# Concept of climate-charged airspaces: a potential policy instrument for internalizing aviation's climate impact of non-CO$_2$ effects

Malte Niklaß, Volker Grewe, Volker Gollnick & Katrin Dahlmann

Published online: 19 Jul 2021.

Submit your article to this journal ☐

Article views: 172

View related articles ☐

View Crossmark data ☐

Taylor & Francis
Taylor & Francis Group

RESEARCH ARTICLE

OPEN ACCESS    Check for updates

# Concept of climate-charged airspaces: a potential policy instrument for internalizing aviation's climate impact of non-CO$_2$ effects

Malte Niklaß [a], Volker Grewe [b,c], Volker Gollnick [a,d] and Katrin Dahlmann [b]

[a]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Lufttransportsysteme, Hamburg, Germany; [b]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre, Oberpfaffenhofen, Germany; [c]Section Aircraft Noise and Climate Effects, Faculty of Aerospace Engineering, Delft University of Technology, HS Delft, Netherlands; [d]Institut für Lufttransportsysteme, Technische Universität Hamburg (TUHH), Hamburg, Germany

## ABSTRACT

Approximately 50–75% of aviation's climate impact is caused by non-CO$_2$ effects, like the production of ozone and the formation of contrail cirrus clouds, which can be effectively prevented by re-routing flights around highly climate-sensitive areas. Here, we discuss options how to incentivize re-routing approaches and apply multicriteria trajectory optimizations to demonstrate the feasibility of the concept of climate-charged airspaces (CCAs). We show that although climate-optimized re-routing results in slightly longer flight times, increased fuel consumption and higher operating costs, it is more climate-friendly compared to a cost-optimized routing. In accordance to other studies, we find that the averaged temperature response over 100 years (ATR$_{100}$) of a single flight can be reduced by up to 40%. However, if mitigation efforts are associated with a direct increase in costs, there is a need for climate policies. To address the lack of incentivizing airlines to internalize their climate costs, this study focuses on the CCA concept, which imposes a climate charge on airlines when operating in highly climate-sensitive areas. If CCAs are (partly) bypassed, both climate impact and operating costs of a flight can be reduced: a more climate-friendly routing becomes economically attractive. For an exemplary North-Atlantic network, CCAs create a financial incentive for climate mitigation, achieving on average more than 90% of the climate impact reduction potential of climate-optimized trajectories (theoretical maximum, benchmark).

### Key policy insights

- Existing climate policies for aviation do not address non-CO$_2$ effects, which are very sensitive to the location and the timing of the emission.
- By imposing a temporary climate charge for airlines that operate in highly climate-sensitive regions, the trade-off between economic viability and environmental compatibility could be resolved: Climate impact mitigation of non-CO$_2$ effects coincides with cutting costs.
- To ensure easy planning and verification, climate charges are calculated analogously to en-route and terminal charges. For climate mitigation it is therefore neither necessary to monitor emissions (CO$_2$, NO$_x$, etc.) nor to integrate complex non-CO$_2$ effects into flight planning procedures of airlines.
- Its implementation is feasible and effective.

**CONTACT** Malte Niklaß ✉ malte.niklass@dlr.de ▣ Deutsches Zentrum für Luft- und Raumfahrt (DLR), Lufttransportsysteme, Hamburg 21079, Germany

## 1. Introduction

With annual air traffic growth rates of around 5% of revenue passenger kilometers, commercial aviation has experienced a steady growth in the past decades with an observed doubling period of 15 years (Airbus, 2019). However, due to the long service life of aircraft and long phases in development, production and certification, technological improvements can only be gradually introduced into the existing aircraft fleet. As a result, historical and projected air traffic growth rates clearly exceed the expected annual fuel efficiency improvement rate of approximately 1–2% (Kharina & Rutherford, 2015). This has resulted in a 130% increase of greenhouse gas emissions from international aviation between 1990 and 2017 (European Environment Agency, 2019). It can, therefore, be assumed that the percentage share of aviation to total greenhouse gas emissions will further increase in the future. A development, which is additionally reinforced by the mitigation success in other sectors: despite continuously rising aviation emissions, EU member states were able to reduce their total emissions by 23.5% between 1990 and 2017. This further increases the importance of the aviation sector in climate research.

The current state of knowledge regarding the impact of aviation on the environment is summarized in various assessment reports (Brasseur et al., 2016; Grewe, Dahlmann, et al., 2017; Lee et al., 2010, 2020). According to these studies, aviation contributed roughly 5% (2–14%, 90% probability range) to the global anthropogenic radiative forcing (RF) in 2005. Since atmospheric conditions at conventional cruise altitudes promote more micro-physical processes and faster chemical reactions (i.a. production of hydroxyl radicals via the photolysis of $O_3$; Köhler et al., 2008) than on ground, 50–75% of the total climate impact of aviation is induced by non-$CO_2$ effects, including emissions of water vapor ($H_2O$), nitrogen oxide ($NO_x$) and aerosols (see Figure 1).
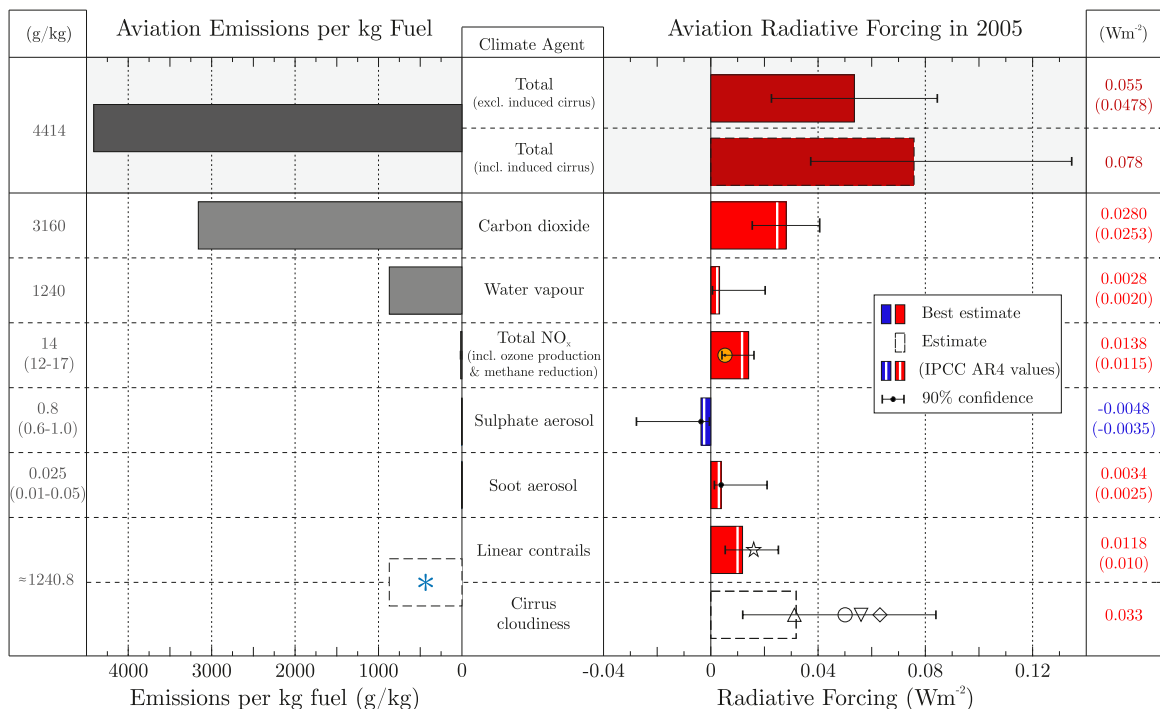


**Figure 1.** Aviation emissions (as reported by Lee et al., 2010) and aviation-induced radiative forcing (RF) (as reported by Lee et al., 2009 and adapted by Grewe, Dahlmann, et al., 2017) (bars and uncertainty ranges) from different components. New findings are added with symbols (Bock & Burkhardt, 2016; Burkhardt & Kärcher, 2011; Grewe et al., 2019; Schumann & Graf, 2013; Schumann et al., 2015; Søvde et al., 2014; Voigt et al., 2011).

Emissions of $NO_x$ affect the climate indirectly by an increase in ozone concentration ($O_3$; warming effect of 26.3 mW/m$^2$) and a reduction in methane concentration ($CH_4$; cooling effect of $-15.4$ mW/m$^2$; Grewe et al., 2019), which are both important greenhouse gases. The level of the positive net $NO_x$ effect, however, varies greatly with the emission location in terms of altitude (Grewe & Stenke, 2008), geographic region (Köhler et al., 2013; Stevenson & Derwent, 2009), and time of the year (Hoor et al., 2009; Søvde et al., 2014), with the consequence that $NO_x$ emissions can even cause a cooling effect in certain regions (Frömming et al., 2021). The largest individual contribution to the total RF of aviation is currently attributed to contrail cirrus (CC), whereas for the induced temperature change the three components $CO_2$, $NO_x$, and CC might be about equally important (Grewe, 2020; Ponater & Bickel, 2020). Although CC might have a cooling effect under certain circumstances (e.g. shortly before sunrise and sunset) (Meerkötter et al., 1999; Myhre & Stordal, 2001), induced CC are expected to contribute to global warming on average in the order of 30–60 mW/m$^2$.

Due to highly non-linear dependencies on emission volume and fuel consumption (see Figure 1), the reduction of emission quantity alone is not a sufficient measure in order to mitigate non-$CO_2$ climate effects. As non-$CO_2$ effects are very sensitive to the location and the timing of the emission, these effects can be effectively reduced by changing the flight pattern, represented by an adjustment in routing or a reduction of the general cruising altitude. Simple operational measures, like the reduction of the general cruising altitude (Dahlmann et al., 2016; Frömming et al., 2012; Grewe et al., 2002; Søvde et al., 2014; Williams et al., 2002, 2003) could be implemented promptly if politically desired. From a climatological point of view, drawbacks of increased emissions are overcompensated by the reduction in the CC coverage, a reduced $O_3$ production and a shortening of the lifetime of $CH_4$. Besides lowering the general flight altitude, non-$CO_2$ effects can also be mitigated by daily adjustments of the routing. Due to the high location and time dependency of many non-$CO_2$ climate effects, a deviation of the economic flight planning of present-day, minimizing the operating costs, is often meaningful to significantly reduce the resulting overall climate impact of a flight. Taking various non-$CO_2$ effects into account, different optimization strategies have been investigated by Avila et al. (2019), Chen et al. (2014), Grewe, Dahlmann, et al. (2017), Hartjes et al. (2016), Lührs et al. (2016, 2018, 2020), Matthes et al. (2017, 2020), Rosenow and Fricke (2019), Soler et al. (2014), Sridhar et al (2010), Teoh et al. (2020), Yamashita et al. (2016, 2019), Yin et al. (2018), and Zou et al. (2016). Throughout all these studies, however, changes in the routing strategy also result in increased values of flight time, fuel burn and operating costs. According to Lührs et al. (2016), for example, climate-optimized trajectories (COTs) can reduce the averaged temperature response over 20 years (ATR$_{20}$) of a North-Atlantic flight either by $-23.7\%$ for a cash operating cost (COC) increase of $+0.8\%$ (additional fuel burn of $+1.3\%$) or by $-51.9\%$ for a $\Delta$COC of $+11.6\%$ ($+15.3\%$ fuel burn) relative to a cost-optimized operation. Resulting flight times increase by a few minutes only (Grewe, Champougny, et al., 2014). Matthes et al. (2020) showed that climate-cost-efficient re-routing is robust with respect to the choice of climate metrics – *ATR, GTP (Global Temperature Potential), and GWP (Global Warming Potential) over 20, 50, and 100 years*.

