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Flying low and slow: Application of algorithmic climate change functions to assess the climate mitigation potential of reduced cruise altitudes and speeds on different days

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Abstract

The climate effect from aviation's non-CO_2 emissions such as contrail cirrus, water vapor and nitrogen oxide induced ozone and methane changes depend on emission location and time. Among other approaches, the resulting climate effect can be reduced by lowering cruise flight levels. However, aircraft typically aim to fly at optimum altitudes and perform step climbs with increasing flight length to enhance fuel efficiency and reduce operating cost, what also limits climate effects from CO_2 emissions. To account for this and to reduce the overall climate effect of flights, the higher fuel consumption at lower flight altitudes can be compensated by also reducing flight speeds. Therefore, this study analyzes the mitigation potential of flying lower and slower with regard to the overall climate effect along flight trajectories. Specifically, actually flown point profiles are combined with related meteorological parameters to evaluate the effect from reduced cruise altitudes and speeds with an updated set of prototype algorithmic climate change functions. Different case studies show varying effects for individual days during different seasons, and significant mitigation potentials due to flying lower and slower can be observed (up to 9 % on a summer day and 16 % on a winter day). A sensitivity study to explore uncertainties with regard to the quantification of contrail effects is performed as well as an investigation on possible economic consequences in terms of changes in direct operating cost and eco-efficient solutions.

Keywords: aviation climate impact, operational improvements, trajectory modelling, non-CO_2 effects, contrail effects

1 Introduction

Non-CO_2 emissions represent a significant share of air traffic's contribution to anthropogenic climate change. These effects caused by emission species such as contrail cirrus, water vapor (H_2O) or nitrogen oxides (NO_x) account for about two thirds of aviation's net radiative forcing (Lee et al., 2021). While effects from CO_2 are directly related to fuel consumption, non-CO_2 climate effects highly depend on the emission location, the time of release and atmospheric background conditions (Frömming et al., 2021; Lee et al., 2010; Lee et al., 2009; Irvine et al., 2012). Nevertheless, the quantification of non-CO_2 effects is still subject to large uncertainties according to the current scientific understanding (Lee et al., 2021). Technical, operational and regulatory improvements will be required to reduce aviation's contribution to climate change from both CO_2 and non-CO_2 emissions and to comply with the ambitious climate goals that have been defined (Grewe et al., 2021; ATAG, 2021; ICAO, 2019). In addition to fuel efficiency enhancements and the associated reduction in CO_2 emissions, operational improvements are also applicable to reduce non-CO_2 effects by optimizing trajectories. In this course, emission quantities, location and time can be improved to minimize the resulting climate impact and climate-optimized trajectories can be determined as summarized by Simorgh et al. (2022) in a recent literature review.

A reduction of flight levels to less climate-sensitive altitudes has been subject to previously published research. Existing studies show significant climate mitigation potentials of up to 20 % due to reduction in non-CO_2 effects that largely overcompensate increased CO_2 climate impact from higher fuel consumption (Matthes et al., 2021; Frömming et al., 2012; Williams et al., 2002). Other studies focusing on individual species' effects such as NO_x-induced ozone and methane changes or contrail-induced cirrus (CiC) further confirm the effectiveness of this measure to reduce the resulting radiative forcing (Castino et al., 2021; Teoh et al., 2020a; Teoh et al., 2020b; Søvde et al., 2014; Fichter et al., 2005; Grewe et al., 2002). To additionally address the effect of rising CO_2 emissions at lower flight altitudes, one option is to reduce cruise speeds leading to higher fuel efficiency and lower cli-

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mate impact from CO_2 emissions (Dahlmann et al., 2016b; Koch, 2013; Koch et al., 2011). For example, Dahlmann et al. (2016b) found a reduction potential of more than 40 % in terms of average temperature response over 100 years (ATR100) by adjusting cruise altitude and speed while keeping cash operating cost increase below 10 %. These altitude-dependent effects have been found to vary across the seasons of the year: Castino et al. (2021) investigated differences between cost-optimal cruise altitudes and such altitudes with a minimum NO_x-induced climate impact, where they found smaller gaps between those during the summer months (July–September). Yin et al. (2018) showed a comparable correlation for minimizing trajectories' contrail distance, stating that optimizations are less effective in summer compared to winter. However, a detailed analysis of the influence of reduced cruise altitudes and speeds on the effects from different emission species for various meteorological background conditions has not yet been performed.

Hence, the goal of this study is to assess the climate mitigation potential of reduced cruise altitudes and speeds on individual days during different seasons applying realistic representative atmospheric background conditions. In addition to previously published work e.g. by Matthes et al. (2021) and Lührs et al. (2021), (1) we incorporate actually flown point profiles of the selected days and combine these with the weather situation along the respective flight mission. Furthermore, (2) we utilize an updated set of prototypical algorithmic Climate Change Functions (aCCFs, Matthes et al., submitted). By doing so, we aim to demonstrate their applicability to assess the climate mitigation potential of such trajectory-related operational improvements as well as in a contrail-specific sensitivity study. Finally, (3) the resulting change in climate impact described as average temperature response over 20 years (ATR20) can be combined with resulting changes in fuel consumption and flight time to estimate both costs and benefits of implementing this measure for different meteorological effects and in relation to the actually performed flight mission.

The paper is structured as follows: After this introduction, we describe the applied method with regard to the climate impact assessment and trajectory modelling as well as the definition of the study scope in Section 2. Achieved results are presented in Section 3, before we discuss limitations and possible further research (Section 4) and conclude the paper in Section 5. Results of this study have been achieved in context of the project ClimOP[1], which aims to assess several operational improvements in-flight and on-ground to mitigate the climate impact of aviation. On this basis, policy recommendations are supposed to be derived to enable an implementation of efficient climate mitigation measures (Tedeschi 2020).

[1]www.climop-h2020.eu

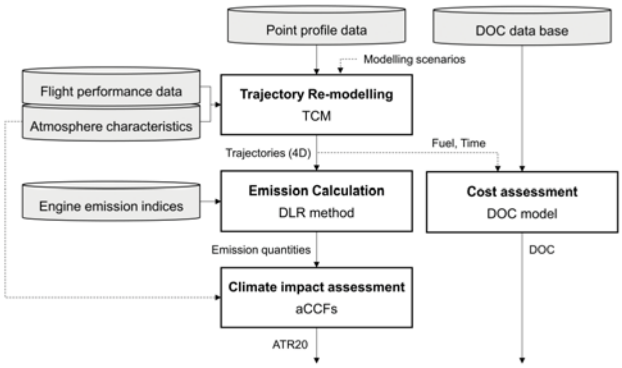

Figure 1: Workflow and applied data of the study.

2 Method and study set-up

The approach of this study follows the workflow as described in Figure 1. Assessment of climate effects is performed with aCCFs (Section 2.1), which is based on trajectory and emission calculation (Section 2.2). Trajectories are re-modelled according to given point profile data under actual weather conditions applying aircraft specific flight performance data to obtain the required performance metrics in terms of fuel consumption, flight time and operating costs as the considered economic key performance indicators (KPIs). Fuel flow correlation methods are applied to obtain the required emission quantities fed into the aCCFs. The set-up of this study as part of the project ClimOP is described in Section 2.3.

2.1 Algorithmic climate change functions (aCCFs)

As CO_2 emissions come along with extended atmospheric residence times and long-term concentration changes in the atmosphere, the resulting climate impact is essentially determined by the amount of fuel that is consumed in the respective scenario. By contrast, non-CO_2 emissions contributing to the majority of aviation's climate impact (Lee et al., 2021) are associated with shorter atmospheric residence times (several hours for contrails to decades for methane changes). Hence, these emissions are more heterogeneously distributed and their effects vary with chemical and meteorological background conditions (Brasseur et al., 2016; Frömming et al., 2021). As non-CO_2 effects are thus sensitive towards emission location and time, this needs to be incorporated when estimating the climate impact of aviation emissions under specific temporal and geographical conditions.

