IMPLEMENTATION OF ECO-EFFICIENT PROCEDURES TO MITIGATE THE CLIMATE IMPACT OF NON-CO_2 EFFECTS

Malte Niklaß[1], Benjamin Lührs[2], Volker Grewe[3,4], Volker Gollnick[1,2]
[1]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Lufttransportsysteme,
[2]Technische Universität Hamburg (TUHH), Institut für Lufttransportsysteme,
[3]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für Physik der Atmosphäre,
[4]Delft University of Technology (TU Delft), Section Aircraft Noise & Climate Effects

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Abstract

Within this study, the lack of incentivizing airlines to internalize their climate costs is tried to be closed by the introduction of climate-charged airspaces, as non-CO_2 emissions have location- and time-dependent effects upon the climate. In order to create an incentive for airlines to minimize flight time and emissions in highly climate-sensitive regions, a climate charge is imposed for airlines when operating in these areas. Cost-minimizing airlines are expected to re-route their flights to reduce their climate charges and hence cash operating costs. Accordingly, this leads to the desired outcome of incentivizing climate mitigation and even of driving technological innovation towards cleaner technologies.
The evaluation of the climate impact mitigation potential of climate-charged airspaces is performed based on optimal control techniques. Climate sensitivities are expressed by climate change functions characterizing the climate impact caused by an emission at a certain location and time. The cost-benefit potential (climate impact mitigation vs. rise in operating costs) is investigated for a Transatlantic route and benchmarked against climate-optimized trajectories.

1 Introduction

Inter-dependencies between aircraft emission and climate impact are complex and highly non-linear. Approximately two-thirds of aviation-induced global warming is expected to be caused by non-CO_2 climate effects like the formation of contrail induced cloudiness (CiC) and the enhanced ozone (O_3) production triggered by NO_x emissions, which are highly sensitive to chemical and meteorological background conditions. Consequently, non-CO_2 climate responses depend strongly on emission location and time [1, 2]. Environmental policy making should therefore change the focus on climate impact mitigation instead of emission reduction only.

However, climate impact mitigation has a special difficulty from an environmental economics point of view, since it is highly susceptible to the free-riding problem: consequences of climate change are long-lasting and widely spread around the globe. Polluters benefit of the *non-excludability* and partially of the *non-rivalry* character of environmental goods, even if they are not willing to contribute to the costs to prevent environmental degradation adequately.

The study at hand is focusing on the question how to include aviation's climate impact of non-CO_2 effects adequately into an environmental policy measure.

2 Concept of Climate-Charged Airspaces

To create an incentive for airlines to minimize flight time and emissions in highly climate-sensitive regions, we impose a climate charge for operators of aircraft that fly in these areas (see figure 1). Within the concept of climate-charged airspaces (CCA) [4, 5], an airspace j is levied with an climate unit charge U_{cj} per kilometer flown, d_j, if its climate sensitivity with respect to aircraft emissions[1] exceeds a specific threshold value (c_{thr}) (compare figure 1a,b):

$$\text{CCA}_j(\mathbf{x}) = \begin{cases} U_{cj}, & \text{if } \text{CCF}_{\text{tot}}(\mathbf{x}) \geq c_{\text{thr}} \\ 0, & \text{if } \text{CCF}_{\text{tot}}(\mathbf{x}) < c_{\text{thr}} \end{cases} \quad (1)$$

Thus, cost-minimizing airlines will re-route their flights to reduce both the climate charges and their cash operating costs (Trajectory 3 in fig. 1). In this manner, climate impact mitigation coincides with the cutting of costs.

As CCA could be defined and monitored by air traffic control, complex climate-change functions do not need to be integrated into the responsibility of an airline and their planning processes to mitigate non-CO_2 effects on climate.

Climate charges, C_{cj}, are expressed for a flight through an climate-charged area j in analogy to en-route and terminal charges (see Eq. 10 and Eq. 11 in Sec. 3.1):

$$C_{cj} = U_{cj} \cdot \left(\frac{m_{\text{TOW}}}{k_1}\right)^{k_2} \cdot I_{ac} \cdot d_j \quad (2)$$

where m_{TOW} is the maximum take-off weight of an aircraft, d_j is the distance traveled in CCA_j (in km), $I_{ac} \in [0,1]$ is an incentive factor for climate-friendly technologies and k_1, k_2 are country-specific parameters.

The operator of an aircraft can thus decide individually for each flight according to personal needs whether to minimize flight time and to pay compensation for higher climate damage (Trajectory 1 in fig. 1) or to minimize costs and, concurrently, reducing the climate impact by total or partial avoidance of CCA.

