 3.1% on December 11th, the climate impact increases by 3.8% on December 21st. We can show that reducing lateral routing inefficiencies by following the great circle leads to climate mitigation potentials of up to 1.5% over the entire sample of

flights and meteorological situations. Moreover, shifting flight routes to higher latitudes reduces the climate impact by 2.0% on average.
On this basis, it seems feasible to consider the average expected weather situation per month to select a suitable mission adaptation per flight if feasible and compare this to the mitigation potentials that can be realized with the actual weather situation of the considered day. Figure 10 shows climate mitigation potentials of different vertical trajectory adaptations for an exemplary route from EGKK to KJFK for the average meteorological situation per month in comparison to the consideration of meteorological parameters per day. On average, a reduction in cruise flight altitudes represent the most promising vertical adaptation measure providing a reduction in climate impact over different weather situations within and across different months. Nevertheless, significant variations occur over individual days (between -13.0 and +10.8%). Furthermore, the average monthly weather situation shows a mitigation potential of 1.7% in June (3.3% in December), while the average over the considered days lower at 1.3% (2.6 % in December).

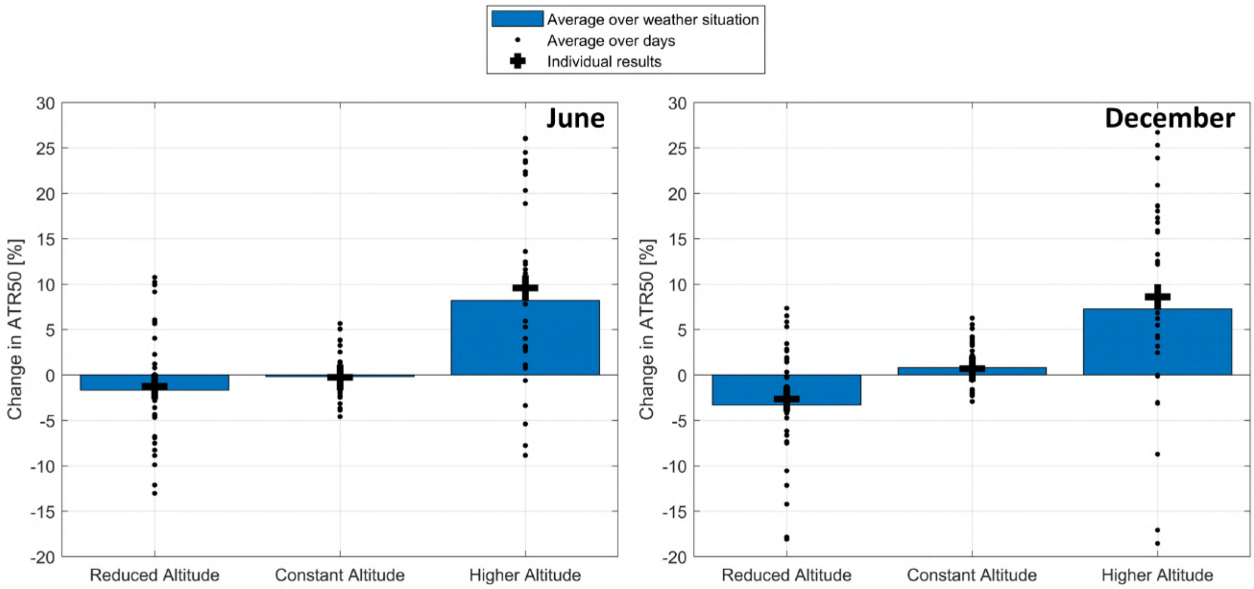


Figure 10 – Variation of mitigation potentials from vertical adaptations for an exemplary mission from EGKK to KJFK for all days in June and December 2018 in relation to average results.

4. Assessing Efficiency of Different Climate Mitigation Measures - Discussion

The results of this paper show the dependence of different trajectory adaptation mechanisms from mission boundary conditions, especially regarding meteorology. Our results are consistent with previous literature showing seasonal variability of NO_x and CiC effects and confirm higher mitigation potentials from lateral and vertical adaptations in winter compared to summer [18, 17]. Moreover, strongly varying contrail effects for different missions and weather conditions imply large mitigation potentials for high-impact flights without affecting a majority of missions [11].
The comparison between strategic approaches, e.g. reducing the cruise flight altitudes of missions in general, and tactical approaches, i.e. selecting the best suitable trajectory adaptation based on the actual weather situation reveals significant differences in actual mitigation potentials. Obviously, tactical implementations lead to higher mitigation potentials as the individual characteristics along each flight mission can be considered. By contrast, strategic approaches aim to identify one solution that addresses average meteorological conditions and reduces the climate impact with one approach that suits all missions facilitating operational implementation. However, lower mitigation potentials are observed in this context relying on general climatological correlations excluding detailed meteorological information.
Nevertheless, the results need to be put in context of the study set-up and method (section 4.1) as well as operational applicability of selected climate mitigation measures from stakeholder perspective (section 4.2).