To provide an assessment method for those spatially and temporarily varying effects of non-CO_2 species, climate change functions (CCFs, also referred to as climate cost functions) have been developed with the atmospheric climate chemistry model EMAC (ECHAM/MESSy Atmospheric Chemistry Model, Jöckel et al., 2016; Jöckel et al., 2010) as described by Grewe et al.

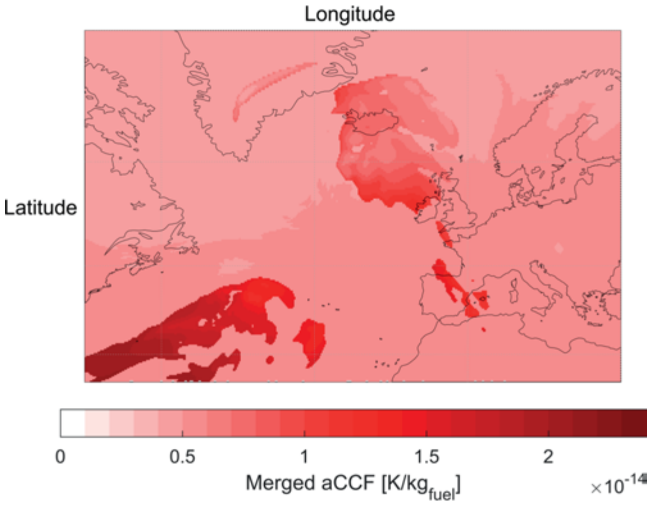

Figure 2: Exemplary evaluation of the merged aCCF of non-CO_2 effects including NO_x, H_2O and contrail effects for a wide-body aircraft at pressure level 200 hPa on December 11, 2018 at 00 UTC.

(2014a) and Frömming et al. (2021). These CCFs have been calculated for eight representative weather patterns (five for winter, three for summer season as identified by Irvine et al., 2013) for the North Atlantic flight corridor between 1989 and 2010 and give ATR20 per emission for the species NO_x-induced ozone and methane, water vapor and contrail cirrus in four-dimensional data fields.

As an application of these climate model based CCFs for trajectory optimization is computationally extensive (Grewe et al., 2014b), an extension of the concept towards aCCFs was introduced by van Manen and Grewe (2019) to enhance operational applicability. In this context, basic mathematical linear equations were derived by statistically relating model generated CCF data with meteorological conditions at time and location of the emission. The so derived aCCFs for NO_x-induced ozone and methane changes, contrail cirrus and water vapor are functions of certain atmospheric parameters, such as temperature, potential vorticity or solar radiation (van Manen, 2017; van Manen and Grewe, 2019; Yamashita et al., 2020). The contrail aCCF is further divided in day and night-time functions to account for different positive and negative radiative forcing effects depending on the time of day (Yin et al., 2022). The aCCF for CO_2 is a constant value derived from the climate chemistry response model AirClim (Dahlmann et al., 2016a). These aCCFs of the different climate forcing agents can be used to calculate ATR20 as a function of emission time and location, namely latitude, longitude and altitude, under certain weather conditions. Individual aCCFs per climate forcing species can be combined into a merged aCCF representing the climate impact from all considered climate forcing agents. An exemplary illustration of the merged aCCF for the North Altantic region, i.e. the regional climate sensitivity per fuel burnt, is displayed in Figure 2.

The aCCFs can be used to quantify the climate impact along flight trajectories according to actual weather conditions without applying extensive climate-chemistry model simulations. Although this clearly represents a simplification of the underlying atmospheric processes, their validity for the North Atlantic region was shown by van Manen and Grewe (2019) and Yin et al. (2022). On this basis, optimization of trajectories can be carried out with different degrees of freedom as performed in a variety of previously published research (e.g. Matthes et al., 2017; Matthes et al., 2020; Lührs et al., 2021; Yamashita et al., 2021). However, validation of these aCCFs is currently limited to the North Atlantic flight corridor as well as to summer and winter meteorological conditions (Dietmüller et al., 2023). Every application outside of this scope needs to be considered off-design, thus is not recommended. Also, the strong dependence of the discontinuous contrail aCCF from the atmospheric input data, inaccuracies of the applied weather data and the high uncertainties in general scientific understanding of non-CO_2 climate effects play an essential role with regard to robustness of results and have to be taken into account when interpreting the results (Yin et al., 2022; Lee et al., 2021).

2.2 Trajectory simulation, emission and cost modelling

Climate impact assessment with aCCFs and calculation of mitigation potentials by changed cruise flight altitudes and speeds require a re-modelling of the considered flight missions. This does not only include provision of the four-dimensional trajectories but also calculation of required flight performance data in terms of thrust and fuel flow, which is the basis for the following estimation of emission quantities.

In contrast to existing research investigating climate mitigation potential of changed emission altitudes or optimized trajectories (e.g. Frömming et al., 2012; Koch, 2013; Dahlmann et al., 2016b; Matthes et al., 2021; Lührs et al., 2021), we do not assume great circle connections between origin and destination airports in the reference case, but incorporate actually flown point profiles of the respective flight missions. Furthermore, we replace the assumption of fuel-optimal or constant cruise altitudes in the reference case with the true cruise flight altitudes including en-route step climbs and descents as performed on the considered missions. An exemplary visualization of the detailed incorporation of flight-specific point profiles can be found in Figure 3. By combining the detailed flight mission description with realistic atmospheric data at the considered point and time, we can describe each of the considered missions as accurate as possible.

Horizontal and vertical re-modelling of the trajectories is performed with the Trajectory Calculation Module (TCM) developed at DLR's Institute of Air Transport (Linke, 2016). This tool implements a Total Energy model approach to describe changes in aircraft state. For this purpose, Base of aircraft data version 4.2 (BADA4) as provided by EUROCONTROL (Nuic et al., 2010) is

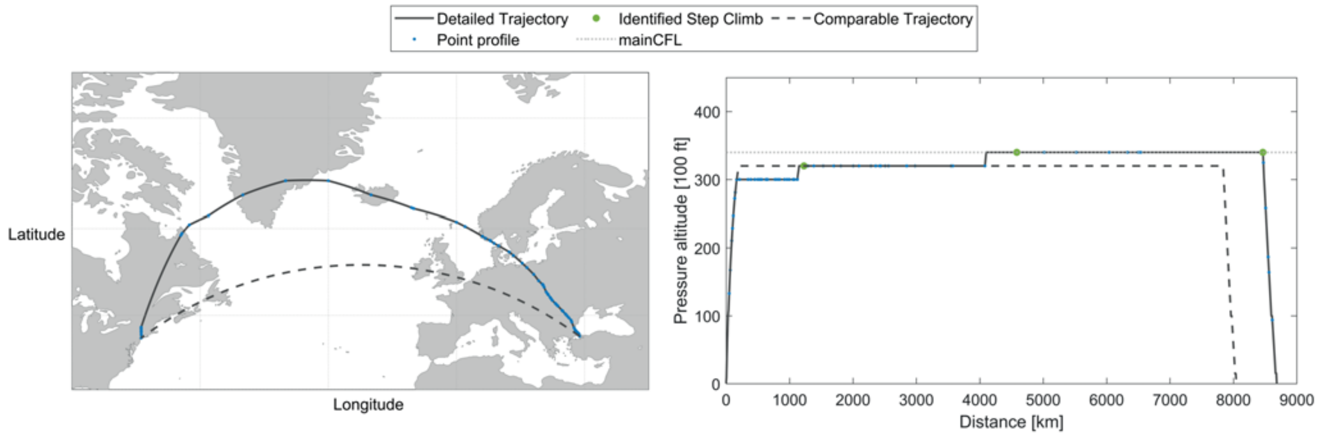

Figure 3: Horizontal (left) and vertical trajectory re-modelling (right) for an exemplary mission from Istanbul (LTBA) to New York (KJFK) with a Boeing 777 according to the detailed and comparable mission description on December 11th, 2018.

applied. To incorporate detailed point profile information, modelling capabilities of the TCM are enhanced. Besides a consideration of way points with regard to their latitudinal and longitudinal position and the associated deviation from the great circle connection, we expand the tool to incorporate also vertical components of given way points by including the required additional climb, cruise and descent segments.