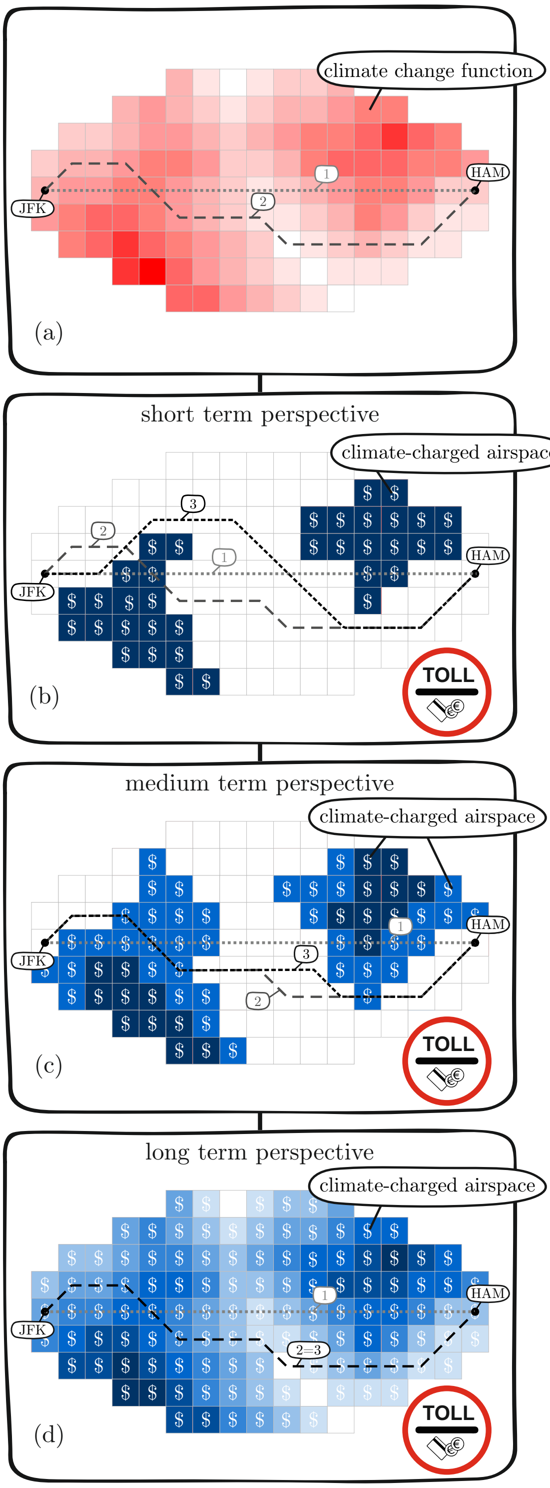

Fig. 1 Concept of climate-charged airspaces (CCA): creating a financial incentive for airlines to minimize flight time and emissions in highly climate-sensitive regions: (1) time-optimized, (2) climate-optimized trajectory and (3) cost-optimized trajectory within the CCA concept [4]

[1] The climate sensitivity of an area is expressed here by total climate change functions (CCF_{tot}) characterizing the environmental impact caused by non-CO_2 effects of aircraft's emissions at a certain location and time. [3]

By linking C_{cj} with the climate-friendly technology factor I_{ac} also a technological incentive for airlines is generated to invest in new climate-friendly aircraft technologies:

$$I_{ac} = \begin{cases} 1 & \text{for current technology level} \\ \vdots & \text{for more climate-friendly aircraft technology levels} \\ 0 & \text{for zero-emission aircraft} \end{cases} \quad (3)$$

To enable a timely introduction without neglecting the existing uncertainties in climate research, CCAs are introduced in the short term only in those areas which are very likely highly sensitive to climate (see fig. 1b). With increasing scientific understanding, the CCA concept can be extended incrementally by introducing various climate unit charges U_{cj} for regions j with different climate sensitivity (see fig. 1c) and/or by taking further trace substances, such as aerosols, into consideration. In the final expansion phase (fig. 1d), climate-friendly flying (Traj. 2) becomes cost-optimal (Traj. 3) [4, 5]:

$$\mathrm{COC}(\text{climate-optimal flying}) \stackrel{!}{=} \mathrm{COC}(\text{cost-optimal flying}) \quad (4)$$

3 Modeling Approach

Within this study, the cost-benefit potential of the CCA concept is evaluated and benchmarked against the mitigation potential of climate optimized trajectories (COT). Therefore, optimized aircraft trajectories are determined by employing optimal control techniques within the *Trajectory Optimization Module (TOM)* [6].