As mitigation efforts of non-$CO_2$ effects do not coincide with cutting costs, it is essential to identify climate-cost-efficient routing strategies with the highest mitigation potential at the lowest possible costs.

$$\text{COC}(\text{climate-cost-efficient routing}) \geq \text{COC}(\text{cost-efficient routing}) \qquad (1)$$

Most of the aforementioned studies focus on the assessment of the cost-benefit potential of climate-cost-efficient routing (climate impact reduction vs. costs penalties). Questions of the feasibility or short-term practicability of climate-cost-efficient routing are hardly considered, disregarding the major challenges of introduction. Policies are needed to bridge the discrepancy between the social objectives of climate protection and the economic interests of the market.

This study addresses the question of how to include aviation's climate impact of non-$CO_2$ effects adequately into environmental policy. Section 2 presents and discusses a wide range of potential approaches to create an incentive or a need for aircraft operators for adjustments of the routing. In Section 3, the lack of incentivizing airlines to internalize their climate costs is addressed by the concept of climate-charged airspaces (CCAs). The basic functionality and effectiveness of this concept is demonstrated in Section 4 with trajectory simulations. The paper ends with discussion and conclusions in Sections 5 and 6.

## 2. Policy instruments for implementing climate-cost-efficient routing

For regulating international activities, such as aviation, market-based instruments (taxes, charges, marketable permits, etc.) are often the preferred choice because they theoretically achieve climate goals in a very cost-effective manner (see i.a. Nordhaus, 1982). In recent years, several countries – including the EU, New Zealand, South Korea and China (market pilots in Shanghai, Guangdong, and Fujian) – have begun to integrate the aviation sector into national emissions trading schemes (ETS). According to EU ETS, aircraft operators are obliged to hold and surrender allowances for $CO_2$ emissions for all flights within the European economic area from 2012 (European Union, 2009a, 2009b). In order to stabilize $CO_2$ emissions from international aviation at a 2020 level ($CO_2$-neutral growth), the International Civil Aviation Organization (ICAO) agreed in 2016 to implement the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), focusing primarily on compensation and alternative fuels (International Civil Aviation Organization, 2016). A global carbon tax does not exist in international aviation due to a resolution of International Civil Aviation Organization (1993), which generally exempts jet fuel from all customs and other duties. For a detailed review of international and national $CO_2$ policy in the aviation sector, see Larsson et al. (2019).

As non-$CO_2$ effects are not yet fully understood and still linked with medium to high uncertainties (Lee et al., 2020), no environmental policy instruments have yet been established in aviation for non-$CO_2$ effects. However, at the 1992 United Nations Conference on Environment and Development (UNCED) it was decided that a 'lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation' (United Nation, 1992, Annex 1, Principle 15).

### 2.1. Integration of non-$CO_2$ effects into existing policy instruments

A variety of economic concepts have recently been proposed for non-$CO_2$ effects. Most ideas try to integrate non-$CO_2$ effects into existing and planned market-based instruments, like EU ETS or CORSIA, based on the principle of equivalent $CO_2$ emissions ($^{eq}E_{CO_2}$ or $CO_2$e), a way of standardizing the impact of all climate agents. $^{eq}E_{CO_2}$ represent for a given type ($i$) and amount ($E_i$) of a climate agent the concentration of $CO_2$, that would cause the same climate response over a specific time horizon (e.g. 20, 50 or 100 years) as $CO_2$:

$$^{eq}E_{CO_2}(i) = {}^{eq}CO_2{}^i \cdot E_i \qquad (2)$$

The total amount of $^{eq}E_{CO_2}$ resulting from all non-$CO_2$ effects thus determines the quantity of emission certificates to be surrendered or respectively the level of emission charge/tax to be paid.
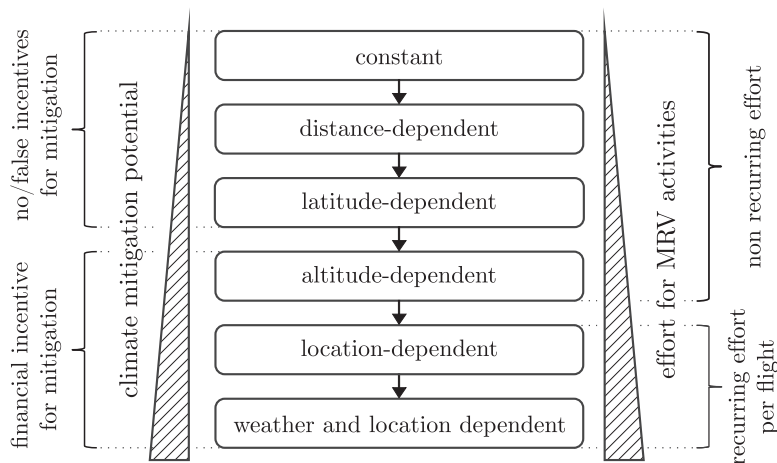


**Figure 2.** Mitigation benefit and effort for monitoring, reporting and verification (MRV) activities of different $^{eq}E_{CO_2}$ calculation methods (adapted from Niklaß et al., 2020, p. 43).

As visualized in Figure 2, there are various ways of calculating $^{eq}E_{CO_2}$ for different purposes. Constant $^{eq}E_{CO_2}$ approaches, such as the Radiative Forcing Index (RFI), as well as distance-dependent ones (see Equation (3)) are heavily criticized (Forster et al., 2006) and proven to be inappropriate, though they have the advantage of being easily (i) integrated into existing instruments, (ii) predicted and (iii) verified (Jung-bluth & Meili, 2019):

$$^{eq}E_{CO_2}(d) = \left(1 + \sum_i {}^{eq}CO_2{}^i(d)\right) \cdot E_{CO_2} \tag{3}$$

But an increase of $CO_2$ emissions pro rata merely intensifies the focus on reducing fuel consumption and does not provide any incentive for reducing non-$CO_2$ effects. If airlines consequently choose to generally fly higher to cut fuel consumption – *which reduces the $^{eq}E_{CO_2}$ level in these cases* –, there is a risk that the resulting increase in the climate impact of CC, $H_2O$ and $O_3$ overcompensate the $CO_2$ reduction. Simple $CO_2$ equivalence factors should, therefore, only be used to estimate the overall climate impact of avia-tion, e.g. for the purpose of $CO_2$ offsetting or for estimating the ecological footprint of a person. It is possible, however, to avoid misguiding incentives, if at least the altitude dependency of non-$CO_2$ effects is considered in the $^{eq}E_{CO_2}$ calculation method (Faber et al., 2008; Niklaß et al., 2020; Scheelhaase et al., 2016). Significantly higher incentives for mitigating non-$CO_2$ effects can be generated with location-dependent or detailed weather- and route-dependent $^{eq}E_{CO_2}$ factors (Grewe, Dahlmann, et al., 2017; Niklaß et al., 2020), as long as more climate-friendly routings lead to a reduction of $^{eq}E_{CO_2}$:

$$^{eq}E_{CO_2}(\mathbf{x}, t) = E_{CO_2}(\mathbf{x}, t) + \sum_i {}^{eq}CO_2{}^i(\mathbf{x}, t) \cdot E_i(\mathbf{x}, t) + {}^{eq}CO_2{}^{CC}(\mathbf{x}, t) \cdot d(\mathbf{x}, t) \tag{4}$$

Latter two calculation methodologies require detailed flight trajectory information including the location ($\mathbf{x}$), volume ($E_i$) and timing ($t$) of emission release for $CO_2$, $H_2O$ and $NO_x$. As a result, $^{eq}E_{CO_2}$ values have to be calculated individually for each flight, causing a recurring effort. Consequently, important issues of operationalization, such as the implementation of an effective and robust MRV system – *in particular for $NO_x$ emission inventories* – have not yet been fully clarified for these approaches.

## 2.2. Flanking instruments for non-$CO_2$ effects

As an alternative to integrating non-$CO_2$ climate effects into existing instruments for $CO_2$ emissions, research is being conducted to investigate whether non-$CO_2$ effects can be reduced more effectively and efficiently by designing flanking instruments. An EU wide charge for $NO_x$ emissions during cruise (en route) or landing and take-off (with distance factor) has been suggested by Faber et al. (2008) and others. However, as before, these concepts are based on the mass of $NO_x$ emissions which cannot yet be determined empirically on each flight. Correlation methods are hence required for estimating $NO_x$ emissions, which are subject to particu-larly high uncertainties for new engines with staged combustion.

Another possible option is the formulation of regulatory policies for non-$CO_2$ effects, like a cruise cer-tification standard for $NO_x$ emissions (Wit et al., 2004). Williams et al. (2002, 2003) proposed altitude restrictions for commercial aircraft in order to reduce the likelihood of contrail formation (see Figure 3 (a)). Instead of generally closing high flight levels, Niklaß et al. (2017, 2019) investigated the cost-benefit potential resulting from the application of climate-restricted airspaces. In this concept, an airspace area will be temporarily closed for air traffic, in analogy to military restricted zones, if the climate sensi-tivity of a region exceeds a certain limit (see Figure 3(c)). Accordingly, all affected flights should be re-routed around these non-fly zones at the lowest possible cost. With a mitigation potential of the same order of magnitude as for COTs (climate impact reduction of −10% for an operating cost increase of +1%), they clearly demonstrated the efficiency and effectiveness of focusing on the most ecologically harmful airspaces. But since it is more climate-friendly to fly through climate-sensitive regions over a short distance than to bypass it by a long detour, the implementation of market-based measures that
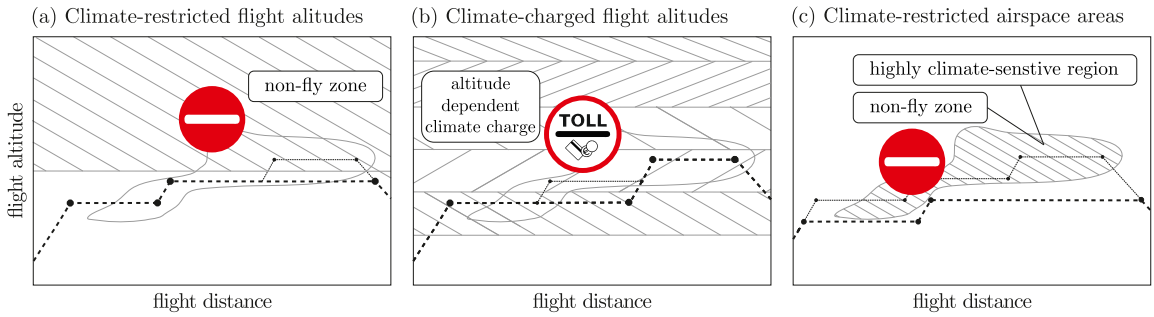
**Figure 3.** Visualization of the concepts of (a) climate-restricted flight altitudes (i.a. Williams et al., 2002, 2003), (b) climate-charged flight altitudes (i.a. Faber et al., 2008; Scheelhaase et al., 2016) and (c) climate-restricted airspaces areas (Niklaß et al., 2017, 2019).

incentivize airlines for avoiding these regions might be more promising for climate mitigation than hard restrictions.