Subsequently, the trajectory output in terms of geographic position, altitude, time increment, atmospheric background conditions and fuel flow is used to calculate the emission flows for each time step individually. CO_2 and H_2O emissions are directly derived from a proportional relation to fuel burn, while NO_x emissions are modelled with the fuel flow correlation method by DLR (Deidewig et al., 1996; Schäfer and Bartosch, 2013) under application of emission indices as provided by ICAO Engine Emission Databank (ICAO, 2021). Afterwards, aCCFs are evaluated for every time step along the trajectory, so that the total climate impact can be aggregated for the entire trajectory. In this context, also contrail distances along the trajectories are assessed, defined as the distance of the flight mission where contrails form and contribute to ATR20.

Cost modelling is performed based on the approach by TU Berlin as applied in the Central Reference Aircraft data System (Thorbeck and Scholz, 2013; Risse et al., 2016). We assume that direct operating costs (DOC) of a mission consist of a fixed and a variable part. While fixed cost per mission depend on the selected aircraft type of the investigated mission (such as aircraft ownership costs), variable cost are driven by aircraft utilization. The latter can further be divided into ground and landing charges, maintenance cost, fuel cost, navigation charges and crew cost. These elements are not only considered to depend on the applied aircraft type, but also on the number of cycles performed, fuel consumption, distance and block time of the considered mission. Applied cost unit data was derived in the course of the ClimOP project based on average airline cost data. DOC and climate impact can be combined to assess eco-efficient operation set-ups (Grewe and Linke, 2017).

2.3 Study set-up

We divide our analysis on climate effects from flying lower and slower into two different sub-studies: First, we investigate the mitigation potential in terms of climate effects for alternative altitudes and speeds compared to the actually flown missions on the selected representative summer and winter day in detail (*detailed study*, Section 3.1). Second, we aim to isolate effects resulting from different atmospheric and meteorological background conditions by evaluating an identical set of missions during different seasons of the year investigated on four individual case study days (*comparative study*, Section 3.2).

In the project context and with the overall goal of comparing different operational climate mitigation measures, a set of comparable boundary conditions is defined to ensure comparability along all investigated measures of the project (Tedeschi, 2020; Zengerling et al., 2023). Therefore, the geographical scope of this study is limited to flights from or to the area of the European Civil Aviation Conference (ECAC). The temporal focus is set on the reference year 2018 to exclude possible influences of the COVID19 pandemic.

2.3.1 Assessment of climate mitigation potential

In this study, climate effects are assessed with global near-surface temperature change over 20 years resulting from a pulse emission (p-ATR20) of the investigated mission. The advantages of using ATR as the evaluated physical climate metric are its direct relation to effects on the climate (i.e. temperature) and its reduced dependency from the time horizon in comparison with other metrics such as radiative forcing or global warming potential (e.g. Grewe and Dahlmann, 2015). Furthermore, it has widely been applied in literature and was found to be well suitable for assessing possible mitigation potentials from technical or operational measures (Fuglestvedt et al., 2010; Dallara et al., 2011; Grewe and Dahlmann, 2015). In addition to the metric selection, the assumed temporal evolution of emissions and the time horizon need to be determined. In this study, we use a pulse emission scenario, which compares the future impact of emissions in a given year, leading to p-ATR20 as the selected climate metric. In contrast to sustained or future-emission scenario-based ATR, p-ATR limits considerations to the individual flights' emissions at a certain point in time excluding emission perpetuation to following years. This matches the study's context as we aim to estimate the climate effect of the flights performed on a certain day and route. Therefore, we concentrate on a 20-year time horizon to put equivalent weight on the long-term and short-term climate forcers. The climate mitigation potential is in the following defined as the relative change in p-ATR20 of the optimized solution compared to the respective reference case. However, the metric selection significantly influences the achieved results in the following. For instance, an investigation of longer time periods (e.g. 50 or 100 years) would put more weight on CO_2 as a long-lived climate forcer and is expected to reduce the overall mitigation potentials, as flying lower is expected to decrease non-CO_2 effects while increasing fuel consumption and resulting CO_2 effects.

p-ATR20 is calculated by applying prototype aCCFs (Version V1.0A) including efficacies as described by Matthes et al. (submitted) and as accessible via the python library CLIMaCCF V1.0 (Dietmüller et al., 2023; Dietmüller, 2022). To derive other climate metrics such as future-emission scenario based ATR (F-ATR) as well as for considering longer time horizons (i.e. ATR over 50 or 100 years), Dietmüller et al. (2023) provide metric conversion factors.

2.3.2 Meteorological background conditions

To identify days with representative weather patterns, the objective weather type classification provided by German meteorological service (DWD) was utilized (Bissolli and Dittmann, 2001). In this context, every day of the year is classified into one out of forty weather types regarding large-scale wind direction, cyclonality and humidity over Germany. Frequencies of every weather type in 2018 are evaluated, so that days described by the most frequent type per season can be identified. For each of the four months with detailed traffic data available (i.e. March, June, September and December), one of those possible days is selected as representative, if the weather circulation pattern over Europe is stable due to similarity regarding the adjacent days. The temporal progress of weather patterns and its persistence around the selected days have been analyzed qualitatively with the Global Forecast system (GFS) model output. The selected days can be found in Table 1. We introduce three-digit abbreviations for the selected representative days to simplify the result description in the following, namely J16 for the representative summer day (June 16, 2018) and D11 for the representative winter day (December 11, 2018) as well as M28 and S27 for the representative days in spring and autumn (March 28 and September 27, 2018).

Table 1: Selected representative days and number of investigated flights in 2018 for the different sub-studies.

Selected day	**Detailed Study** ECAC	North-Atlantic	**Comparative study**
March 28, 2018	–	–	157
June 16, 2018	831	213	157
September 27, 2018	–	–	157
December 11, 2018	651	123	157

The applied atmospheric data is derived from European Centre for Medium-Range Weather Forecasts (ECMWF) in terms of ERA5 reanalysis data (Hersbach et al., 2020). Temporal resolution is set to three-hour steps, spatial resolution is selected to 0.25° both longitudinally and latitudinally and 137 model levels vertically.

2.3.3 Definition of traffic scenario and measure implementation

The applied air traffic samples comprise operational flight plans as provided by the EUROCONTROL Demand Data Repository (DDR2, Urjais, 2022). The flight plans contain individual mission parameters as well as detailed four-dimensional point profiles used as a representative mission description. We restrict our analysis to flights either departing or landing in the ECAC area. Based on an analysis of the covered available seat kilometers (ASK) per aircraft type on the selected days, we find that Boeing 777 and Airbus A330 cover a major share of ASK from the wide-body segment on flights from or to the ECAC area that are also eligible for a reduction of flight altitudes. Therefore, we restrict our analysis to these aircraft types. The resulting flight sample sizes per day are displayed in Table 1. We differentiate a sample of all flights starting or landing in the ECAC area, a reduced North-Atlantic flight sample in the detailed study as well as a comparable flight sample for the comparative study investigating effects from different meteorological background conditions.

Detailed reference missions for the first sub-study are described by the detailed point profile data including both lateral and vertical position of the aircraft along the respective mission on the selected day. For further discussion, the sample can be reduced to the North-Atlantic region for which aCCFs have been validated so far. In general, we see a larger number of flights for the selected day in June (J16) compared to December (D11). By contrast, we aim to investigate a comparable set of flights for comparing individual days in different seasons to solely analyze the differences caused by varying meteorological conditions. Hence, we identify a sub-sample of representative and comparable flights that are performed on

Table 2: Considered combinations of cruise flight level and speed change to model implementation of flying lower and slower in different scenarios (Naming convention: S.x.y composed of change of flight level x and speed y).