4.1 Critical Evaluation of Method and Results

An interpretation of results requires to take assumptions and limitations of the study into account. On the one hand, the set-up of the study, its geo-temporal scope as well as the selected trajectory-adaptation measures influence the obtained mitigation potentials. For simplicity reasons, we limit our consideration of mitigation measures to nine different options excluding, for instance, larger altitude shifts [13, 14] or integrated trajectory optimization [10, 16]. These measures have the potential to result in even higher mitigation potentials. Furthermore, obtained results are only valid for the North Atlantic region in the selected month. A transfer of June and December results to summer and winter season as well as to a broader geographic scope requires further research.
On the other hand, uncertainties and inaccuracies in the assessment process need to be considered. A climate impact assessment of aviation emissions is still associated with high uncertainties according to the current level of scientific understanding [2]. Especially the assessment of contrails and nitrogen oxides with aCCFs includes significant simplifications, so that realistic climate mitigation potentials can only be approximated. A comparison with other climate models could help to reduce the uncertainties in this context. Further uncertainties result from trajectory and emissions modelling, though we expect these uncertainties to be significantly below the uncertainties of the climate assessment.
Moreover, the selection of climate metric significantly influences the results. Shorter time-horizons put more weight on the short-lived climate forcers, especially CiC, compared to other species. The species considered in climate impact assessment also influence the results. For instance, other studies [11, 12] focus on the energy forcing from CiC and CO_2 only, showing generally higher mitigation potentials than this study. Additionally, applied weather data and forecast models underly uncertainties. We have based our analysis on reanalysis data as provided by the ECWMF ERA5 data set. In the course of trajectory optimization and adaptation in tactical flight planning, the mitigation potentials are typically based on meteorological forecasts as reanalysis data is not yet available. Uncertainties in forecasting and meteorological modelling further extend the uncertainties in this context, but have been excluded from this study.

4.2 Stakeholder Effects

We show significant mitigation potentials of different adaptation approaches for the considered flight missions. In most cases, these trajectory changes do not lead to significant changes in DOC (Table 2, Figure 7). However, it needs to be considered that besides cost changes, the stakeholders of the air transport system are affected in different intensities as displayed in Table 4.

	Airlines	**ATC & ATFM**	**Airports**	**Passengers**
Vertical adaptations	medium	medium	low	low
Lateral adaptations	medium	medium	low	low
Temporal adaptations	high	medium	medium	medium

Table 4 – Impact from different adaptation mechanisms on stakeholder of the air transport system.

Beyond changes in operating cost from different trajectory adaptations leading to deviations from cost optimal routes, especially temporal adaptations result in interruptions of airline networks as schedules need to be adjusted. Furthermore, air traffic control and air traffic flow management are affected by trajectory adaptations. For instance, regions and times of low climate sensitivity are expected to see higher traffic density. Also, airports can be affected of the above modelled trajectory adaptations. A shift of take-off times as well as an increase of flight times can have an affect on local traffic densities within certain time intervals during the day. Even today, the negotiation between calculated take-off times (CTOT) and target start-up approval times (TSAT) at coordinated airports is sometimes challenging during operations. Further prioritization procedures would have to be compared in particular with climate-friendly concepts for ground operations. Passengers are also only marginally affected by lateral and vertical deviations from the original trajectories. On the one hand, their travel preferences might change if DOC increases are directly transferred to higher ticket prices or if re-routings lead to longer travel times. On the other hand, temporal deviations and change of take-off times could reduce travel comfort especially when shifting departure and arrival times to night or early morning. From ATC perspective, the consideration of climate sensitive areas has the potential for en-route capacity reduction, since less airspace is available for safely separated flights. Technological developments can enable capacity stability by increasing planning and coordination flexibility for controllers.

5. Conclusion and Outlook

All in all, our study results in the following findings. First, we present and establish an efficient method enabling a computationally inexpensive climate assessment of different flight trajectories. Based on a climate sensitivity grid derived from aCCFs in V1.0A [24], we can assess the climate impact of a large set of trajectories for different meteorological conditions. Second, we investigate effectiveness of different trajectory adaptation approaches showing promising mitigation potentials for vertical, lateral and temporal adaptations in dependence of the reference mission itself as well as the respective meteorological situation. We show a relation between contrail intensity of a reference mission and potential reduction in climate impact for missions in June and December 2018. For mission-specific case studies as well as the North-Atlantic flight sample, we observe higher mitigation potentials in December compared to June. Finally, we relate mitigation potentials from tactical trajectory adaptations in dependence of the actual weather situation to strategic approaches. For a single-mission case study, we show the suitability of reduced flight altitudes in June and December on average over all days of the month as well as for the average weather situation.