TOM minimizes a cost functional $\mathcal{J}$ while satisfying dynamic constraints as well as state (i.e. maximum speed), control (i.e. thrust limit) and path limitations (i.e. max pressure altitude):

$$\begin{aligned} \mathcal{J}(t,\mathbf{x}(t),\mathbf{u}(t)) &= c_\Psi \cdot \int_{t_0}^{t_f} \Psi(\mathbf{x}(t),\mathbf{u}(t),t)\, \mathrm{d}t \\ &+ c_\Upsilon \cdot \Upsilon\left(t_0,t_f,\mathbf{x}(t_0),\mathbf{x}(t_f)\right) \end{aligned} \quad (5)$$

where a vector of state variables $\mathbf{x}(t)$ is describing the motion of an aircraft and $\mathbf{u}(t)$ is defining the control variables (i.e. thrust). Aircraft performance are obtained with BADA 4.2 performance models [7], and emissions are estimated using the Eurocontrol modified Boeing Fuel Flow Method 2 [8, 9]. Penalty functions Ψ and Υ are weighted by corresponding scaling factors c_Ψ, c_Υ:

$$c_\Upsilon + c_\Psi = 1 \quad \text{with } c_\Upsilon, c_\Psi \in [0,1] \quad (6)$$

3.1 Calculation of optimized trajectories with respect to climate and economy

For calculating optimized trajectories with respect to climate and economy, monetary costs (COC) and climate change functions (CCF) are integrated into TOM's cost functional $\mathcal{J}$ according to equation 7:

$$\begin{aligned} \mathcal{J}_{\mathrm{COT}} = \; & c_\Upsilon \cdot \mathrm{COC}\left(t_f - t_0, m_0 - m_f\right) + \\ & c_\Psi \cdot \left(\sum_i \int_{t_0}^{t_f} \mathrm{CCF}_i(\mathbf{x}) \cdot \dot{m}_i(t)\, \mathrm{d}t \right. + \\ & \left. \int_{t_0}^{t_f} \mathrm{CCF}_{\mathrm{CiC}}(\mathbf{x}) \cdot v_{\mathrm{TAS}}(t)\, \mathrm{d}t \right) \end{aligned} \quad (7)$$

where $i \in \{CO_2, H_2O, NO_x\}$. The Pareto optimal set is found by varying the weights (c_Υ, c_Ψ) of monetary and climate 'costs'. Trajectories are optimal with regard to (i) COC for $c_\Upsilon = 1$ and (ii) climate for $c_\Psi = 1$.

3.1.1 Climate change functions

$\mathrm{CCF}_i(\mathbf{x})$ are expressed as average temperature response over 100 years (ATR_{100}) and calculated individually for CO_2, H_2O, NO_x (ATR_{100} per unit emission), and CiC (ATR_{100} per flown unit distance) by Niklaß et al. (2017) [18]. $\mathrm{CCF}_i(\mathbf{x})$ are superposed to total climate change functions $\mathrm{CCF}_{\mathrm{tot}}(\mathbf{x})$ according to Eq. 8:

$$\mathrm{CCF}_{\mathrm{tot}}(\mathbf{x}) = \sum_i \mathrm{CCF}_i(\mathbf{x}) \quad (8)$$

3.1.2 Monetary cost functions

Cash operating costs (COC) are calculated as function of mission time $(t_f - t_0)$ and mission fuel $(m_0 - m_f)$ according to equation 9:

$$\mathrm{COC} = C_f + C_c + C_m + C_{ei} + C_{ti} \quad (9)$$

Fuel costs, C_f, are derived by multiplying the unit cost per fuel, U_f [\$/kg], with the mission fuel $(m_0 - m_f)$. Costs for crew, C_c, are the product of unit crew costs, U_c [\$/h], and flight time

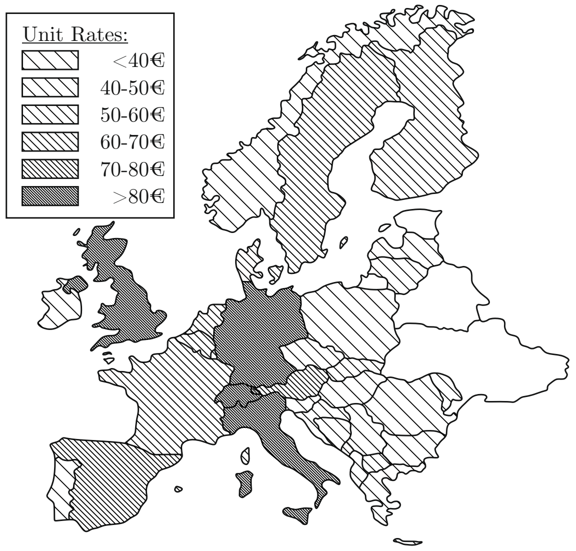

Fig. 2 En-route unit rates (U_{ei}) over Europe applicable from 01/01/2016 [13]