Scenario CFL change	Cruise Mach number change 0 %	−5 %	−10 %
−2000 ft	S1.1	S1.2	S1.3
−4000 ft	S2.1	S2.2	S2.3
−6000 ft	S3.1	S3.2	S3.3

all of the four selected days (see Table 1) between the same origin and destination airport as well as with the same aircraft type. Unlike the detailed study, these *comparable reference missions* do not incorporate detailed point profiles in the vertical and lateral routing. Instead, we define a median cruise flight level (CFL) from the observed flights over the selected days of the four seasons and assume a direct great circle connection between origin and destination airport. Figure 3 illustrates the differences in detailed and comparable trajectory characteristics for an exemplary flight mission.

Based on the reference case described by the identified days and respective flight missions, the trajectories are adjusted to include the implementation of the introduced operational improvement in different scenarios. We assume that lateral positions do not change, whereas cruise speeds and CFLs are varied as follows: Instead of the reference mission's altitude information, a constant flight level for the respective mission is assumed based on the most frequent CFL (*mainCFL* in Figure 3) during the flight and reduced for the different scenarios in 2,000 ft steps up to a 6,000 ft CFL reduction. In addition, cruise flight speed changes are considered in terms of a 5 % and 10 % reduction in cruise Mach number compared to the reference case as summarized in Table 2. The optimized scenario can then be selected from the calculated set of scenarios minimizing the climate impact and by considering boundary conditions such as limits to additional cost or fuel consumption.

3 Results from evaluating climate mitigation potentials of reduced cruise altitudes and speeds

We calculate the climate mitigation potentials associated with alternative cruise altitudes and speeds for the detailed flight sample considering CO_2 and non-CO_2 effects. In Section 3.1, evaluations are performed on two distinct days, one in June and one in December 2018 and resulting mitigation potentials are presented. In this context, eco-efficient solutions can be derived and sensitivities towards highly uncertain contrail effects can be discussed. After that, varying mitigation potentials due to different meteorological background conditions are evaluated for one selected case study day per season assuming a comparable mission description in Section 3.2.

Table 3: Flight-specific case studies and associated changes in selected climate and non-climate KPIs for the climate-optimized solution in June (S2.3) and December (S3.1) in comparison to the detailed reference case.

	KEWR–LPPR June 16, 2018	**EIDW–KLAX December 11, 2018**
Start Time (UTC)	01:41	15:55
Reference CFL [100 ft]	410	380
Optimized Scenario	S2.3	S3.1
Fuel Burn	+0.6 %	+2.3 %
Flight Time	+7.4 %	−1.6 %
DOC	+4.2 %	−0.2 %
NO_x Emissions	−8.1 %	−6.6 %
Contrail Distance	−54.1 %	+431.0 %
ATR20	−54.8 %	−63.7 %

3.1 Climate mitigation potential on individual days

A combination of reduced cruise altitudes and speeds shows high mitigation potentials for a large sample of flight missions. We identify a maximum climate mitigation potential (p-ATR20) per individual flight mission of more than 50 % on J16 (54.8 %) and even higher values for D11 (63.7 %). However, we also find a significant share of flights from the North Atlantic sample where the climate impact cannot be reduced for any of the above described implementation scenarios of reduced cruise altitudes and speeds (27 % on J16, 17 % on D11). Relative changes in the selected climate and performance metrics of flights with the highest climate mitigation potential for the two selected case study days are displayed in Table 3. For the exemplary flight on J16 from Newark (KEWR) to Porto (LPPR), we observe that the significant reduction in climate impact (−54.8 %) is mainly caused by a reduction in contrail-induced ATR20 (see Figure 4) by avoiding contrail forming regions as the contrail distance is reduced by more than 50 % in S2.3 (Table 3). Climate impact from other species changes moderately in the case of CO_2 (+0.6 %) and H_2O (−2.1 %) and increases for NO_x-induced changes (+29.8 %, Figure 4). Furthermore, we find that the increase in fuel consumption for lower flight levels can almost totally be compensated by reducing the cruise Mach number by 10 %, whereas we observe an increase in fuel consumption by 4.8 % without speed adjustments in S2.1. On the downside, the speed reduction in this case leads to longer flight times (+7.4 %), what causes an increase in DOC (Table 4).

By contrast, the climate-optimized scenario for the selected example flight on D11 from Dublin (EIDW) to Los Angeles (KLAX) is represented by a CFL reduction from 38,000 to 32,000 ft without adjusting the speed (S3.1, Table 4). Therefore, increase in fuel consumption is higher but flight time can be reduced, so that DOC do not change markedly. In this case, we observe even higher mitigation potentials of more than 60 %. However, underlying reasons for this significantly dif-

Table 4: Average relative change in ATR20 [%], fuel consumption and DOC over the different scenarios implemented for selected exemplary flights. Scenarios with maximum mitigation potentials are highlighted in bold.

Scenario	KPIs	S1.1	S1.2	S1.3	S2.1	S2.2	S2.3	S3.1	S3.2	S3.3
KEWR–LPPR on June 16, 2018	ATR20	−44.3	−44.6	−44.8	−53.0	−54.3	**−54.8**	−41.8	−44.2	−45.6
	Fuel	+1.3	−1.3	−0.8	+4.8	+1.5	**+0.6**	+9.6	+5.3	+3.2
	DOC	−0.2	+1.5	+4.2	+0.4	+0.2	**+4.2**	+1.4	+2.5	+4.6
KEWR–LPPR on June 16, 2018	ATR20	+10.4	+10.1	+12.5	−40.9	−40.8	−39.8	**−63.7**	−63.1	−62.5
	Fuel	−0.4	−3.2	+0.0	−0.5	−3.2	−2.2	**+2.3**	−1.0	−1.6
	DOC	+0.0	+1.8	+5.8	−0.6	+1.2	+4.5	**−0.2**	+1.5	+4.2

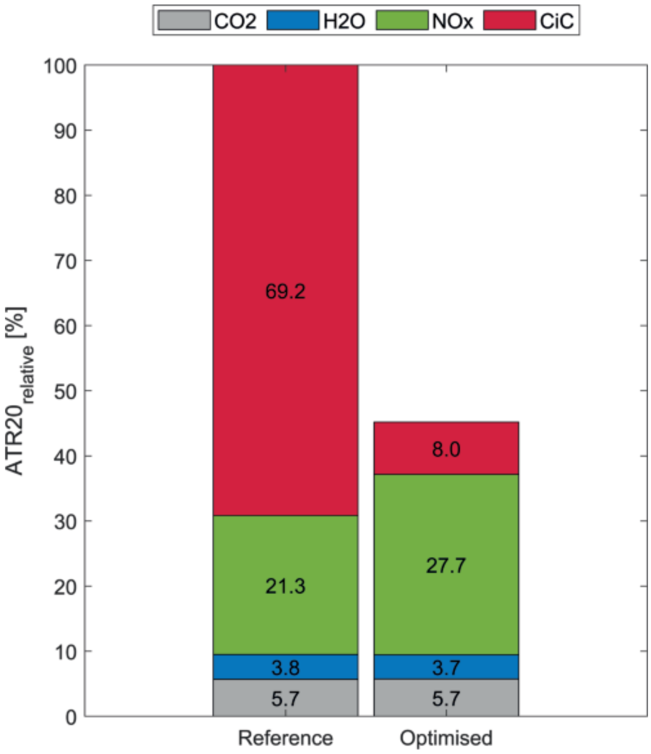

Figure 4: Relative contributions to total climate effect in ATR20 per species for mission KEWR–LPPR flight on June 16, 2018 (Reference case and S2.3, normalized to the reference ATR20)

fer from the above-mentioned example flight for J16. As this flight is mainly performed during day times, the evaluation of aCCFs leads to both warming and cooling effects caused by the formation of contrail cirrus. Hence, the climate-optimized solution in the defined set-up is represented by a flight altitude where contrails form to make use of their cooling effect, i.e. contrail distance is extended (Table 3).