## 3. Concept of climate-charged airspaces (CCA)

In order to create an incentive for airlines to mitigate non-$CO_2$ effects, we propose to expand the concept of climate-charged flight altitudes into the concept of climate-charged airspaces (CCA) by imposing a climate charge for airlines that operate in highly climate-sensitive regions (see Figures 3(b) and 4).
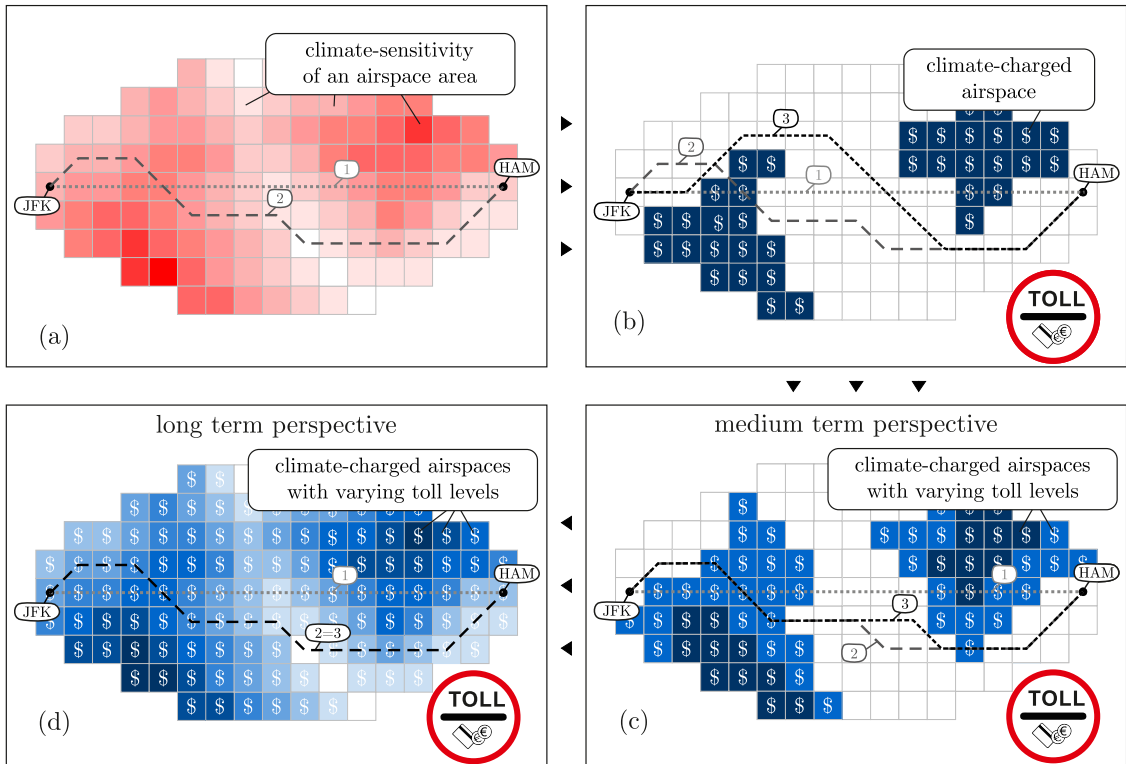


**Figure 4.** Short- (b), medium (c) and long-term strategy (d) for implementing the CCA concept: time-optimized (1), climate-optimized (2), and cost-optimized trajectory within the CCA concept (3) are simplified by dashed lines (Niklaß et al., 2018).

### 3.1. Concept design

An airspace area **x** will be levied at a time $t$ with an environmental unit charge, $U_{cj}$, per kilometer flown, $d_j$, if its climate sensitivity with respect to aircraft emissions exceeds a specific threshold value ($c_{thr}$):

$$CCA_j(\mathbf{x}, t) = \begin{cases} U_{cj}, & \text{if } CCF_{tot}(\mathbf{x}, t) \geq c_{thr} \\ 0, & \text{if } CCF_{tot}(\mathbf{x}, t) < c_{thr} \end{cases} \tag{5}$$

The climate sensitivity of an area is expressed here by total climate change functions ($CCF_{tot}$) characterizing the environmental impact caused by aircraft emissions at a certain location and time (Grewe, Frömming, et al., 2014).

In order to ensure easy planning and verification, resulting climate charges, $C_{cj}$, are calculated analogously to en-route and terminal charges according to

$$C_{cj} = U_{cj} \cdot m_{TOW} \cdot I_{ac} \cdot d_j. \tag{6}$$

Parameters under consideration are the maximum take-off weight $m_{TOW}$ of an aircraft and an incentive factor $I_{ac}$ for green technologies. Emissions of $CO_2$, $H_2O$ and $NO_x$, therefore, do not need to be monitored.

By coupling the climate charge with a technology incentive factor, aircraft operators are provided with both an operational incentive for re-routing and a technological incentive for investments in more climate-friendly aircraft technologies:

$$I_{ac} = \begin{cases} 1 & \text{for current technology level} \\ \vdots & \text{for greener technology levels} \\ 0 & \text{for zero} - \text{emission aircraft} \end{cases} \tag{7}$$

The CCA concept also allows the operator to decide individually for each flight whether to minimize flight time and to pay compensation for higher climate impact (trajectory 1 in Figure 4(b)) or to minimize costs and, concurrently, mitigating the climate impact by total or partial avoidance of CCAs (trajectory 3). In this manner, climate impact mitigation coincides with the cutting of costs. There is also no need to integrate complex non-$CO_2$ effects into airlines' flight planning procedures to ensure climate mitigation, as CCAs can be defined and monitored by air traffic control. As a result, airlines can continue with their purely cost-optimized flight planning, taking into account the corresponding CCAs.

The practicability of our cost-driven re-routing approach can already be demonstrated today with the operating behavior of airlines on trans-European journeys. With the aim of cutting costs, a number of airlines took particularly large detours in 2015 relative to 2012-2014 – *a year when fuel costs were comparatively low* – and re-routed their flights over countries with lower air traffic control charges, such as Eastern and South-Eastern Europe (see exemplary Figure 5) (Delgado, 2015; Ehlers et al., 2020; Eurocontrol, 2016). A price-driven re-routing approach is therefore already well-established in the airline industry.

### 3.2. Key decisions of the CCA concept

When implementing a climate policy, there are several decisions that need to be made, which require a collaborative process involving policymakers and scientists. An overview of these key decisions is given in Table 1 and discussed below for the CCA concept.

Given the existing uncertainties in climate impact modeling of a flight, a robust management of uncertainties is necessary to avoid optimized trajectories that clearly over- or underestimate the impact of individual climate agents. For this reason, the CCA concept is planned to be introduced gradually. In a first step, the implementation of the CCA concept should be limited to selected non-$CO_2$ effects and those areas that are most likely highly climate sensitive (see Figure 4(b)). But its implementation can be adapted any time to the current level of scientific understanding by introducing varying unit charges for areas with different levels of climate sensitivities and/or by taking further trace substances, e.g. aerosols, into
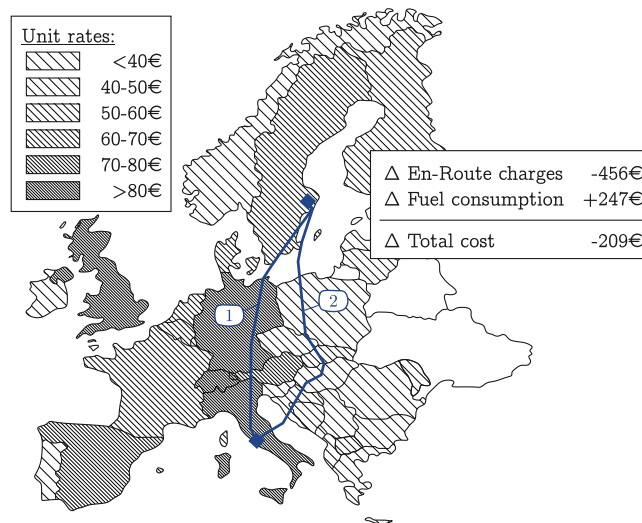
**Figure 5.** Influence of current air traffic control (ATC) unit rates on operating costs and flight route for a full-service carrier flight from Stockholm, Sweden to Rome, Italy adapted from Delgado (2015), unit rates accord with Eurocontrol (2016).

consideration. In the final expansion phase, the entire airspace and all relevant climate agents should be included into the concept.

Due to the considerable differences in lifetime – *ranging from minutes (linear contrails) to centuries* ($CO_2$) – a climate metric has to be selected for assessing the net climate impact of the CCA policy. Climate metrics can be regarded as the combination of climate indicator (e.g. RF and $\Delta T$), time horizon (often 20, 50, 100 or 500 years) and emission scenario (emission course, background emissions, etc.) (see i.a. Fuglestvedt et al., 2010). The choice of time horizon goes beyond natural sciences and requires multi-criteria value judgments – *including aspects of (intergenerational) justice, equity, and responsibility* – that depend on the specific question to be answered. The use of longer horizons, e.g. 100 years, is recommended if the focus is on sustainable aviation, while a focus on climate change mitigation in the near future would imply shorter time horizons of, e.g. 20 years (Grewe & Dahlmann, 2015).

The data set used for climate modeling (weather forecast data vs. climatological mean data) significantly determines the charging period of an airspace area (hours or weeks). The choice of climate agents under consideration also influences the predictability of CCAs. For example, weather-based CCAs could be scheduled three days before departure, as specialist services, such as the European Centre for Medium-Range Weather Forecasts, can forecast ice supersaturated regions (ISSR) very accurately (Rädel & Shine, 2010; Spichtinger et al., 2003).

**Table 1.** Key decisions of the CCA concept.

| Key decision | Options | Applied in Section 4 |
|---|---|---|
| Selection of climate metric | {ATR, GWP, GTP, …} over {20, 50, 100, …} years | $ATR_{100}$ |
| Selection of climate agents | {$CO_2$, $H_2O$, $NO_x$, CC, soot, …} | $CO_2$, $H_2O$, $NO_x$, CC |
| Data set used for climate modeling | numerical weather prediction (NWP) data or climatological mean data | climatological mean data |
| Charging period of an airspace | hours (NWP) data to weeks | weeks |
| CCA scheduling before take-off | three days (NWP) to weeks | weeks |
| Variability of climate unit charges | uniform or varying in dependency of the climate sensitivity | uniform |
| Expansion of CCAs | total airspace or limited to highly climate-sensitive areas | limited to highly climate-sensitive areas |
| Detail definition of $l_{ac}$ | according to ICAO engine emissions standards, etc. | not defined (no variation of aircraft types) |

### 3.3. Modeling approach

The basic feasibility and effectiveness of the CCA concept is demonstrated below with trajectory simulations on nine North-Atlantic routes (see Figure 6) and benchmarked against the potential of climate-cost-efficient trajectories. The selected routes cover a large area of the North-Atlantic flight corridor (from London – Toronto to Lisbon-Miami).