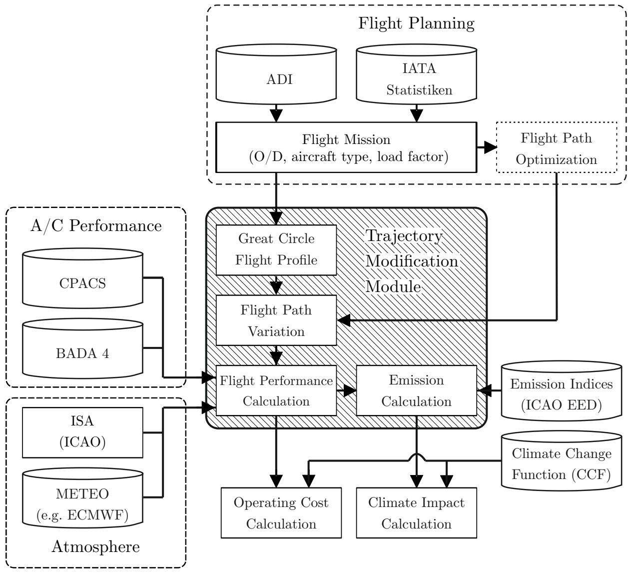

Fig. 3 Overview of the *Trajectory Modification Module* (TMM) [4]

$(t_f - t_0)$. Costs for maintenance, C_m, are derived from Liebeck et al. (1995) [11] and scaled to 2012 US dollars with the average US inflation rate of average consumer prices [12]. En-route charges, C_{ei} are expressed for a country i as:

$$C_{ei} = U_{ei} \cdot \left(\frac{m_{\mathrm{TOW}}}{k_1}\right)^{k_2} \cdot d_i \tag{10}$$

where U_{ei} is defined as unit rate per distance (\$/km), m_{TOW} as maximum take-off weight of an aircraft (expressed in 1000 kg) and d_i as the distance traveled in the country i (in km). The parameters U_{ei}, k_1 and k_2 are county-specific and vary widely from each other. The high variation of en-route unit rates (U_{ei}) over Europe applicable from 01/01/2016 are shown in figure 2 as examples. The parameter k_1 has a value of 50 in the European countries and a value of 1 in Canada and the United States; k_2 can accommodate values between 0 (US) and 1 (European countries, Canada).

Terminal charges, C_{ti}, are imposed for departing and landing and expressed for airport i as:

$$C_{ti} = U_{ti} \cdot \left(\frac{m_{\mathrm{TOW}}}{k_3}\right)^{k_4} \tag{11}$$

with the unit terminal rate U_{ti} and airport-specific parameters k_3 and k_4.

3.2 Calculation of cost minimal flight trajectories through climate-charged airspaces

To enable a fast execution of detailed sensitivity analysis of climate-charged airspaces, an exhaustive search algorithm has been applied within the *Trajectory Modification Module* (*TMM*). *TMM* performs a fast-time 4D trajectory modification and calculates flight performance calculation as well as detailed emission inventories based on the total energy model (see fig. 3) [4].

Within this study, a large number of varying 4D flight trajectories is simulated with *TMM* by systematically changing the way-point profile of *TOM*'s optimized flight trajectories with respect to climate and economy (sec. 3.1). Flight path variations are based on a Bernstein-Bézier approximation of curves defining the orthogonal deflection along the lateral and vertical path. For numerous combinations of threshold values (c_{thr}) and climate unit charges (U_{cj}), operating costs and climate impact of modified flight trajectories are calculated ex-post according to Eq. 12 & 13:

$$\begin{aligned} \mathrm{COC}^* &= C_f + C_c + C_m + C_{ei} + C_{ti} + \\ &\quad \sum_j \mathrm{CCA}_j(\mathbf{x}) \cdot d_j(\mathbf{x}) \cdot I_{ac} \cdot \left(\frac{m_{\mathrm{TOW}}}{k_1}\right)^{k_2} \quad (12) \\ \mathrm{ATR} &= \sum_i \mathrm{CCF}_i(\mathbf{x}) \cdot m_i(\mathbf{x}) + \mathrm{CCF}_{\mathrm{CiC}}(\mathbf{x}) \cdot d(\mathbf{x}) \quad (13) \end{aligned}$$

with $i \in \{CO_2, H_2O, NO_x\}$.