If an implementation of this operational improvement is investigated for the sample of all investigated flights (Figure 5), the optimized combination of altitude and speed is selected individually for every mission. We observe a mitigation potential of 8.7 % on J16, respectively 16.1 % on D11 for the North Atlantic flight sample. The reduction in climate impact can be explained with an overcompensation of rising effects from CO_2 and NO_x by a reduction in climate impact induced by H_2O and contrail cirrus. Also, performance metrics are highly affected by an implementation of this operational measure. For J16, we observe an increase in fuel consumption by 1.0 % and an increase in flight time by more than 4.3 % leading to a rise in direct operating cost of 2.7 % (2.2 % for D11). Detailed changes in climate and performance metrics for the full flight sample on J16 and D11 are illustrated in Figure 5.

Figure 6 shows the change of main CFLs for the investigated December day if missions are optimized individually regarding cruise altitude and speed according to the predefined scenarios. Especially flight levels of 36,000 ft and higher are avoided in the optimized case and flight levels are shifted to altitudes between 29,000 and 35,000 ft. We also observe that a flight speed reduction in combination with a lower CFL is typically preferred compared to a sole shift of the CFL. For a CFL reduction of 2,000 ft, a cruise speed decrease of 5 % is on average associated with the highest mitigation potentials for that flight level shift, whereas a speed reduction by 10 % is preferred if CFLs are shifted down by 4,000 ft or 6,000 ft in the climate-optimized scenario.

The investigations on climate mitigation potentials in this study show that a significant part of the climate effect reduction is caused by changes in contrail-induced effects. We observe that contrail distances are reduced on J16 (−9.7 % in contrail distance for the optimized sample in comparison to the reference case), whereas we find an increase in contrail distances for D11 (+13.7 % in contrail distance for the optimized sample in comparison to the reference case). That means, instead of avoiding contrail forming regions on this day, net cooling effects during day time increase by crossing contrail forming regions. Furthermore, we observe that the contribution of species to the total ATR20 varies over the investigated case study days. While direct effects induced by H_2O contribute with a higher share to the reference ATR20 on D11 compared to J16, the share of NO_x is significantly lower. Consequently, rise in NO_x effects as well as reduction of H_2O effects in both samples lead to higher reduction potentials for D11 (Figure 7).

The observed differences in climate mitigation potential across the considered days are caused by the following aspects:

- Change in atmospheric background conditions: The individual non-CO_2 effects of aviation emissions highly depend on the meteorological situation at

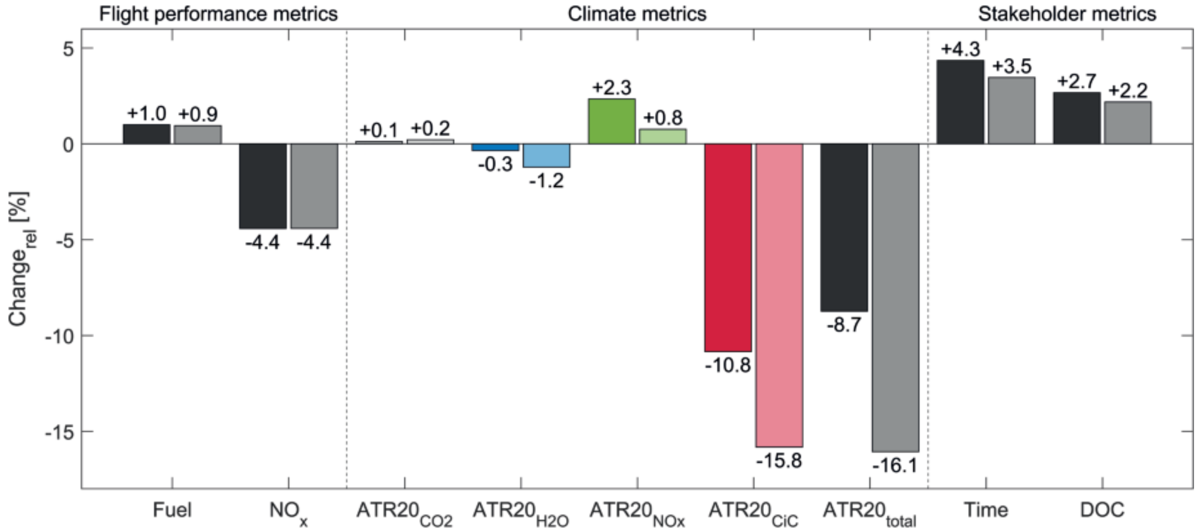

Figure 5: Relative change in selected climate and non-climate KPIs for the full sample of North-Atlantic flights on June 16, 2018 and December 11,2018. Darker bars represent values for J16, lighter bars represent results for D11. Relative changes in ATR per species is given in relation to the absolute ATR20 of the sample.

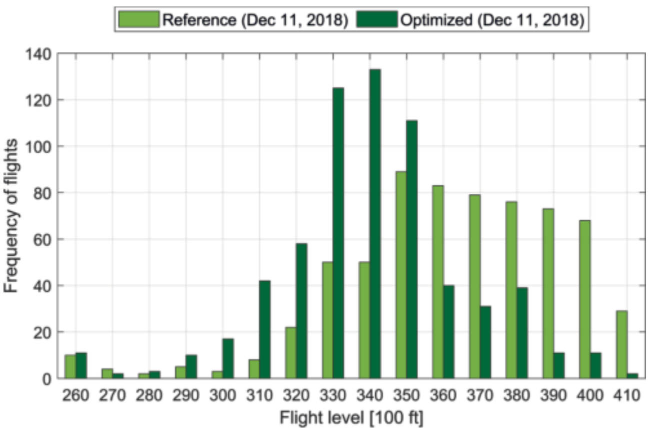

Figure 6: Absolute frequency distribution of CFL over flights in the optimized scenario compared to the reference case for the full flight sample on December 11th, 2018.

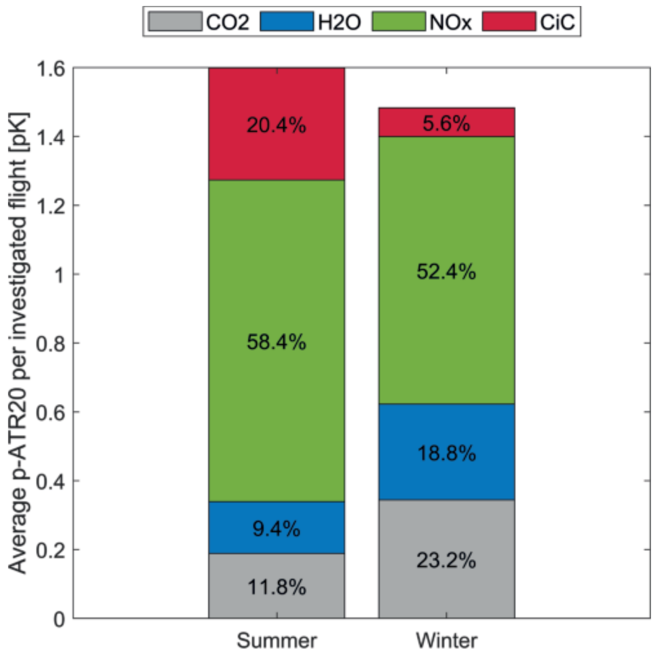

Figure 7: Different species contribution to p-ATR20 in the reference case of the North-Atlantic flight sample for the individual case study days in summer and winter.

the time and location of the emission. For example, contrail forming regions change in size and distribution due to differences in ambient temperature and relative humidity in the upper troposphere/lower stratosphere. Furthermore, shorter duration of days and differences in the sun's position in the Northern hemisphere during winter leads to longer periods, where only warming effects of contrails occur.