On each route, a multicriteria trajectory optimization is performed with regard to monetary costs (here: COC) and climate costs (here: $ATR_{100}$) by applying optimal control techniques as introduced by Lührs et al. (2016). ATR considers the different climate sensitivities and lifetimes of individual climate agents as well as the thermal inertia of the atmosphere. Furthermore, ATR is less dependent on the time horizon than GTP and might be more easily comprehensible than RF and GWP because of a direct relation to temperature change. 100 years are long enough for an adequate consideration of long-lived species like $CO_2$, but short enough to be relevant for people themselves.

In order to obtain Pareto efficient allocations (maximum reductions of $ATR_{100}$ for minimum increases in COC), well over 100 optimizations with varying climate weighting factors were performed for each route with Lührs et al.'s Trajectory Optimization Module (TOM). Operating costs are calculated according to the direct operating costs method developed by Liebeck (1995) but only the share of COC – *including the costs for fuel, crew, maintenance, as well as navigation and landing fees* – is considered within this study (no depreciation, insurance or interest costs). As Liebeck's calculation method is based on US$ from mid-1993, expenses are scaled to the year 2012 with the average US inflation rate of average consumer prices published by the International Monetary Fund (2014). The climate impact assessment is based on monthly CCFs according to Niklaß et al. (2017), which are calibrated by Airbus A330-200 mean aircraft emissions in specific flight altitudes. The temporal evolution of these aircraft emissions is scaled by the IPCC scenario Fa1, characterizing an annual mid-range traffic growth of 3.1% and technologies for both improved fuel efficiency and $NO_x$ reduction (Henderson & Wickrama, 1999). Atmospheric background composition and emission rates are taken from the IPCC scenario A1B (Houghton et al., 2001). In this study, we apply climate change functions $CCF_i^{mo}$ for $i \in \{CO_2, H_2O, NO_x, CC\}$ and annual mean values (mo = 13). Accordingly, we do not consider wind effects in this study, which have a similar influence on the reference case (COT) as on the CCA concept. All trajectories are simulated with a BADA 4.0 Airbus A330-200 aircraft performance model (Nuic & Mouillet, 2012) assuming a constant cruise Mach number of 0.82, a load factor of 85% as well as free flight and International Standard Atmosphere (ISA) conditions. Aircraft emissions are calculated based on the Eurocontrol modified Boeing Fuel Flow Method 2 (DuBois & Paynter, 2014; Jelinek et al., 2004). Since today's flight planning is optimized in terms of time and economic costs, all values regarding COC, $ATR_{100}$, mission time and mission fuel are expressed for each simulated trajectory relative to the route-specific minimum COC trajectory ('Business as Usual', BAU). In case of CCAs, sensitivity analyses are conducted to investigate the influence of both the level of climate unit charges ($U_{cj}$) and the threshold value ($c_{thr}$), representing the size and location of CCAs (for $c_{thr} = 1$, no CCAs occur; for a threshold
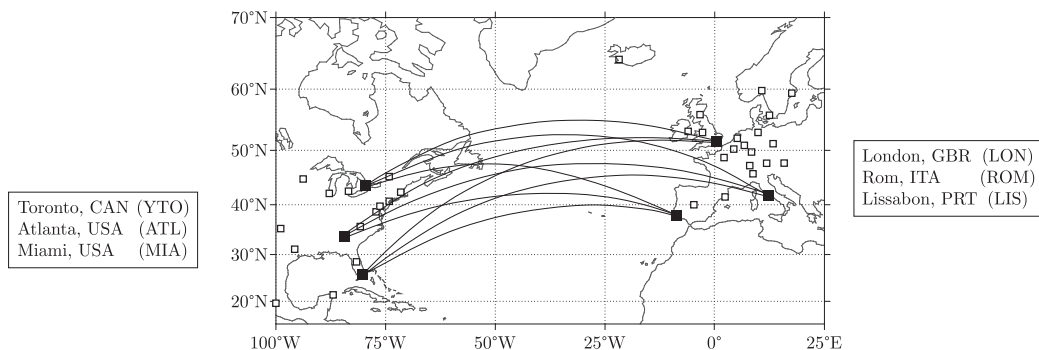


**Figure 6.** Overview of the simulated route network between three North American and three European airports (■). All routes are plotted as great circle routes; the most frequently used airports on transatlantic flights in 2016 are symbolized by □.

value of zero, the entire airspace is subject to climate charges; see Equation (5)). For this purpose, a fast-time 4D trajectory modification of optimized trajectories is performed according to the total energy model as described by Niklaß (2019). For each set of ($c_{thr}$, $U_{cj}$), cost-effective trajectories passing through CCAs are identified ex post by applying an exhaustive search algorithm.

## 4. Initial cost-benefit and feasibility assessment

In the following, the mitigation effectiveness of the CCA concept is analyzed and benchmarked against the potential of climate-cost-efficient trajectories:

### 4.1. Mitigation potential of climate-cost-efficient routing (benchmark)

In Figure 7, lateral and vertical flight profiles of cost- and climate-optimized flying are depicted for the North-Atlantic route from LIS (Lisbon) to MIA (Miami). Without consideration of wind effects and ATC constraints, COC-optimized trajectories (BAU) result in a continuous cruise climb on the great circle, the shortest connection between both cities. By increasing the importance of climate impact reduction, the trajectories are shifted to regions with lower climate sensitivities (particularly in vertical dimension), which in turn results in longer flight distances, higher fuel burn, and additional operating costs (see Table 2). The resulting Pareto front, plotted in Figure 8(a), clearly outlines the trade-off between cutting of cost and climate impact mitigation. The reduced climate impacts of CC, $NO_x$ and $H_2O$ clearly exceed an increased $CO_2$ impact.

For the route LIS-MIA, the Pareto front reaches a maximum mitigation potential of 34.8%, accompanied by a COC penalty of about 10.6%. However, as mitigation efforts are linked with additional expenses, it is essential to identify cost-effective re-routing strategies with the highest mitigation potential at the lowest possible costs. On the exemplary route, significantly higher mitigation efficiencies can be achieved for cost penalties below
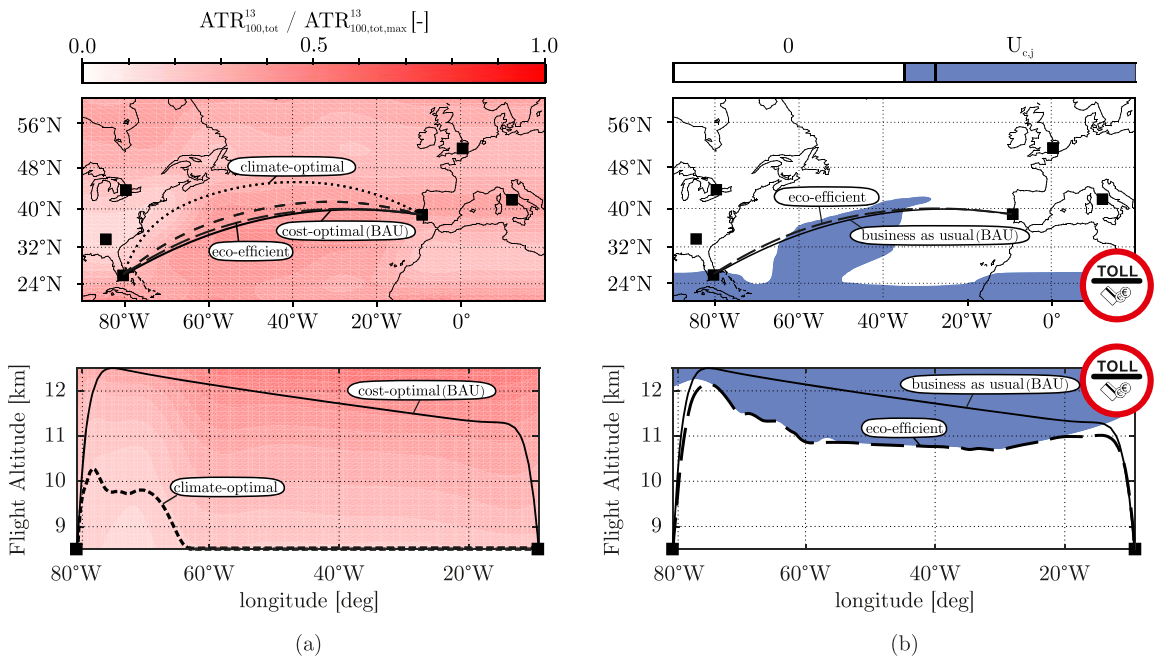


**Figure 7.** Lateral and vertical flight profiles of cost- and climate-optimized flying (a) and the CCA concept (b) on the North-Atlantic route LIS-MIA (wind effects are not considered). Horizontal contour lines of $CCF_{tot}$ based on annual mean values (left) and CCAs (right) are visualized for an altitude of 10,500 m and $c_{thr} = 0.664$; vertical contour lines are drawn along the cross-section of the lateral path of the flights (adapted from Niklaß et al., 2018, p. 6).

**Table 2.** Mitigation potentials of COTs.

| COC increase (%) | ATR reduction (%) | Av. Altitude (m) | Fuel burn (%) | Mission distance (%) |
| --- | --- | --- | --- | --- |
| 0.0 | 0.0 | 11,645 | 0.0 | 0.00 |
| 0.4 | 9.0 | 11,031 | +1.1 | +0.03 |
| 3.4 | 22.6 | 9,845 | +9.9 | +0.33 |
| 10.6 | 34.8 | 8,910 | +22.8 | +4.02 |

2.5%; climate-cost-efficient trajectories are highlighted in red in Figure 8(a) (compare Table 2). For example, at a cost increase of 0.4%, a total climate impact reduction of 9.0% is observed. Average Pareto-elements of COTs are colored in black. These results are in line with those presented by Grewe, Matthes, et al. (2017), Lührs et al. (2016, 2018, 2020), Matthes et al. (2017, 2020) and Yamashita et al. (2019).

## 4.2. Mitigation effectiveness of climate-charged airspaces

The demonstration of the CCA concept is described below in several steps. At first, the general mechanism of CCAs is explained exemplarily for a single North-Atlantic route. For this purpose, the size and location of CCAs as well as the level of climate unit charges are presumed to be known ($c_{thr}$ = constant; $U_{cj}$ = constant). Subsequently, sensitivity analyses are conducted to quantify the significance of these variables. Finally, it is analyzed whether the CCA concept can ensure region- or country-specific climate targets.