Based on this, the optimal flight trajectory that minimize operating costs is derived for each set of (c_{thr}, U_{cj}), route and aircraft type [4].

4 Systems Analysis

The study at hand investigates the functionality and effectiveness of climate-charged airspaces on the North Atlantic route from Lisbon, Portugal (LIS), to Miami, USA (MIA). The results are bench-marked against the potential of climate-optimized trajectories (COTs; optimum as a reference), which is widely discussed in the literature [2, 6, 14, 15, 16, 17].

All trajectories are simulated with a BADA 4.2 Airbus A330-200 aircraft performance model under consideration of a constant mach number of 0.82, a load factor of 85 % and free flight conditions.

4.1 Cost-benefit analysis of climate optimized trajectories

Results presented below are based on applying *TOM*'s optimal trajectory algorithm (sec. 3.1).

For $c_\Psi = 0$, flight trajectories are optimized with respect to cash operating costs (COC). Without wind, COC-optimized trajectories result in a continuous cruise climb on a great circle (R1 in Fig. 4, 5). If climate impact savings are getting more important ($c_\Psi > 0$), optimized flight trajectories are shifted more and more to regions with

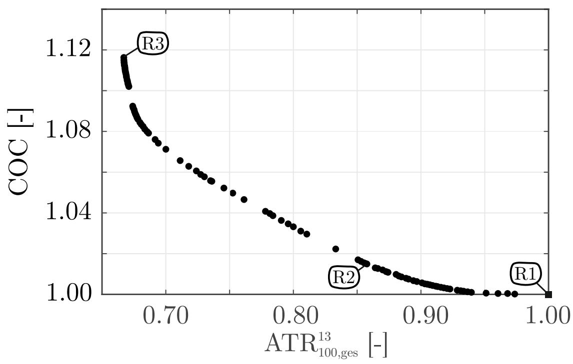

Fig. 4 Pareto-front of climate reduction potential (ATR) and cash operating costs (COC) for climate optimized trajectories (COTs; Reference) on the Transatlantic route LIS-MIA

lower climate sensitivities while flight distance, fuel burn, and COC are rising. The climate impact of the flight, which is expressed here as average temperature response (ATR), decreases simultaneously (see, i.a., R2 in Fig. 4, 5).

For $c_\Psi = 1$, trajectories are optimized with regard to climate. On the route LIS-MIA, ATR can be maximally reduced by 33.3 % for an additional fuel consumption of more than 20.0 % and a COC increase of 11.5 % (R3; dotted line in Fig. 5a,i). This highlights the superordinate role of flight planning and operation for climate mitigation: Additional emissions caused by detours, supplementary climb- and descent phases, and off-design altitudes (see Fig. 5) are heavily predominated by the 3D avoidance of climate-sensitive regions. Nevertheless, climate-optimal flying is linked with considerable extra costs. Mitigation does not coincide with cost reduction:

$$\text{COC}(\text{climate-optimal flying}) \neq \text{COC}(\text{cost-optimal flying}) \quad (14)$$

4.2 Functionality analysis of the concept of climate-charged airspaces

To create a financial incentive for airlines for climate mitigation, climate-charged airspaces (CCAs) are implemented, if the climate sensitivity of an area exceeds a threshold value (Eq. 1).

Location and extension of CCAs are plotted exemplary in Fig. 6 for $c_{thr} = 0.664$ and various flight levels (FL250 to FL390) over the North Atlantic flight corridor (NAFC). As the climate sensitivity to aircraft emissions is increasing strongly with rising altitude [18], more airspace areas are charged in higher flight levels.

For $c_{thr} = 0.664$, the business as usual (BAU) flight trajectory from Lisbon to Miami runs straight through climate-charged airspaces (see C1 in Fig. 5b,d) and results in an increase of cash operating costs for airlines as ecological and social costs of the flight are (partly) internalized. If, for instance, a climate unit charge of 0.5 \$/km is implemented, COC of the flight rise by +4.3 % (C1 in Fig. 5b,d and 7).