- Change in investigated routes: J16 and D11 full flight samples consist of different flight plans. With the framework as described in Section 2.3, we observe 831 flights on June 16, while we consider 667 flights on December 11 from or to the ECAC area and operated with the selected aircraft types. Also, combination of origin and destination, assigned aircraft types and departure times vary between the samples.
- Flight specific changes in routing: Even for equal combinations of aircraft type, origin and destination airport, we observe significant differences in lateral and vertical routing, for instance due to weather or air traffic management (ATM) restrictions. Especially the selected flight altitudes and the corresponding definition of reference cases and implementation scenarios change thereby.

To exclude the resulting potential bias, we assume great circle connections and equal flight altitudes for the reference missions in Section 3.2 to investigate effects from different in meteorological background conditions.

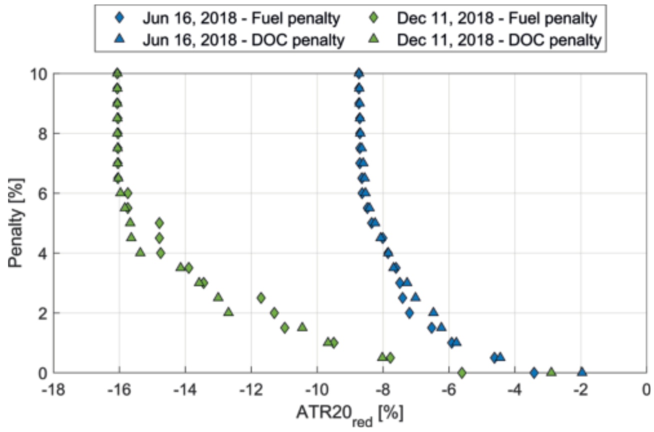

Figure 8: climate mitigation potential in dependence of different penalties for the North-Atlantic flight sample on J16 and D11 (*pareto fronts*).

Eco-efficient routing options

As a reduction in cruise altitudes typically increases fuel consumption while a reduction in speeds increases flight times, operating costs rise by flying lower and slower. Hence, stakeholders of the air transportation system such as airlines or passengers are affected. Consequently, a limit to these adverse effects is introduced to identify the maximum possible mitigation potential for a certain limit of fuel consumption or DOC (referred to as *fuel* or *DOC penalty*) on every individual mission of the considered sample, so that pareto fronts can be derived. In other words, the scenario with the highest mitigation potential is selected per flight mission, where DOC or fuel increase remains below the defined penalty. The resulting pareto fronts for different fuel and DOC penalties as well as the two selected case study days are shown in Figure 8. Despite the rise in fuel burn and flight time, we find that up to 3 % in ATR20 can be mitigated without an increase in DOC due to occurring vertical routing inefficiencies. For a DOC penalty of 1 %, we see that ATR20 can be reduced by more than 9 % on D11 (and almost 6 % on J16). Furthermore, changes in average fuel consumption or DOC over the full sample is found to be significantly below the flight individual penalties. For example, while ATR20 is reduced by more than 1 % without increased DOC, flight individual fuel consumption, time and DOC even improve marginally on average. By limiting DOC penalty to 1 %, increase in total DOC for the full sample is below 0.1 % and below 1 % for DOC penalty values up to 5 %.

In addition, we identify individual flights along which cost and climate impact can be reduced with an implementation of flying lower and slower, referred to as *win-win-missions*. For J16, we observe 519 flights (62.4 %) with climate mitigation potential due to reduced cruise altitudes and speeds. For 280 of these flights (33.7 %), ATR20 can be reduced without an increase in fuel consumption due to a compensation by reduced speeds but also due to exploitation of wind effects that vary over different flight levels. Furthermore, climate impact of 149 flights (17.9 %) can be reduced without an increase in DOC. For D11, a higher share of flights is associated with a win-win solution (reduction in ATR20 for 47.0 % of the flights without increase in fuel consumption, 28.3 % without increase in DOC).

Moreover, particularly *eco-efficient missions* can be identified offering a large climate impact reduction while keeping cost increase for stakeholders low. For this purpose, we define an eco-efficient mission to be characterized by both a mitigation potential of more than 20 % in climate effects and an associated increase of less than 1 % in DOC. We find, that this is possible for 3.7 % of the flights on J16 and 5.8 % of the flights on D11.

Sensitivity towards contrail effects

To account for the high uncertainties in contrail climate effects, we incorporate different scaling approaches to the contrail aCCF and investigate these scaling influences on the climate mitigation effects of flying lower and slower individually. We assume a linear scaling of contrail effects resulting from the aCCF evaluation with factors between 30 % and three times the originally calculated effect (referred to in the following with scaling schemes *SCA0.3* to *SCA3*, in accordance with radiative forcing uncertainties as provided by Lee et al., 2021). Besides, we incorporate a contrail scheme with only warming contrails (*WARMC*) that does not rely on additional creation of cooling contrails by crossing ice supersaturated regions in order to reduce climate effects. In the zero scaling case (*SCA0*), i.e. excluding contrail effects from the analysis of reduced cruise altitudes and speeds, CO_2 and other non-CO_2 effects are focused. Figure 9 illustrates the different mitigation potentials of ATR20 over the different sensitivity experiments in relation to the reference case for J16. We observe that all considered scenarios confirm a reduction in ATR20 by implementing reduced cruise altitudes and speeds. Even without considering contrail effects, climate impact can be reduced mainly due to reduction in NO_x-induced effects. For lower contrail scaling factors (e.g. SCA0 or SCA0.3), decrease in ATR20 is predominantly caused by reduction of NO_x-induced effects instead of contrail-induced ones. Also, the frequency distribution of preferred scenarios changes: The higher the contrail impact is assumed, the more flights benefit from a reduction in CFL. Scenarios characterized by higher reductions in speed and altitude are selected in the optimized case (e.g. 21.6 % of flights with minimum climate impact in S3.3 for SCA10, whereas only 10.8 % in S3.3 for SCA0). Figure 10 shows the pareto fronts resulting from the different scaling factors for the two investigated days. On this basis, we confirm robustness of the mitigation potentials of flying low and slow towards different considerations of contrail effects as well as the higher potentials for D11 compared to J16. However, this correlation between the different days changes if contrail effects are neglected completely.

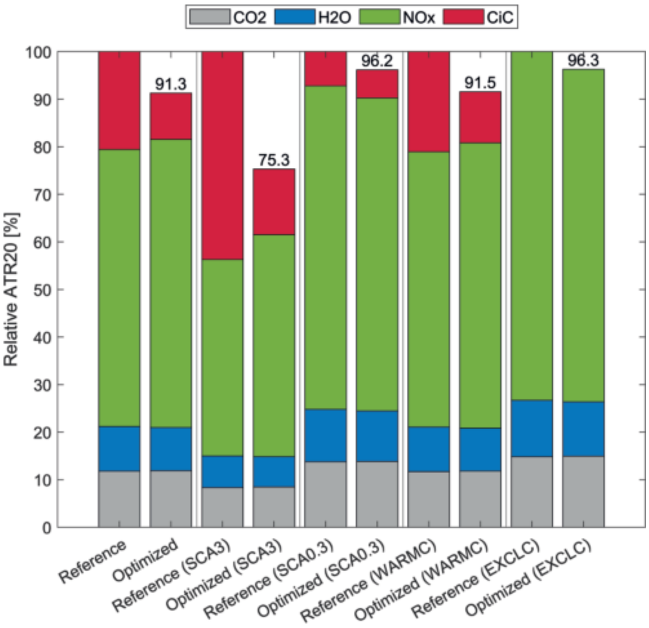

Figure 9: Relative changes in ATR20 over selected contrail scaling schemes for the North-Atlantic flight sample on J16.