Figure 7(b) illustrates the expected impact of CCAs on flight operations for the route LIS-MIA and a threshold of 0.664. Since the BAU trajectory runs straight through CCAs, BAU operation is only possible with significantly higher operating costs (○ → ○) (see Figure 8(b)), partially internalizing the climate-related damage of the flight. In the example shown, a COC increase of about 7.9% is observed for a climate unit charge of one dollar per kilometer. The additional costs of internalization, however, can largely be avoided if the aircraft operator changes its flight behavior and (partly) re-routes the flight around CCAs. In this case, it is possible to lower the costs of internalization by 89.9% ($\Delta$COC =-7.1%) (red dot in Figure 8(b)) if CCAs are avoided completely. This in turn results in a 9.4% climate impact mitigation of the flight. Climate impact mitigation thus coincides with cutting costs, climate-cost-efficient routing becomes economically attractive. By creating a financial incentive for mitigation, the trade-off between economic viability and environmental compatibility can therefore be solved:

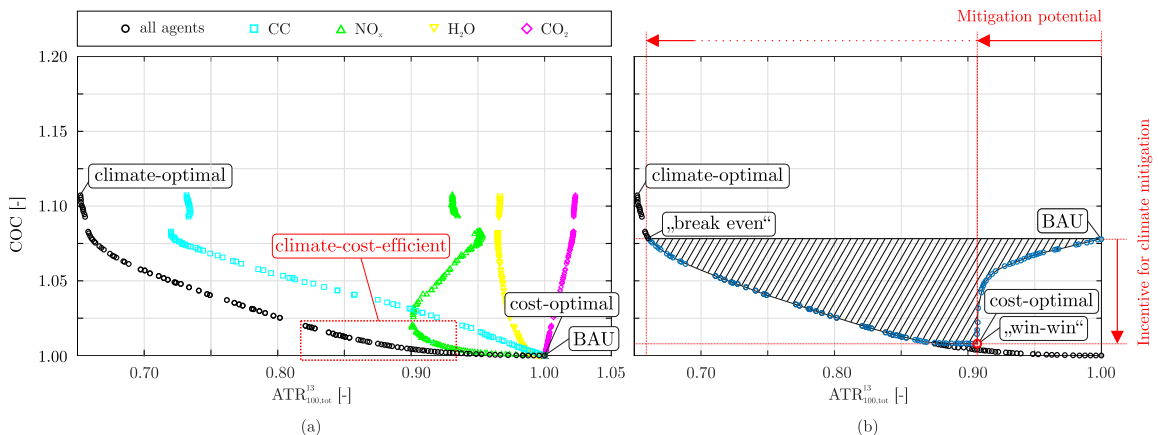$$\text{COC(climate-cost-efficient routing)} \, ! = \text{COC(cost-efficient routing)} \tag{8}$$



**Figure 8.** Climate mitigation potential (in ATR) and cash operating costs (COC) of (a) COTs and (b) the CCA concept (blue circles) on the transatlantic route LIS-MIA, assuming a climate unit charge of 1 \$/km, a threshold of 0.664, and no wind effects.

If CCAs are circumnavigated more spaciously, further climate impact reductions can be achieved. But with growing detour, fuel burn and operating costs also increase, which in turn reduces the financial incentive for climate mitigation. For the selected example, a cost-neutral climate mitigation potential of around −30% can be realized ($\Delta COC = 0$; 'break even' in Figure 8(b)). Any further reduction of ATR requires additional expenditures, eliminating the effect provided by the CCA concept of creating financial incentives for climate mitigation.

Sensitivity analyzes are carried out to quantify the influence of climate charges ($U_{cj}$) and threshold values ($c_{thr}$) on both the mitigation potential and the incentivizing effect of the CCA concept. Exemplary results are presented in Figure 9 for the route LIS-MIA. In Figure 9(a), $U_{cj}$ is varied from 0.01 \$/km to 5.0 \$/km while keeping the threshold at a constant level of 0.664. The higher $U_{cj}$, the greater is the financial incentive for re-routing. But there is no effect of $U_{cj}$ on the climate mitigation potential, which remains constant at −9.4%. In this example, a climate unit charge of minimum 0.10 \$/km is necessary to create a 'win-win' situation. If $U_{cj}$ increases towards infinity, CCAs turn into non-fly zones, corresponding to the concept of climate-restricted airspaces (see Niklaß et al., 2017, 2019).

Exactly the reverse is true for the threshold value (see Figure 9(b)). Here, the threshold is alternated between 0 and 1 at a constant climate unit charge of 0.5 \$/km. For $c_{thr} = 1$ (□), there is no CCA, resulting in a match of a purely cost-optimized operation and BAU (□ compare Figures 7(a) and 8(a)). With decreasing threshold, the size of CCAs increases, which in turn raises the mitigation potential of the CCA concept while keeping the incentive level for mitigation almost unchanged. By implementing a $c_{thr}$ of 0.664 (○) or 0.564 (⬠) COC initially increase by almost the same amount of roughly +5% for BAU operation (□ → ○, ◇, ⬠). But by operational adjustments in the routing, it is again possible to cut both internalization costs and climate impact ('win-win'). For $c_{thr} = 0.664$ (○), COC and ATR can be reduced roughly by −4% and −9.4% respectively (○); for $c_{thr} = 0.564$ (⬠) a 'win-win' situation (⬠) of $\Delta COC \approx -2\%$ and $\Delta ATR \approx -17.5\%$ is achievable (see Figure 9(b)). The independent variables of the threshold ($c_{thr}$) and the climate unit charge ($U_{cj}$) are thus the key parameters of the CCA concept. An optimal set of these variables can be found for each route to create a monetary incentive for a targeted mitigation potential.

Based on the results of nine North-Atlantic routes (see Figure 6), an averaged mitigation potential, $\overline{ATR}(y)$, is calculated for two different selection criteria $y$ – *a given threshold and a maximum cost increase* – as follows:

$$\overline{ATR}(y) = \sum_{i=1}^{n} f_i \cdot ATR_{100,tot,i}(y) \tag{9}$$
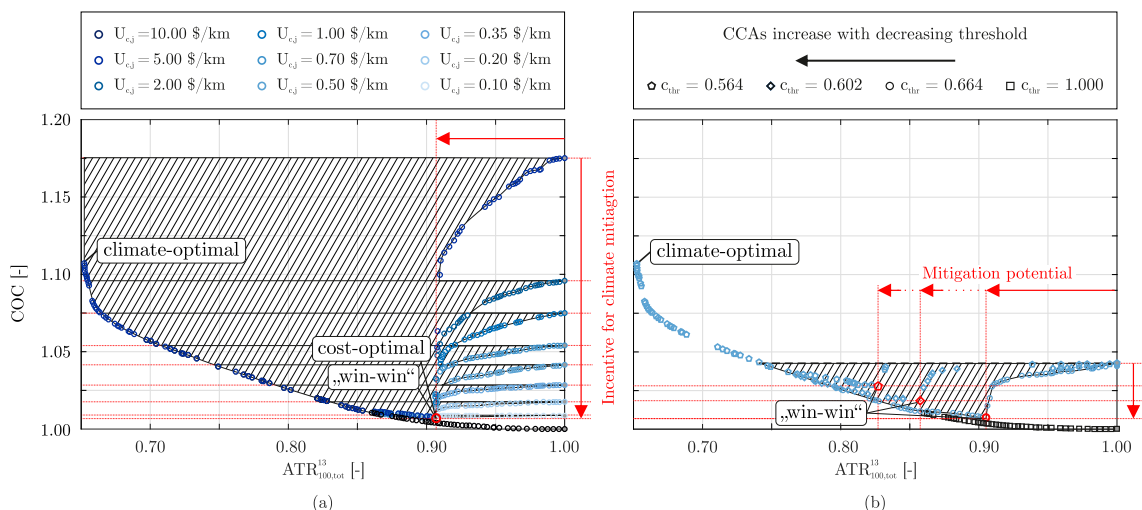


**Figure 9.** Impact of (a) climate unit charges ($U_{cj}$) and (b) threshold values ($c_{thr}$) on the cost-benefit potential of CCAs for the route LIS-MIA.

with the Pareto-elements (ATR$_{100,\text{tot},i}$, COC$_{100,\text{tot},i}$) of the route $i$ and the simplified flight frequency $f_i = 1/n\ \forall\ f_i$ with $\sum_{i=1}^{n} fi = 1$.

The resulting additional average cost, $\overline{COC}(y)$, is determined according to Equation (10):

$$\overline{COC}(y) = \sum_{i=1}^{n} f_i \cdot COC_{100,\text{tot},i}(y) \tag{10}$$

In this way, a financial incentive for climate mitigation has been identified for the CCA concept that achieves on average more than 90% of the mitigation potential of COTs (theoretical maximum) in case of a total avoidance of charged airspaces ($U_{cj} \rightarrow \infty$) (compare averaged Pareto fronts of both concepts in Figure 10(a)). For example, at additional costs of roughly 3%, the climate impact can be reduced by either 22% (◯, 100%) or 20% (◯, >90%). The idea of avoiding only the most climate-sensitive regions is therefore an extremely effective mitigation approach.

More relevant, however, is the question whether a combination of a threshold value and a climate unit charge ($c_{\text{thr}}$, $U_{cj}$) can be defined for the entire network that ensures achievement of regional or country-specific environmental targets. Is it possible, for instance, to achieve a climate impact mitigation of at least 5% on each North-Atlantic flight with the CCA concept? For this purpose, the minimum (blue), average (grey) and maximum (red) mitigation potentials of all simulated routes are plotted in Figure 10 (b) over the threshold. Accordingly, a mitigation potential of 5% would require a threshold value of 0.564. On average, the climate impact is then mitigated by −11.4% and by a maximum of −17.2% for the most-efficient re-routing. In this case, a minimum charge of at least 0.35 \$/km must be levied for the entire route network in order to provide a financial incentive for mitigation on each route. This results in an averaged COC increase of +1.2%. With an assumed price elasticity of about −1.0, this would cause an additional ATR reduction of −1.04% due to a volume reduction of −1.2%. A climate-optimized routing results in an average reduction in climate impact per flight of more than −26% for a COC increase of about +8%. Transport volume reductions induced by extra costs would further mitigate the climate impact by −5.8%.
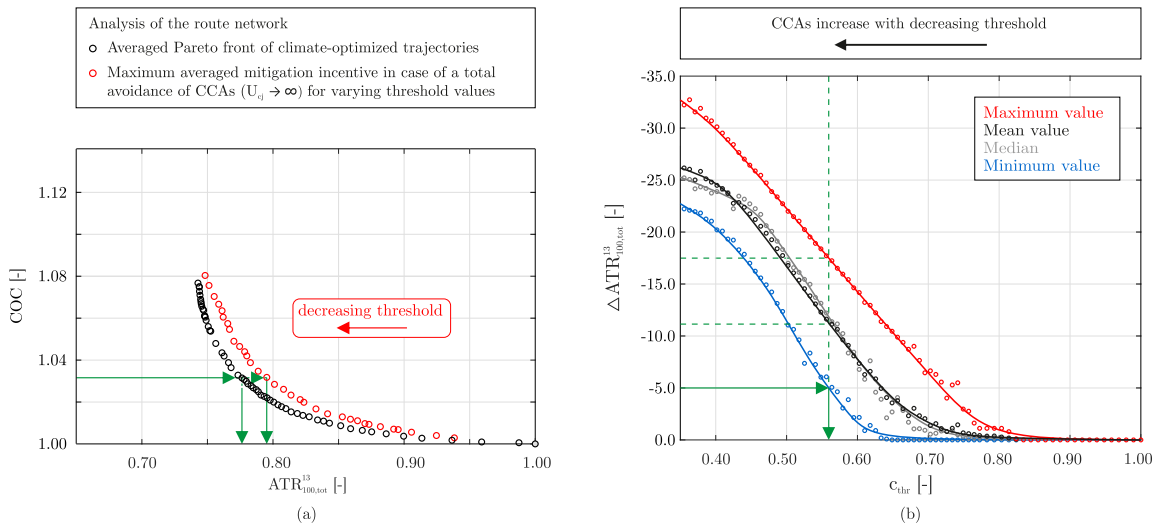


**Figure 10.** (a) Averaged mitigation potential of the route network for COTs (◯) and the CCA concept in case of a total avoidance of CCAs (◯). (b) CCA mitigation potential of the route network in dependence on the threshold value ($c_{\text{thr}}$).