However, aircraft operators have the possibility to avoid major parts of these extra costs by

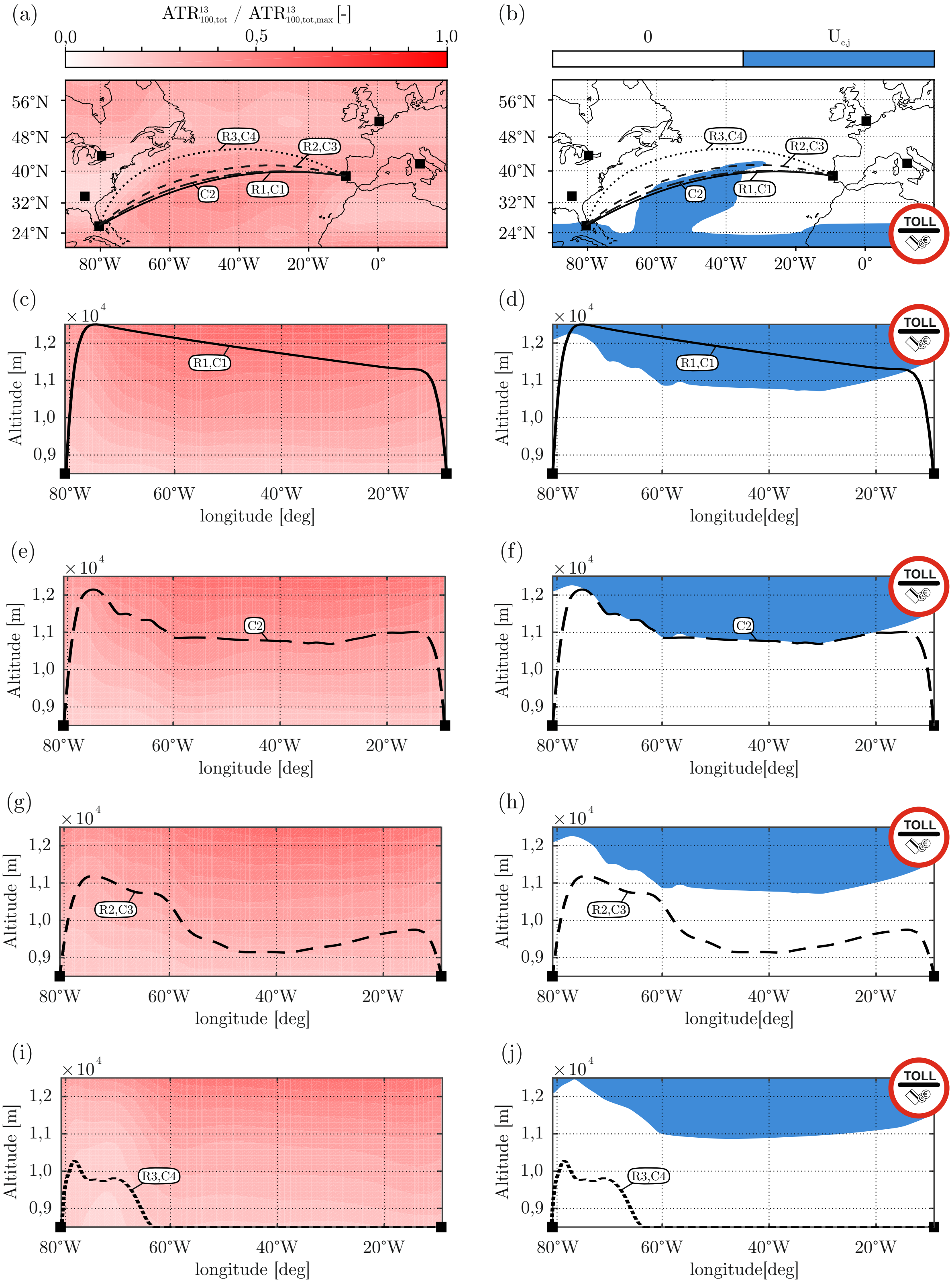

Fig. 5 Lateral and vertical flight profiles on the North Atlantic route from Lisbon, Portugal (LIS) to Miami, USA (MIA). Contour lines of total climate change functions (CCF_{tot}; shades of red) and climate-charged areas (CCAs; blue tone) are plotted for horizontal (top row) and vertical cross-sections (all other rows) and a threshold value (c_{thr}) of 0.664