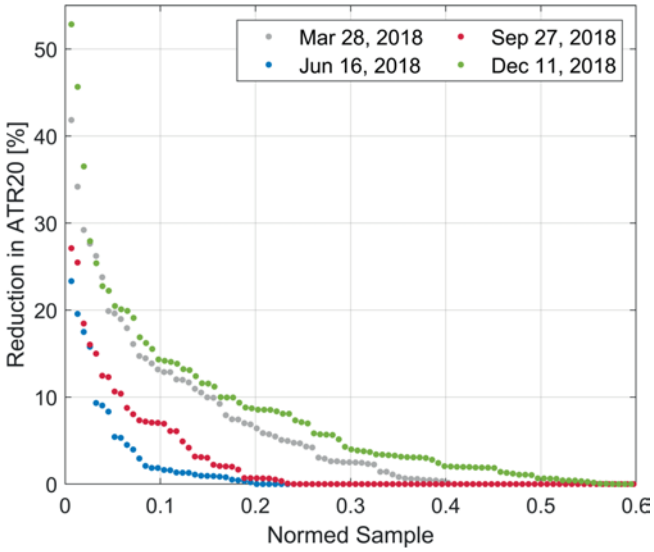

Figure 11: Relative reduction in ATR20 per flight mission over relative sample size for different season-representative days.

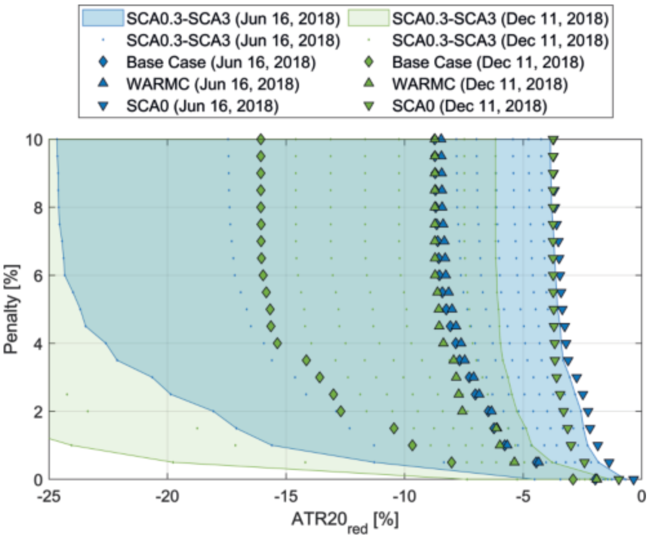

Figure 10: Pareto fronts resulting from different contrail scaling schemes for the North-Atlantic flight sample on J16 and D11; shaded areas comprise contrail scaling schemes SCA0.3 to SCA3.

3.2 Comparison of climate mitigation potential on individual days during different seasons

To further systematically explore the influence of varying seasonal meteorological background conditions, we analyze effects from reduced cruise altitudes and speeds for selected days in four different seasons (i.e. M28, J16, S27 and D11; see Table 1). To this end, we investigate a representative traffic sample of comparative reference case missions departing from or arriving at the ECAC area (as described in Section 2.3.3).

We find that on M28 and D11, relative mitigation potentials are larger than on J16 and S27. If we restrict the analysis to the North-Atlantic flight sample only, these findings are confirmed showing a 2.1 % reduction potential in ATR20 for J16 and 6.5 % for D11. Also, the highest mitigation potential per individual flight is above 40 % for M28 and D11 (41.8 % on M27 and 52.8 % on D11), while it is around 25 % on J16 and S27 (23.3 % on J16, and 27.1 % on S27). Figure 11 underlines the higher mitigation potentials on the selected winter and early spring days in comparison to the selected days in summer and early autumn and confirms the results from the individual studies investigating day-specific missions in Section 3.1. For M28 and D11, more than 10 % of the investigated flight missions are associated with mitigation potentials of more than 12 %, whereas these potentials are markedly lower for J16 and S27. In addition, we observe that mitigation potentials are generally lower in this study assuming great circle connections and constant flight levels as the reference case in comparison to the actually flown missions on the investigated days. This can be explained by the fact that additional step climbs and descents are excluded not providing additional mitigation potentials through the reduction of vertical routing inefficiencies. Due to the high contribution of contrails to the total ATR20 and their strong variability in dependence of meteorological background conditions such as temperature and humidity, the change in contrail-induced ATR20 is one reason for the different results over the selected case study days. A comparison of the missions and their respective contrail distances underlines this. Figure 12 exemplary illustrates different climate effects from contrails vertically and temporally integrated for two of the selected days. For the purpose of illustration, we focus on the absolute value of the contrail-aCCF to exclude

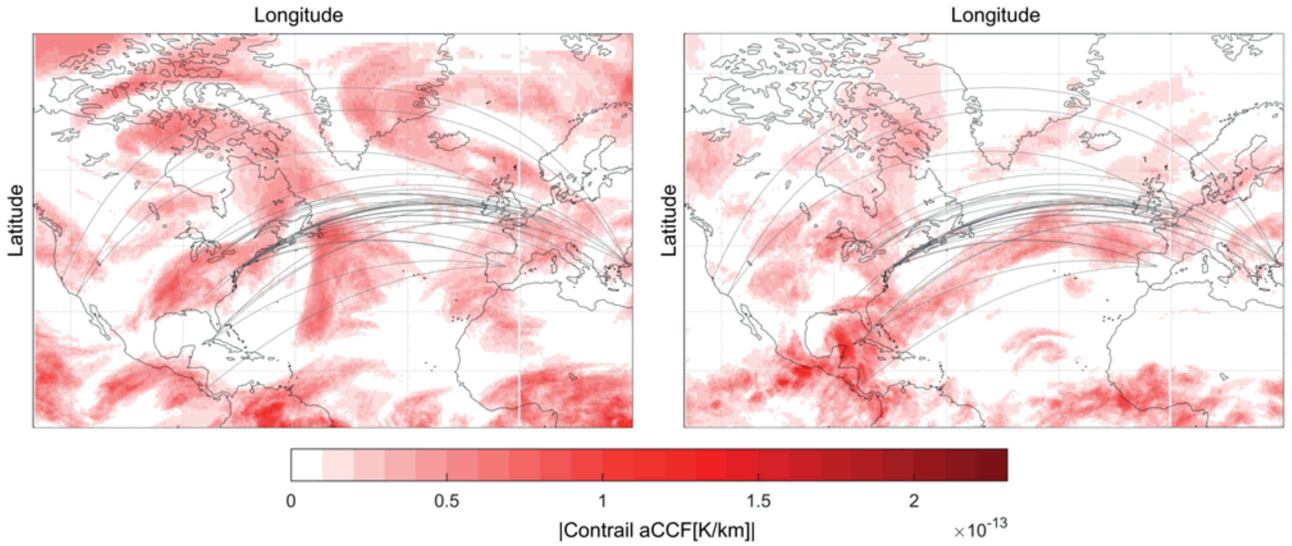

Figure 12: Daily average of vertically integrated contrail aCCF for case study days March 28, 2018 (left) and June 16, 2018 (right) in the North Atlantic region along investigated flight connections. To account for mutually canceling cooling and warming effects, absolute value of the contrail aCCF is given.

Table 5: Change in ATR20 per species relative to total ATR20 of the reference case for the North Atlantic flight sample and one representative day per season.

Selected day	CO_2	H_2O	NO_x	CiC
March 28, 2018	+0.1 %	−0.3 %	+1.1 %	−4.1 %
June 16, 2018	+0.0 %	−0.1 %	+2.5 %	−4.5 %
September 27, 2018	+0.0 %	−0.0 %	+3.8 %	−6.8 %
December 11, 2018	+0.2 %	−0.5 %	+0.1 %	−6.0 %

mutually offsetting of cooling and warming effects in this context. Hence, regions of contrail formation with a high contrail-induced climate effect (both cooling and warming) can be distinguished from areas with lower or no contrail-induced effects. As we see larger contrail forming regions along the investigated North-Atlantic trajectories on M27 compared to J16, leading to longer contrail distances in the reference case (24.5 % relative contrail distance on M27, 15.1 % on J16), also the mitigation potential is higher as contrail forming regions can be avoided by adjusting the cruise altitude. Table 5 shows the change in ATR20 per species relative to the total ATR20 per selected day. We see that increase in CO_2 effects and reduction in H_2O effects are higher in winter and early spring than in summer, while changes in NO_x effects are relatively lower on these days.