## 5. Discussion

This study has presented the climate-charged airspace (CCA) concept with the aim to consider how to incentivize airlines to internalize their climate costs. The feasibility and effectiveness of CCAs have been demonstrated with trajectory simulations on a selected route network in the North-Atlantic flight corridor. The results of the study naturally depend on underlying assumptions, like the choice of the climate metric ($ATR_{100}$), the application of pre-calculated climate change functions (CCFs), the neglect of wind effects as well as inaccuracies in the aircraft performance model (BADA 4.0 Airbus A330-200), trajectory simulation (TOM), emission quantification (Eurocontrol modified Boeing Fuel Flow Method 2) and cash operating cost (COC) estimation (Liebeck). All calculated values of $ATR_{100}$, COC, mission fuel, mission time and emission levels are therefore normalized with respect to the corresponding values of the route specific minimum COC trajectory and benchmarked with those values of climate-optimized trajectories (theoretical optimum as reference), which are in broad agreement with previous studies.

Moreover, results are highly affected by the existing uncertainties regarding the contribution of different radiative forcing agents to the overall climate impact of aviation (see Figure 1). If individual climate agents are clearly over- or underestimated, this could cause significant deviations in the 4-D routing of COTs. In the worst case, the resulting increase in fuel consumption could lead to a further warming instead of the intended climate mitigation. For the purpose of avoiding misguided incentives for re-routing, we propose a stepwise implementation of the CCA concept. Initially, the CCA concept should be limited to those areas that are easily detectable and most likely highly climate sensitive. A tightening of the policy – *from cost-effective options to the climate-optimal solution* – is possible at any time.

Any influence of climate metrics (ATR, GWP or GTP) and time horizon (20, 50 or 100 years) on key parameters of the CCA concept – *in particular on the climate unit charge and the threshold* – must be analyzed in future studies. To increase the validity of the CCA concept, detailed analyses within a comprehensive route network have to be performed under consideration of wind effects.

Furthermore, the choice of data set used for climate impact modeling (weather forecast data vs. climatological mean data) highly influence the climate mitigation potential and the CCA charging period (hours or weeks). As weather-based CCFs provided by Grewe, Frömming, et al. (2014) cover only main parts of the North-Atlantic flight corridor without the neighboring countries (Canada, EU, USA), we decided to apply the climate-response model *AirClim* (Grewe & Stenke, 2008) for generating monthly CCFs for the entire globe. But monthly CCFs show significantly lower gradients than CCFs of individual weather situations. Climate-based CCAs are correspondingly smooth, especially for annual mean values. As a result, long transit distances immediately occur on trans-Atlantic routes (>6000 km) when flights pass through a charged area. Accordingly, operating costs increase rapidly. In previous work, we also analyzed seasonal influences on climate-cost-efficient routing and observed large fluctuations of the maximum reduction potential between summer (up to 50% in August) and winter months (up to 20% in February) (Niklaß et al., 2017). According to Lührs et al. (2018), who conducted a similar investigation on a North-Atlantic surrogate network for eight representative weather patterns (five representative days for winter and three days for summer), even higher variations (9–60%) of the maximum climate impact savings seem to be possible for individual days. But if on individual days mitigation potentials differ by a factor of up to six, we should concentrate all mitigation efforts on those days – *or even hours* – with the highest potential. This way, we can achieve a maximum reduction of climate impact at minimal increase of operating costs. Under the assumption that the airline industry will pass on all costs of internalization to their customers, prices of air services would increase at a lower rate.

Due to the increasing climate impact of non-$CO_2$ effects with altitude, CCAs will primarily be located at cruising altitudes. Arrivals and departures should therefore be less affected by the concept. Recognizing that there are regions of the world with higher climate sensitivity with respect to aircraft emission (see i.a. Grewe & Stenke, 2008) – *and thus higher social costs* – CCAs will be located more frequently there than in others regions. It is obvious that this might not always be in the interest of the corresponding nation.

In general, climate policy in aviation faces complex challenges, including the necessity to internalize the social costs of pollution without denying individuals access to international markets for travel. To provide policymakers with information to make a socially optimized decision, further studies have to compare the total

costs of the CCA concept with other options, including external costs of $CO_2$. There is also a need to explore to what extent the CCA concept fits with other measures, like existing market-based instruments or a shift to sustainable aviation fuels (SAFs). By using SAFs that follow the Jet A1 specification – *SAFs must be drop-in fuels that are equivalent in function and performance to fossil jet fuels* – $CO_2$ emissions can be cut significantly over the entire life cycle. Due to very little, if any, aromatics and no sulphur, SAFs might reduce particle number and mass emissions by 50–70% relative to conventional fuels (Moore et al., 2017). As a result, ice crystals from bio-jets are fewer but larger than crystals from kerosene under equal ambient conditions, lowering optical thickness, lifetimes and radiative forcing of contrails (Burkhardt et al., 2018; Gierens et al., 2016). Depending on the type, SAFs are currently certified by ASTM International as blends of up to 50%. But a 100% mixing is becoming a viable option for the whole family of SAFs (Holladay et al., 2020). The gradual introduction of SAFs could therefore reduce $CO_2$ emissions down to zero, while increasing more and more the importance of non-$CO_2$ effects, like $NO_x$ emissions. Resulting efficiency improvements on climate-optimized routings must be investigated in further studies.

## 6. Conclusions

The main goal of the study at hand is to identify and analyze options on how to internalize the climate impact of aviation. Due to the high sensitivity of non-$CO_2$ effects on the location and the timing of emissions, these effects can be effectively mitigated by changing the flight pattern, represented by a reduction of the general cruising altitude or an adjustment in routing. Although all of these changes result in slightly increased values of flight time, fuel burn and operating costs, they are significantly more climate compatible than current practices. First, we reviewed the literature on policy instruments for implementing climate-cost-efficient routing. When integrating non-$CO_2$ effects into existing market-based instruments (EU ETS, CORSIA, etc.), detailed weather- and route-dependent $^{eq}E_{CO_2}$ factors provide the highest incentives for climate mitigation. Since they raise open questions regarding the implementation of an effective and robust MRV system, we concentrated on designing flanking instruments for non-$CO_2$ effects. Based on the findings of atmospheric physics and environmental economics, the CCA concept is developed here to impose a temporary climate charge on airlines when operating in highly climate-sensitive areas.

With the implementation of the *polluter-pays principle* and the *precautionary principle* of environmental economics into the field of aviation, socio-economic costs of climate change are integrated into the accounting and decision-making process of aircraft operators. Accordingly, all affected flights are expected to be re-routed at the lowest possible cost around CCAs, which in turn mitigates the climate impact of the flight. In this way, the trade-off between economic viability and environmental compatibility is resolved and a financial incentive for climate protection is created. Climate impact mitigation thus coincides with cutting costs, climate-cost-efficient routing becomes economically attractive.

The feasibility and effectiveness of the concept has been demonstrated here with trajectory simulations on a selected North-Atlantic route network relative to the potential of climate-cost-efficient routing (benchmark). For CCAs, a financial incentive for climate mitigation is identified that achieves on average more than 90% of the climate impact reduction potential of COTs (theoretical maximum). The idea of avoiding only the most climate-sensitive regions is therefore an extremely effective mitigation approach. The key parameters of the concept are threshold value ($c_{thr}$), defining size and location of CCAs, and the climate unit charge ($U_{cj}$). As demonstrated, an optimal set of these parameters can be found for the entire route network to create a monetary incentive on each route for a targeted mitigation potential.

In order to ensure easy planning and verification, climate charges are calculated analogously to en-route and terminal charges. For climate mitigation, it is therefore neither necessary to monitor $CO_2$ and $NO_x$ emissions nor to integrate complex non-$CO_2$ effects into flight planning procedures of airlines. Instead, aircraft operators can continue to operate in a purely cost-optimized manner. The practicability of our cost-driven re-routing approach exemplifies the operational behavior of airlines on trans-European journeys, which took particularly large detours in the years with comparatively low fuel prices and re-routed their flights over countries with lower air traffic control charges to reduce operating costs.

This study demonstrates clearly for the very first time that a climate impact mitigation of non-$CO_2$ effects can coincide with cutting costs. The introduction of climate-charged airspaces might boost climate-cost-efficient routing and its implementation is feasible and effective.

In future work, we will further investigate interactions between the CCA concept and the air transport system. The trajectory simulation will consider social costs, wind effects, as well as existing uncertainties regarding (i) climate modeling of individual agents and (ii) weather forecast. The additional effort of the concept has to be analyzedboth for operators (planning, execution and reporting) and regulatory authorities (verification) in comparison to other options. There is also a need to understand the possible competitive disadvantages for local airlines when implementing the CCA concept at a national level as well as the implications of choosing a climate metric.

## Abbreviations

The following abbreviations are used in this article:

| | |
|---|---|
| ATC | Air Traffic Control |
| ATR | Average Temperature Response |
| BAU | Business As Usual |
| CCA | Climate-Charged Airspace |
| CC | Contrail Cirrus |
| CCF | Climate Change Function |
| COC | Cash Operating Cost |
| COT | Climate-Optimized Trajectory |
| CORSIA | Carbon Offsetting and Reduction Scheme for International Aviation |
| ETS | Emissions Trading System |
| GTP | Global Temperature Potential |
| GWP | Global Warming Potential |
| ISSR | Ice Supersaturated Region |
| MRV | Monitoring, Reporting and Verification |
| NWP | Numerical Weather prediction |
| RF | Radiative Forcing |
| SAF | Sustainable Aviation Fuel |
| TOM | Trajectory Optimization Module |

## Acknowledgements

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## ORCID

*Malte Niklaß* 🆔 http://orcid.org/0000-0001-6760-8561
*Volker Grewe* 🆔 http://orcid.org/0000-0002-8012-6783
*Volker Gollnick* 🆔 http://orcid.org/0000-0001-7214-0828
*Katrin Dahlmann* 🆔 http://orcid.org/0000-0003-3198-1713

## References

Airbus (2019). *Global market forecast. Cities, airports & aircraft 2019–2038*. ISBN:978-2-9554382-4-6.

Avila, D., Sherry, L., & Thompson, T. (2019). Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous United States. *Transportation Research Interdisciplinary Perspectives*, *2*, Article ID 100033. https://doi.org/10.1016/j.trip.2019.100033

Bock, L., & Burkhardt, U. (2016). Reassessing properties and radiative forcing of contrail cirrus using a climate model. *Journal of Geophysical Research*, *121*(16), 9717–9736. https://doi.org/10.1002/2016JD025112.