We suggest future research in this context aiming for a broader temporal and geographical scope. For instance, variations of climate impact and mitigation potentials a longer time period (e.g. several years) are interesting to investigate. Moreover, additional measures could extent the significance of the study as well as quantitatively incorporating further stakeholder effects. A sensitivity analysis regarding applied climate metric, different meteorological data sets and assessment models could complete the results.

6. Contact Author Email Address

zarah.zengerling@dlr.de

7. Copyright Statement

References

[1] Volker Grewe, Arvind Gangoli Rao, Tomas Grönstedt, Carlos Xisto, Florian Linke, Joris Melkert, Jan Middel, Barbara Ohlenforst, Simon Blakey, Simon Christie, Sigrun Matthes, and Katrin Dahlmann. Evaluating the climate impact of aviation emission scenarios towards the paris agreement including COVID-19 effects. *Nature Communications*, 12:3841:10, 2021.

[2] D.S. Lee, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.R. De León, L.L. Lim, M.T. Lund, R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, R. Sausen, and L.J. Wilcox. The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 244:117834:29, 2021.

[3] Ulrich Schumann. Influence of propulsion efficiency on contrail formation. *Aerospace Science and Technology*, 4(6):391–401, 2000.

[4] European Union. Eu directive 2023/958 of the european parliament and of the council (10 may 2023) 'amending directive 2003/87/ec as regards aviation's contribution to the union's economy-wide emission reduction target and the appropriate implementation of a global market-based measure. *Official Journal of the European Union*, L 130, 10 May 2023. Accessed: 2023-08-06.

[5] Dieter Schmitt and Volker Gollnick. *The Air Transport System*, pages 1–17. 01 2016.

[6] Florian Linke, Grewe Volker, and Volker Gollnick. The implications of intermediate stop operations on aviation emissions and climate. *Meteorologische Zeitschrift*, 26, 03 2017.

[7] Zarah Lea Zengerling, Florian Linke, Christian Martin Weder, and Katrin Dahlmann. A comparison of climate-optimised and fuel-optimised intermediate stop operations for selected case studies. In *33rd Congress of the International Council of the Aeronautical Sciences*, September 2022.

[8] Alexander Koch. *Climate Impact Mitigation Potential given by Flight Profile and Aircraft Optimization*. PhD thesis, 2013.

[9] Mahdi Noorafza, Bruno F. Santos, Alexei Sharpanskykh, Zarah L. Zengerling, Christian M. Weder, Florian Linke, and Volker Grewe. Airline network planning considering climate impact: Assessing new operational improvements. *Applied Sciences*, 13(11), 2023.

[10] Benjamin Lührs, Florian Linke, Sigrun Matthes, Volker Grewe, and Feijia Yin. Climate impact mitigation potential of european air traffic in a weather situation with strong contrail formation. *Aerospace*, 8(2), 2021.

[11] Roger Teoh, Ulrich Schumann, Arnab Majumdar, and Marc E. J. Stettler. Mitigating the climate forcing of aircraft contrails by small-scale diversions and technology adoption. *Environmental Science & Technology*, 54(5):2941–2950, 2020. PMID: 32048502.

[12] Michael Becker, Florian Linke, and Volker Gollnick. Untersuchungen zum Ansatz der Vermeidung nächtlicher Kondensstreifen zur Reduktion der Klimawirkung des Luftverkehrs. In *Deutscher Luft- und Raumfahrtkongress 2022*. Deutsche Gesellschaft für Luft- und Raumfahrt - Lilienthal-Oberth e.V., September 2022.

[13] Sigrun Matthes, Ling Lim, Ulrike Burkhardt, Katrin Dahlmann, Simone Dietmüller, Volker Grewe, Amund S. Haslerud, Johannes Hendricks, Bethan Owen, Giovanni Pitari, Mattia Righi, and Agnieszka Skowron. Mitigation of non-CO2 aviation's climate impact by changing cruise altitudes. *Aerospace*, 8(2), 2021.

[14] Zarah Zengerling, Florian Linke, Benjamin Lührs, Christian M. Weder, and Volker Gollnick. Trajectory-related measures to mitigate the climate impact of aviation: A comparative study. In *AIAA AVIATION 2023 Forum*, June 2023.

[15] Katrin Kölker, Zarah Lea Zengerling, Markus Kühlen, Klaus Lütjens, and Florian Linke. Assessing the impact of contrail avoidance through rescheduling on airline network flows: A case study of north atlantic flights. In *25th Euro Working Group on Transportation Meeting (EWGT 2023)*, September 2023.