Moreover, we observe that changes in altitude are larger in the optimized case for M28 and D11 in comparison to J16 and S27. While the average flight altitude of 33,500 ft for the reference case of the comparative sample is reduced to 32,000 ft in the optimized case on D11, the average optimized altitude for S27 is approximately 500 ft higher. Hence, also the increase in CO_2 effects due to reduced flight altitudes is higher for those days in winter and early spring.

4 Discussion and outlook

This study investigates the climate mitigation potential due to reduced cruise altitudes and speeds relying on aCCFs to estimate spatially and temporally varying climate effects of aviation. The applied method is capable of quantifying climate mitigation potentials of this operational strategy. We confirm that the reduction in non-CO_2 effects overcompensates an increase in CO_2 effects for lower cruise altitudes, which can simultaneously be limited by restricting cruise speeds. This is consistent with what has been found in previous research, e.g. by Matthes et al. (2021) and Frömming et al. (2012) with regard to lower CFLs and by Dahlmann et al. (2016b) and Koch (2013) with regard to combinations of flying lower and slower. We find that this can mainly be explained by a reduction in contrail-induced effects in our study incorporating actually flown point profiles and day-specific weather conditions. Moreover, eco-efficient set ups can be defined by limiting application of lower altitudes and speeds to missions with high mitigation gains or with small influences on DOC. Furthermore, we show a strong variability of mitigation potentials resulting from CO_2 and non-CO_2 effects due to climate-optimized cruise altitudes and speeds over the different investigated days throughout the seasons. Our joint investigation of different emission species shows higher reductions in ATR20 for the selected March and December day relative to the investigated days in June and September. This is consistent with what has been shown by Castino et al. (2021) and Yin et al. (2018) for contrail and NO_x related mitigation potentials.

Nevertheless, the assumptions in course of the modelling process need to be considered when assessing the reliability of the study results in terms of set boundary conditions, trajectory re-modelling as well as climate impact assessment and analysis. The selection of the evaluated KPIs in general and climate metrics in particular influences the outcomes of this research. The selection of p-ATR20 as the preferred climate metric gives us the opportunity to investigate the climate impact of the individual flights over a 20 years time horizon. However, changes of the underlying time horizon (e.g 50 or 100 years) or emission scenario (e.g. sustained instead of pulse emissions) would highly affect the results. The metric selection in climate mitigation studies is crucial and different factors such as policy assumptions need to be included in the selection process (Grewe and Dahlmann, 2015).

Furthermore, the applied aCCFs to investigate the climate impact have so far only been developed for the North-Atlantic flight corridor as well as for winter and summer weather patterns and are still considered prototypical (Dietmüller et al., 2023; Yin et al., 2022). Thus, usage of aCCFs introduces an uncertainty in quantitative estimation of climate effects. Additionally, their application to spring and autumn requires further evaluation, which is currently pending additional comprehensive simulations. Such studies are required to provide a more detailed quantitative estimate of mitigation gains but also of the associated impacts on other performance indicators. As the underlying parameterization of the prototype aCCFs may change in the future, it is necessary to understand how sensitive trajectory optimization is to the strength of non-CO_2 effects. Contrails in particular are subject to considerable uncertainties and could be incorrectly represented in the models, for instance due to varying lifetimes and changing effects between day and night time. Lee et al. (2021) recently identified large uncertainty ranges of contrail-induced climate effects in aviation (the 5–95 % confidence interval for the effective radiative forcing was estimated between 17 and 98 mW/m^2). As we have shown in this study, applying different scaling factors to the contrail aCCFs has a significant impact on the overall ATR20 reduction. A more detailed analysis in this context should be carried out in the future. Further associated inaccuracies result from the uncertainties related to the utilized meteorological input data based on numerical weather prediction models. Also, current state of research still faces large uncertainties with respect to the contribution of non-CO_2 species to the climate impact of aviation emissions in general (Lee et al., 2021).

In addition, uncertainties and modelling inaccuracies are caused by the assumptions in the trajectory calculation process. We apply BADA4 flight performance data and ICAO engine emission indices to estimate fuel consumption, flight time and emission quantities. The resulting mean error in fuel consumption is though estimated to be below 5 % when comparing BADA4 with more sophisticated models (Nuic et al., 2010) and fuel flow correlation methods for NO_x are expected to predict emission quantities during cruise phase with an accuracy of approximately ± 10 % (Schäfer and Bartosch, 2013). However, a focus on relative changes in the selected metrics reduces the influence of the trajectory and emission modelling related inaccuracies.

In extension to this work, analyses of trajectory-related improvements regarding seasonality and mitigation potentials on the basis of the updated aCCFs could be performed including more degrees of freedom. In this context, not only vertical changes to the trajectory but also horizontal re-routings can help to avoid climate sensitive areas without higher fuel consumption caused by lower flight altitudes. The comparison between the actually performed routes and the respective weather data could also expand the work by Lührs et al. (2021) and Matthes et al. (2020). An analysis of more days to further investigate the seasonal variability of climate mitigation potentials of this measure could be performed in the future, especially once aCCFs have also been validated for spring and autumn season. As the current aCCFs are developed for representative summer and winter patterns of the current climate (Dietmüller et al. 2023), application for future climate conditions is not directly possible either. However, as long-term climatological changes occur, their impact on the efficacy of this operational measure should be considered in future work. Following this study, the possibilities of implementing this operational improvement is also of further interest. So far, DOC have been applied as a quantitative indicator to show economic consequences of this measure. However, also passenger acceptance as well as ATM-related aspects should be subject to a broader analysis. For instance, injecting the same load of traffic in smaller airspaces implies an over-concentration of traffic in these areas, which will affect capacities, en-route delays, controllers work load and possibly navigation charges. From passengers' perspectives, longer travel and on-board times are expected to reduce passenger acceptance and might increase willingness to shift to other travel alternatives, if available. In this context, new charging schemes also including climate impact from non-CO_2 species or definition of climate-restricted or climate-charged airspaces (as introduced by Niklass et al., 2021; Niklass et al., 2017) need to be investigated to analyze how DOC changes can be compensated to motivate an implementation of this measure from a regulatory or market-based perspective. For this purpose, also sensitivities towards the selection of climate metrics (e.g. replacing p-ATR20 as the central indicator for climate effects) are of further interest.

5 Conclusion

All in all, this study shows a significant climate mitigation potential from reducing cruise altitude and speed of up to 9 % on the selected summer and 16 % on the selected winter day. Non-CO_2 effects are reduced by lower cruise altitudes on the one hand. On the other hand, resulting higher fuel burn and climate impact from CO_2 emissions can be reduced by lower flight speeds. Furthermore, the observed mitigation potentials differ for the individual selected days of the different seasons and are found to be higher for the selected case study days in winter and early spring compared to summer and early autumn. Nevertheless, increase in travel time, fuel consumption and operating cost limit implementation attractiveness of this operational improvement for the stakeholders of the air transport system in general. Therefore, the right implementation enablers from regulatory side need to be implemented to facilitate the implementation of operational climate mitigation measures such as flying lower and slower. However, the results of this study also indicate that a significant set of flights exists, where the climate impact can be reduced without or with only minor negative stakeholder effects.

To conclude, our study contributes to current state of research, first, by establishing a suitable methodology to perform a climate impact assessment of trajectory-related operational improvements for actually flown trajectories under specific atmospheric background conditions with newly adapted aCCFs, second, by confirming the climate mitigation potential of reduced cruise altitudes and speeds on individual days in different seasons and finally, by directly relating these results to the associated changes in direct operating cost based on realistically re-modelled flights.

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