Brasseur, G. P., Gupta, M., Anderson, B. E., Balasubramanian, S., Barrett, S., Duda, D., Fleming, G., Forster, P. M., Fuglestvedt, J., Gettelman, A., R. N. Halthore, Jacob, S. D., Jacobson, M. Z., Khodayari, A., Liou, K.-N., M. T. Lund, Miake-Lye, R. C., Minnis, P., Olsen, S., …Zhou, C. (2016). Impact of aviation on climate: FAA's aviation climate change research initiative (ACCRI) phase ii. *Bulletin of the American Meteorological Society*, *97*(4), 561–583. https://doi.org/10.1175/BAMS-D-13-00089.1.

Burkhardt, U., Bock, L., & Bier, A. (2018). Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. *npj Climate and Atmospheric Science*, *1*(1). https://doi.org/10.1038/s41612-018-0046-4.

Burkhardt, U., & Kärcher, B. (2011). Global radiative forcing from contrail cirrus. *Nature Climate Change*, *1*(1), 54–58. https://doi.org/10.1038/nclimate1068

Chen, N., Kirschen, P., Sridhar, B., & Ng, H. (2014). Identification of flights for cost-efficient climate impact reduction. In *AIAA aviation*. https://doi.org/10.2514/6.2014-3016

Dahlmann, K., Koch, A., Linke, F., Lührs, B., Grewe, V., Otten, T., Seider, D., Gollnick, V., & Schumann, U. (2016). Climate-compatible air transport system – climate impact mitigation potential for actual and future Aircraft. *Aerospace*, *3*(4). https://doi.org/10.3390/aerospace3040038.

Delgado, L. (2015). European route choice determinants: Examining fuel and route charge tradeoffs. In *11th ATM seminar*.

DuBois, D., & Paynter, G. (2014). *'Fuel flow method 2' for estimating aircraft emissions* (SAE Technical Paper 2006-01-1987). Society of Automotive Engineers (SAE).

Ehlers, T., Niklaß, M., Lau, A., Linke, F., & Lütjens, K. (2020). *On the impact of charging zones in the European airspace on routing*. Proceedings of the AIAA aviation conference. American Institute of Aeronautics and Astronautics. https://doi.org/10.2514/6.2020-2895

Eurocontrol (2016). Why variations in navigation charges can influence traffic pattern. *Skyway Magazine*, *65*, 31–36.

European Environment Agency (2019). *Annual European Union greenhouse gas inventory 1990–2017 and inventory report 2019* (EEA/PUBL/2019/051). Submission under the United Nations Framework Convention on Climate Change and the Kyoto Protocol.

European Union (2009a). *Directive 2008/101/EC of the European parliament and the council of 19 November 2008 amending directive 2003/87/EC so as to include aviation activities in the scheme for greenhouse gas emission allowance trading within the Community*. Official Journal of the European Union, L 8/3, Brussels, 13 January 2009.

European Union (2009b). *Directive 2009/29/EC of the European parliament and of the council amending directive 2003/87/EC so as to improve and extend the greenhouse gas emission allowance trading system of the community*. Official Journal of the European Union, Brussels, 5 June 2009.

Faber, J., Greenwood, D., Lee, D., Mann, M., de Leon, P. M., Nelissen, D., Owen, B., Ralph, M., Tilston, J., van Velzen, A., & van de Vreede, G. (2008). *Lower NO$_x$ at higher altitudes. Policies to reduce the climate impact of aviation NO$_x$ emission*. CE Delft.

Forster, P. M., Shine, K. P., & Stuber, N. (2006). It is premature to include non-CO$_2$ effects of aviation in emission trading schemes. *Atmospheric Environment*, *40*(6), 1117–1121. https://doi.org/10.1016/j.atmosenv.2005.11.005

Frömming, C., Grewe, V., Brinkop, S., Jöckel, P., Haslerud, A. S., Rosanka, S., van Manen, J., & Matthes, S. (2021). Influence of the actual weather situation on non-CO2 aviation climate effects: The REACT4C climate change functions. *Atmospheric Chemistry and Physics*, *21*(11), 9151–9172. https://doi.org/10.5194/acp-21-9151-2021

Frömming, C., Ponater, M., Dahlmann, K., Grewe, V., Lee, D. S., & Sausen, R. (2012). Aviation-induced radiative forcing and surface temperature change in dependency of the emission altitude. *Journal of Geophysical Research*, *117*(D19). https://doi.org/10.1029/2012JD018204.

Fuglestvedt, J. S., Shine, K. P., Berntsen, T., Cook, J., Lee, D. S., Stenke, A., Skeie, R. B., Velders, G. J. M., & Waitz, I. A. (2010). Transport impacts on atmosphere and climate: Metrics. *Atmospheric Environment*, *44*(37), 4648–4677. https://doi.org/10.1016/j.atmosenv.2009.04.044

Gierens, K., Braun-Unkhoff, M., Le Clercq, H., Plohr, M., Schlager, H., & Wolters, F. (2016). *Condensation trails from biofuels/kerosene blends scoping study* (ENER/C2/2013-627). European Commission.

Grewe, V. (2020). Aviation emissions and climate impacts. In *Aviation and climate change*. Taylor and Francis Group. ISBN:9781472479174.

Grewe, V., Champougny, T., Matthes, S., Frömming, C., Brinkop, V., Søvde, O., Irvine, E. A., & Halscheidt, L. (2014). Reduction of the air traffic's contribution to climate change: A REACT4C case study. *Atmospheric Environment*, *94*(1), 616–625. https://doi.org/10.1016/j.atmosenv.2014.05.059

Grewe, V., & Dahlmann, K. (2015). How ambiguous are climate metrics? And are we prepared to assess and compare the climate impact of new air traffic technologies? *Atmospheric Environment*, *106*(1), 373–374. https://doi.org/10.1016/j.atmosenv.2015.02.039

Grewe, V., Dahlmann, K., Flink, J., Frömming, C., Ghosh, R., Gierens, K., Heller, R., Hendricks, J., Jöckel, P., Kaufmann, S., Kölker, K., Linke, F., Luchkova, T., Lührs, B., van Manen, J., Matthes, S., Minikin, A., Niklaß, M., Plohr, M., …Ziereis, H. (2017). Mitigating the climate impact from aviation: Achievements and results of the DLR wecare project. *Aerospace*, *44*(3), 1–50. https://doi.org/10.3390/aerospace4030034

Grewe, V., Dameris, M., Fichter, C., & Lee, D. S. (2002). Impact of aircraft nox emissions. Part 2: Effects of lowering the flight altitude. *Meteorologische Zeitschrift*, *11*(3), 197–205. https://doi.org/10.1127/0941-2948/2002/0011-0197.

Grewe, V., Frömming, C., Matthes, S., Brinkop, V., Ponater, M., Dietmüller, S., Jöckel, P., Garny, H., Tsati, E., Dahlmann, K., Søvde, O. A., Fuglestvedt, J., Berntsen, T. K., Shine, K. P., Irvine, E. A., Champougny, T., & Hullah, P. (2014). Aircraft routing with minimal climate impact: The REACT4C cost function modeling approach. *Geoscientific Model Development*, 7(1), 175–201. https://doi.org/10.5194/gmd-7-175-2014

Grewe, V., Matthes, S., & Dahlmann, K. (2019). The contribution of aviation NOx emissions to climate change: are we ignoring methodological flaws? *Environmental Research Letters*, 14(12). https://doi.org/10.1088/1748-9326/ab5dd7

Grewe, V., Matthes, S., Frömming, C., Brinkop, S., Jöckel, P., Gierens, K., Champougny, T., Fuglestvedt, J., Haslerud, A., & Irvine, E. (2017). Feasibility of climate-optimized air traffic routing for trans-atlantic flights. *Environmental Research Letters*, 12(3). https://doi.org/10.1088/1748-9326/aa5ba0

Grewe, V., & Stenke, A. (2008). AirClim: an efficient tool for climate evaluation of aircraft technology. *Atmospheric Chemistry and Physics*, 8(16), 4621–4639. https://doi.org/10.5194/acp-8-4621-2008

Hartjes, S., Hendriks, T., & Visser, H. G. (2016). Contrail mitigation through 3D aircraft trajectory optimization. In *AIAA aviation*. https://doi.org/10.2514/6.2016-3908

Henderson, S. C., & Wickrama, U. K. (1999). Aircraft emissions: Current inventories and future scenarios. J. Penner, D. Lister, D. Griggs, D. Dokken, & M. McFarland (Eds.), *Aviation and the global atmosphere. A special report of IPCC working groups I and III* (pp. 185–215). Cambridge University Press.

Holladay, J., Abdullah, Z., & Heyne, J. (2020). *Sustainable aviation fuel: Review of technical pathways report* (DOE/EE-2041). US Department of Energy Efficiency & Renewable Energy.

Hoor, P., Borken-Kleefeld, J., Caro, D., Dessens, O., Endresen, O., Gauss, M., Grewe, V., Hauglustaine, D., Isaksen, I. S. A., Jöckel, P., Lelieveld, J., Myhre, G., Meijer, E., Olivie, D., Prather, M., C. Schnadt Poberaj, Shine, K. P., Staehelin, J., Tang, Q., …Sausen, R. (2009). The impact of traffic emissions on atmospheric ozone and OH: Results from QUANTIFY. *Atmospheric Chemistry and Physics*, 9(9), 3113–3136. https://doi.org/10.5194/acp-9-3113-2009

Houghton, J. T., Ding, Y., Griggs, D. J., Noguer, M., van der Linden, P. J., Dai, X., Maskell, K., & Johnson, C. A. (2001). Climate change 2001: The scientific basis. In *Contribution of working group i to the third assessment report of the intergovernmental panel on climate change, scientific basis* (p. 63). Cambridge University Press.

International Civil Aviation Organization (1993). *ICAO resolution* (Document 8632). www.icao.int

International Civil Aviation Organization (2016, October). *Resolution A39-3: Consolidated statement of continuing ICAO policies and practices related to environmental protection*. Global Market-based Measure (MBM) scheme.

International Monetary Fund (2014). World Economic Outlook Database, October 2014.

Irvine, E. A., Hoskins, B. J., & Shine, K. P. (2014). A simple framework for assessing the tradeoff between the climate impact of aviation carbon dioxide emissions and contrails for a single flight. *Environmental Research Letters*, 9(6), 1–6. http://doi.org/10.1088/1748-9326/9/6/064021

Jelinek, F., Carlier, S., & Smith, J. (2004). *Advanced emission model (AEM3) v1.5 – validation report* (EEC/SEE/2004/004). EEC Report.

Jungbluth, N., & Meili, C. (2019). Recommendations for calculation of the global warming potential of aviation including the radiative forcing index. *The International Journal of Life Cycle Assessment*, 24(3), 404–411. https://doi.org/10.1007/s11367-018-1556-3

Kharina, A., & Rutherford, D. (2015). *Fuel efficiency trends for new commercial jet aircraft: 1960 to 2014*. White paper of the International Council on Clean Transportation (ICCT).

Köhler, M. O., Rädel, G., Dessens, O., Shine, K. P., Rogers, H. L., Wild, O., & Pyle, J. A. (2008). Impact of perturbations to nitrogen oxide emissions from global aviation. *Journal of Geophysical Research*, 113(D11). https://doi.org/10.1029/2007JD009140

Köhler, M. O., Rädel, G., Shine, K. P., Rogers, H. L., & Pyle, J. A. (2013). Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics. *Atmospheric Environment*, 64(1), 1–9. https://doi.org/10.1016/j.atmosenv.2012.09.013.