[16] Maximilian Mendiguchía Meuser, Benjamin Lührs, Florian Linke, Volker Gollnick, Sigrun Matthes, Simone Dietmüller, Sabine Baumann, Manuel Soler, Abolfazl Simorgh, Feijia Yin, and Federica Castino. Mitigation of aviations climate impact through robust climate optimized trajectories in intra-european airspace. In *33rd Congress of the International Council of the Aeronautical Sciences*, September 2022.

[17] Federica Castino, Feijia Yin, Volker Grewe, Manuel Soler, Abolfazl Simorgh, Hiroshi Yamashita, Sigrun Matthes, Sabine Baumann, Simone Dietmüller, Florian Linke, and Benjamin Lührs. Seasonal variability of aircraft trajectories reducing nox-climate impacts under a multitude of weather patterns. In *11th SESAR Innovation Days*, 2021.

[18] Feijia Yin, Volker Grewe, Christine Frömming, and Hiroshi Yamashita. Impact on flight trajectory characteristics when avoiding the formation of persistent contrails for transatlantic flights. *Transportation Research Part D: Transport and Environment*, 65:466 – 484, 2018.

[19] Maximilian Mendiguchia Meuser, Alexander Lau, and Volker Gollnick. Investigation on the effects of weather patterns on strategic climate impact mitigation measures: a data-based approach. In *ECATS Conference*, October 2023.

[20] Florian Linke. *Ökologische Analyse operationeller Lufttransportkonzepte*. PhD thesis, 2016.

[21] Doug DuBois and Gerald C. Paynter. "Fuel Flow Method2" for estimating aircraft emissions. *SAE Transactions*, 115:1–14, 2006.

[22] Jesper van Manen and Volker Grewe. Algorithmic climate change functions for the use in eco-efficient flight planning. *Transportation Research Part D: Transport and Environment*, 67:388–405, Februar 2019.

[23] Simone Dietmüller, Sigrun Matthes, Katrin Dahlmann, Hiroshi Yamashita, Abolfazl Simorgh, Manuel Soler, Florian Linke, Benjamin Lührs, and Maximilian M. Meuser et al. A python library for computing individual and merged non-CO_2 algorithmic climate change functions: CLIMaCCF V1.0. *Geoscientific Model Development*, 16(15):4405–4425, 2023.

[24] Sigrun Matthes, Simone Dietmüller, K. Dahlmann, Christine Frömming, Peter Peter, Hiroshi Yamashita, Volker Grewe, Feijia Yin, and Federica Castino. Updated algorithmic climate change functions (aCCF) V1.0A: Evaluation with the climate-response model AirClim V2.0. *Geoscientific Model Development Discussions*, 2023:1–28, 2023.

[25] Benjamin Lührs, Florian Linke, and Volker Gollnick. Erweiterung eines Trajektorienrechners zur Nutzung meteorologischer Daten für die Optimierung von Flugzeugtrajektorien. In *63. Deutscher Luft- und Raumfahrtkongress 2014 (DLRK)*, September 2014.

[26] Angela Nuic, Damir Poles, and Vincent Mouillet. BADA: An advanced aircraft performance model for present and future ATM systems. *International Journal of Adaptive Control and Signal Processing*, 24(10):850–866, 2010.

[27] Martin Schäfer and Sebastian Bartosch. Overview on fuel flow correlation methods for the calculation of NO_x, CO and HC emissions and their implementation into aircraft performance software. Internal report IB-325-11-13, Deutsches Zentrum für Luft- und Raumfahrt, 07 2013.

[28] Zarah Lea Zengerling, Sara Dal Gesso, Florian Linke, Maximilian Clococeanu, Volker Gollnick, Patrick Peter, Sigrun Matthes, Baris Baspinar, Ibrahim Ozkol, and Mahdi Noorafza et al. Operational improvements to reduce the climate impact of aviation - a comparative study from EU project ClimOP. *Applied Sciences*, 13(16), 2023.

[29] Tobias Marks, Katrin Dahlmann, Volker Grewe, Volker Gollnick, Florian Linke, Sigrun Matthes, Eike Stumpf, Majed Swaid, Simon Unterstrasser, Hiroshi Yamashita, and Clemens Zumegen. Climate impact mitigation potential of formation flight. *Aerospace*, 8(1), 2021.

[30] EUROCONTROL. Demand data repository, 2024. Available online: https://www.eurocontrol.int/ddr (accessed on 30 May 2024).

[31] ICAO. ICAO aircraft engine emissions databank, 2021. Available online: https://www.easa.europa.eu/domains/environment/icao-aircraft-engine-emissions-databank (accessed on 18 July 2022).

[32] Hans Hersbach, Bill Bell, Paul Berrisford, Shoji Hirahara, András Horányi, Joaquín Muñoz-Sabater, Julien Nicolas, Carole Peubey, Raluca Radu, and Dinand Schepers et al. The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, 146(730):1999–2049, 2020.