Larsson, J., Elofsson, A., Sterner, T., & Akerman, J. (2019). International and national climate policies for aviation: a review. *Climate Policy*, 19(6), 787–799. https://doi.org/10.1080/14693062.2018.1562871

Lee, D. S., Fahey, D., Forster, P., Newton, P., Wit, R., Lim, L. L., Owen, B., & Sausen, R. (2009). Aviation and global climate change in the 21st century. *Atmospheric Environment*, 43(22), 3520–3537. https://doi.org/10.1016/j.atmosenv.2009.04.024.

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S. J., Freeman, S., Forster, P. M., Fuglestvedt, J., Gettelman, A., De León, R. R., Lim, L. L., Lund, M. T., Millar, R. J., Owen, B., Penner, J. E., Pitari, G., Prather, M. J., …Wilcox, L. J. (2020). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment*, 244(1), 1352–2310. https://doi.org/10.1016/j.atmosenv.2020.117834.

Lee, D. S., Pitari, G., Grewe, V., Gierens, K., Penner, J. E., Petzold, A., Prather, M. J., Schumann, U., Bais, A., Berntsen, T., Iachetti, D., Lim, L. L., & Sausen, R. (2010). Transport impacts on atmosphere and climate: Aviation. *Atmospheric Environment*, 44(37), 4678–4734. https://doi.org/10.1016/j.atmosenv.2009.06.005.

Liebeck, R. (1995). *Advanced subsonic airplane design and economic studies* (NASA CR-195443).

Lührs, B., Linke, F., Matthes, S., Grewe, V., Yin, F., & Shine, K. P. (2020). Climate impact mitigation potential of European air traffic. In *3rd ECATS conference* 1.

Lührs, B., Niklaß, M., Frömming, C., Grewe, V., & Gollnick, V. (2016). Cost-benefit assessment of 2D- and 3D climate and weather optimized trajectories. In *16th AIAA aviation*. https://doi.org/10.2514/6.2016-3758

Lührs, B., Niklaß, M., Frömming, C., Grewe, V., & Gollnick, V. (2018). Cost-benefit assessment of climate and weather optimized trajectories for different North-Atlantic weather patterns. In *31st ICAS*.

Matthes, S., Grewe, V., Dahlmann, K., Frömming, C., Irvine, E., Lim, L., Linke, F., Lührs, B., Owen, B., Shine, K., Stromatas, S., Yamashita, H., & Yin, F. (2017). A concept for multi-criteria environmental assessment of aircraft trajectories. *Aerospace*, *4*(3). https://doi.org/10.3390/aerospace4030042

Matthes, S., Lührs, B., Dahlmann, K., Linke, F., Grewe, V., Yin, F., & Shine, K. P. (2020). Climate-Optimized trajectories and robust mitigation potential: Flying ATM4E. *Aerospace*, *7*(11). https://doi.org/10.3390/aerospace7110156

Meerkötter, R., Schumann, U., Doelling, D., Minnis, P., Nakajima, T., & Tsushima, Y. (1999). Radiative forcing by contrails. *Annales Geophysicae*, *17*(8), 1080–1094. https://doi.org/10.1007/s00585-999-1080-7

Moore, R. H., Thornhill, K. L., Weinzierl, B., Sauer, D., D'Ascoli, E., Kim, J., Lichtenstern, M., Scheibe, M., Beaton, B., Beyersdorf, A. J., Barrick, J., Bulzan, D., Corr, C. A., Crosbie, E., Jurkat, T., Martin, R., Riddick, D., Shook, M., Slover, G., … Anderson, B. E. (2017). Biofuel blending reduces particle emissions from aircraft engines at cruise conditions. *Nature*, *543*(7645), 411–415. https://doi.org/10.1038/nature21420.

Myhre, G., & Stordal, F. (2001). Global sensitivity experiments of the radiative forcing due to mineral aerosols. *Journal of Geophysical Research*, *106*(D16), 18193–18204. https://doi.org/10.1029/2000JD900536

Niklaß, M. (2019). *Ein systemanalytischer Ansatz zur Internalisierung der Klimawirkung der Luftfahrt* [Phd thesis, University of Technology Hamburg, DLR-Forschungsbericht 2019–06].

Niklaß, M., Dahlmann, K., Grewe, V., Maertens, S., Plohr, H., Scheelhaase, M., Schwieger, J., Brodmann, U., Kurzböck, C., Repmann, M., Schweizer, N., & von Unger, M. (2020, July). *Integration of non-CO2 effects of aviation in the EU ETS and under CORSIA. Climate Change: 20/2020*, Umweltbundesamt. FKZ:3717-42-509-0.

Niklaß, M., Lührs, B., Dahlmann, K., Frömming, C., Grewe, V., & Gollnick, V. (2017). Cost-benefit assessment of climate-restricted air-spaces as an interim climate mitigation option. *Journal of Air Transportation*, *25*(2), 27–38. https://doi.org/10.2514/1.D0045

Niklaß, M., Lührs, B., Grewe, V., Dahlmann, K., Luchkova, T., Linke, F., & Gollnick, V. (2019). Potential to reduce the climate impact of aviation by climate restricted airspaces. *Transport Policy*, *83*(1), 102–10. https://doi.org/10.1016/j.tranpol.2016.12.010.

Niklaß, M., Lührs, B., Grewe, V., & Gollnick, V. (2018). Implementation of eco-efficient procedures to mitigate the climate impact of non-CO$_2$ effects. In *31st ICAS congress*.

Nordhaus, W. D. (1982). How fast should we graze the global commons? *American Economic Review*, *72*(2), 242–246.

Nuic, A., & Mouillet, V. (2012). *User manual for the base of aircraft data (BADA) family 4* (ECC Technical/Scientific Report No. 12/11/22-58).

Ponater, M., & Bickel, M. (2020). Towards determining the efficacy of contrail cirrus. In *3rd ECATS conference*, 1.

Rädel, G., & Shine, K. P. (2010). Validating ECMWF forecasts for the occurrence of ice supersaturation using visual observations of persistent contrails and radiosonde measurements over England. *Quarterly Journal of the Royal Meteorological Society. Royal Meteorological Society (Great Britain)*, *136*(652), 1723–1732. https://doi.org/10.1002/qj.v136:652

Rosenow, J., & Fricke, H. (2019). Individual condensation trails in Aircraft trajectory optimization. *Sustainability*, *11*(21). https://doi.org/10.3390/su11216082

Scheelhaase, J., Dahlmann, K., Jung, M., Keimel, H., Nieße, H., Sausen, R., Schaefer, M., & Wolters, F. (2016). How to best address avia-tion's full climate impact from an economic policy point of view? – Main results from AviClim research project. *Transportation Research Part D: Transport and Environment*, *45*(1), 112–125. https://doi.org/10.1016/j.trd.2015.09.002.

Schumann, U., & Graf, K. (2013). Aviation-induced cirrus and radiation changes at diurnal timescales. *Journal of Geophysical Research*, *118*(5), 2404–2421. https://doi.org/10.1002/jgrd.50184.

Schumann, U., Penner, J. E., Chen, Y., Zhou, C., & Graf, K. (2015). Dehydration effects from contrails in a coupled contrail-climate model. *Atmospheric Chemistry and Physics*, *15*(19), 11179–11199. https://doi.org/10.5194/acp-15-11179-2015.

Soler, M., Zou, B., & Hansen, M. (2014). Flight trajectory design in the presence of contrails: Application of a multiphase mixed-integer optimal control approach. *Transportation Research Part C: Emerging Technologies*, *48*(1), 172–194. https://doi.org/10.1016/j.trc.2014.08.009.

Søvde, O. A., Matthes, S., Skowron, A., Iachetti, D., Lim, L., Owen, B., Hodnebrog, O., Genova, G. D., Pitari, G., Lee, D. S., Myhre, G., & Isaksen, I. S. A., 2014). Aircraft emission mitigation by changing route altitude: A multi-model estimate of aircraft NO$_x$ emission impact on O$_3$ photochemistry. *Atmospheric Environment*, *44*(37), 468–479. https://doi.org/10.1016/j.atmosenv.2014.06.0495

Spichtinger, P., Gierens, K., Leiterer, U., & Dier, H. (2003). Ice supersaturation in the tropopause region over Lindenberg, Germany. *Meteorologische Zeitschrift*, *12*(3), 143–156. https://doi.org/10.1127/0941-2948/2003/0012-0143

Sridhar, B., Chen, N. Y., Linke, F., & Ng, H. K. (2010). Design of aircraft trajectories based on trade-offs between emission sources. In *9th ATM seminar*.

Stevenson, D., & Derwent, R. (2009). Does the location of aircraft nitrogen oxide emissions affect their climate impact? *Geophysical Research Letters*, *36*(17). https://doi.org/10.1029/2009GL039422

Teoh, R., Schumann, U., Majumdar, A., & Settler, M. E. J. (2020). Mitigating the climate forcing of Aircraft contrails by small-scale diver-sions and technology adoption. *Environmental Science & Technology*, *54*(5), 2941–2950. https://doi.org/10.1021/acs.est.9b05608

United Nation (1992, June 3–14). *Report of the United Nations conference on environment and development*.

Voigt, C., Schumann, U., Jeßberger, P., Jurkat, T., Petzold, A., Gayet, J. F., Krämer, M., Thornberry, T., & Fahey, D. W. (2011). Extinction and optical depth of contrails. *Geophysical Research Letters*, *38*(11). https://doi.org/10.1029/2011GL047189.

Williams, V., Noland, R. B., & Toumi, R. (2002). Reducing the climate change impacts of aviation by restricting cruise altitudes. *Transportation Research Part D: Transport and Environment*, *7*(6), 451–464. https://doi.org/10.1016/S1361-9209(02)00013-5.

Williams, V., Noland, R. B., & Toumi, R. (2003). Air transport cruise altitude restrictions to minimize contrail formation. *Climate Policy*, *3*(3), 207–219. https://doi.org/10.3763/cpol.2003.0328.

Wit, R. C. N., Kampman, B., & Boon, B. (2004, October). *Climate impacts from international aviation and shipping* (4.4772.44/e). CE Delft.

Yamashita, H., Grewe, V., Jöckel, P., Linke, F., Schaefer, M., & Sasaki, D. (2016). Air traffic simulation in chemistry-climate model EMAC 2.41: AirTraf 1.0. *Geoscientific Model Development*, *9*(9), 3363–3392. https://doi.org/10.5194/gmd-9-3363-2016.

Yamashita, H., Yin, F., Grewe, V., Jöckel, P., Sigrun, M., Kern, B., Dahlmann, K., & Frömming, C. (2019). Various aircraft routing options for air traffic simulation in the chemistry-climate model EMAC 2.53: AirTraf 2.0. *Geoscientific Model Development*, Preprint. https://doi.org/10.5194/gmd-2019-331

Yin, F., Grewe, V., Frömming, C., & Hiroshi, Y. (2018). 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. https://doi.org/10.1016/j.trd.2018.09.017

Zou, B., Gurkaran, S. B., & Hansen, M. (2016). Optimal 4-D Aircraft trajectories in a contrail-sensitive environment. *Networks and Spatial Economics*, *16*(1), 415–446. https://doi.org/10.1007/s11067-013-9210-x.