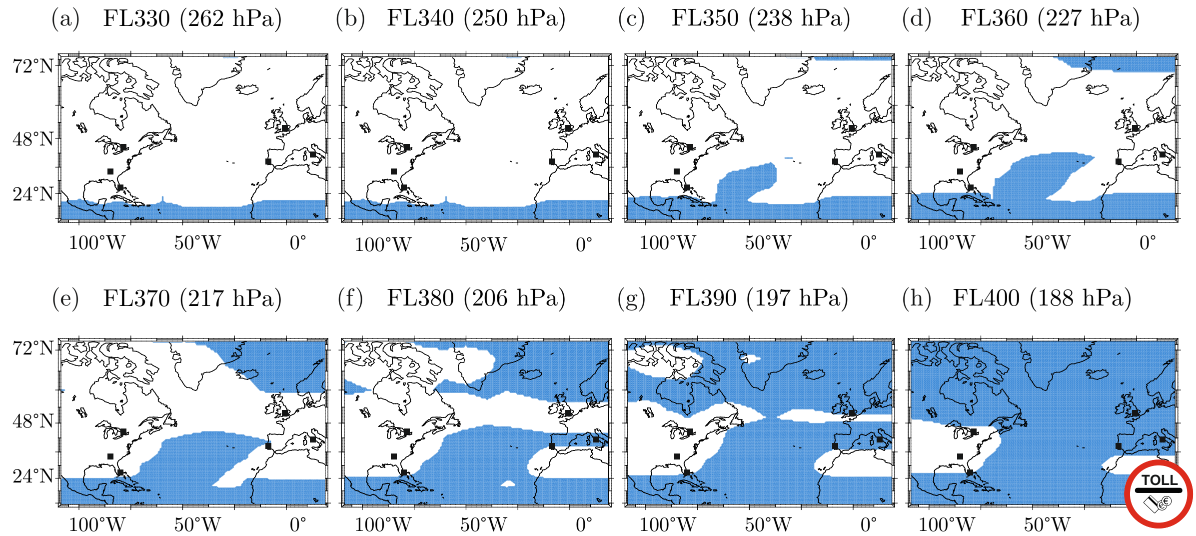

Fig. 6 Climate-charged airspaces (CCA, blue-colored) over the North-Atlantic for different flight altitudes (FL250 to FL390) and a threshold value of $c_{\text{thr}} = 0.664$

changing their flight level and path. If airlines decide to circumnavigate CCAs completely (C2 in Fig. 5, 7), additional costs can be reduced on the selected route by a maximum of -79 % (ΔCOC = −3.4 %). As this trajectory variation also results in a climate impact mitigation of ΔATR = −9.4 %, the trade-off between economic viability and environmental compatibility is resolved here: The implementation of climate-charged airspaces creates a financial incentive to mitigate non-CO_2 climate effects; environmental-friendly operation is getting economically attractive.

The climate impact of the flight can be further reduced, if CCAs are circumnavigated more spaciously. However, as fuel consumption and COC increase with growing detour, monetary incentives for mitigation decrease concurrently. For the selected route, a cost-neutral climate mitigation potential of -22.7 % is reachable (ΔCOC = 0; see R2, C3 in Fig. 5, 7). Further reductions of ΔATR can only be achieved for more considerable expenses (R3, C4), which eliminate the effect of incentivizing climate mitigation.

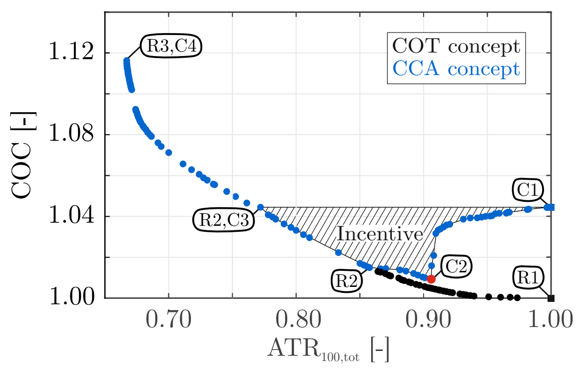

Fig. 7 Climate reduction potential (ATR) and cash operating costs (COC) for the concepts of (i) climate optimized trajectories (COTs; black) and (ii) climate-charged airspaces (CCAs; blue)

4.3 Sensitivity analysis of the location and extension of climate-charged airspaces

Within the CCA concept, the threshold value c_{thr} (see Eq. 1) defines whether an airspace area j is levied with a climate unit charge ($U_{c,j}$) or not. To analyze the influence of c_{thr} on the resulting cost-benefit potential, trajectory simulations are carried out in the following with c_{thr} varying between 1 (no charged airspace) and 0 (fully charged airspace). Results (ATR vs COC) are plotted in Fig. 9 for a constant climate unit charges of 0.5 \$/km for the route LIS-MIA:

The higher c_{thr}, the lower ΔATR (see red dots in Fig. 9). For $c_{\text{thr}} \leq 0.502$, COC and ATR can be reduced simultaneously by changing flight level and path (Fig. 9a-f). In these cases, monetary incentives for climate-friendly routing are created by implementing CCAs. While cutting cash operating costs, climate impact can be mitigated by up to 22.2 % (Fig. 9f). Further reductions of c_{thr} do not create financial incentive any more. But, however, if additional expenses are accepted, ΔATR can be reduced by almost 35 % on the transatlantic route LIS-MIA (Fig. 9g-i).

On this account, there is a direct dependency between the mitigation potential of climate-charged airspaces and the selection of c_{thr}.

4.4 Sensitivity analysis of the climate unit charge per kilometer flown ($U_{c,j}$)

Below, simulations with varying $U_{c,j}$ and constant c_{thr} are conducted on the LIS-MIA route to analyze the impact of climate unit charges ($U_{c,j}$) on the monetary incentive level of the CCA concept. Results are plotted in Fig. 10:

As shown in Fig. 5, cash operating costs (COC) of an exclusively cost-optimized flight trajectory (BAU; Traj C1) increase proportionally with rising $U_{c,j}$. For $U_{c,j} \geq 0.01$ $/km (■), climate mitigation coincides with the the cutting of costs. In these cases, relative cost savings of at least 0.75 % are achievable. For climate unit charges bigger than 3 $/km (■), climate-friendly routings are always more cost-efficient than the "Business as Usual" flight from LIS to MIA, as a financial incentive is created for all COT-Pareto elements. For $U_{c,j}$ = 10$/km, airlines can reduce their COC by more than 40 % by flight trajectory modification. Independently of $U_{c,j}$ a cost-optimal mitigation potential of 9.4 % (red dot) can be achieved for $c_{\text{thr}} = 0.664$ by avoiding CCAs totally (compare Fig. 9c).

This sensitivity analysis clearly demonstrates a direct link between the monetary incentive level of the CCA concept and $U_{c,j}$.

5 Conclusion and Outlook

The concept of the climate-charged airspaces (CCA) is designed to prevent damages of climate change by implementing both polluter pays and precautionary principle of environmental economics into the aviation sector. Within the concept, highly climate-sensitive regions are levied with a climate unit charge to include socio-economic costs of climate change in the accounting and decision-making process of airlines. The expansion of the balance sheet results in additional costs for airlines, which can be largely prevented by changing their flight behavior. If CCAs are (partly) bypassed, both climate impact and operating costs of a flight can be reduced. This resolves the trade-off between economic viability and environmental compatibility and creates a financial incentive for climate mitigation. Environmental-friendly operation is getting economically attractive. However, if operating costs for climate-friendly re-routing are higher than for "business as usual" (see Fig. 10), no financial incentive occur. But, since there are direct connections between the mitigation potential of the concept and the threshold value (see Fig. 9) as well as between the monetary incentive level and the climate unit charge (see Fig. 10), an optimal set of both parameters can be found to reach a specific climate target.

The practicability of this cost-driven re-routing approach can be demonstrated by the comparable behavior of airlines in times when fuel costs are comparatively low (see Fig. 8): In the years 2012 to 2015, for instance, several airlines decided to fly longer routes around airspaces with higher flight control fees, such as Germany, Switzerland or Italy, to reduce their direct operating costs [13, 19].

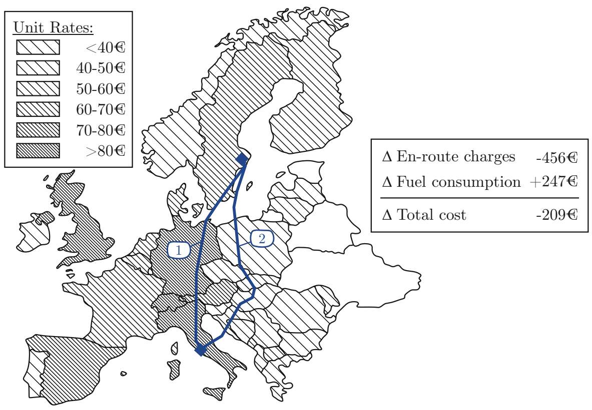

Fig. 8 Influence of current ATC unit rates on operating costs and flight route for a full service carrier flight from Stockholm, Sweden to Rome, Italy [19]; navigation unit rates accord with [13]

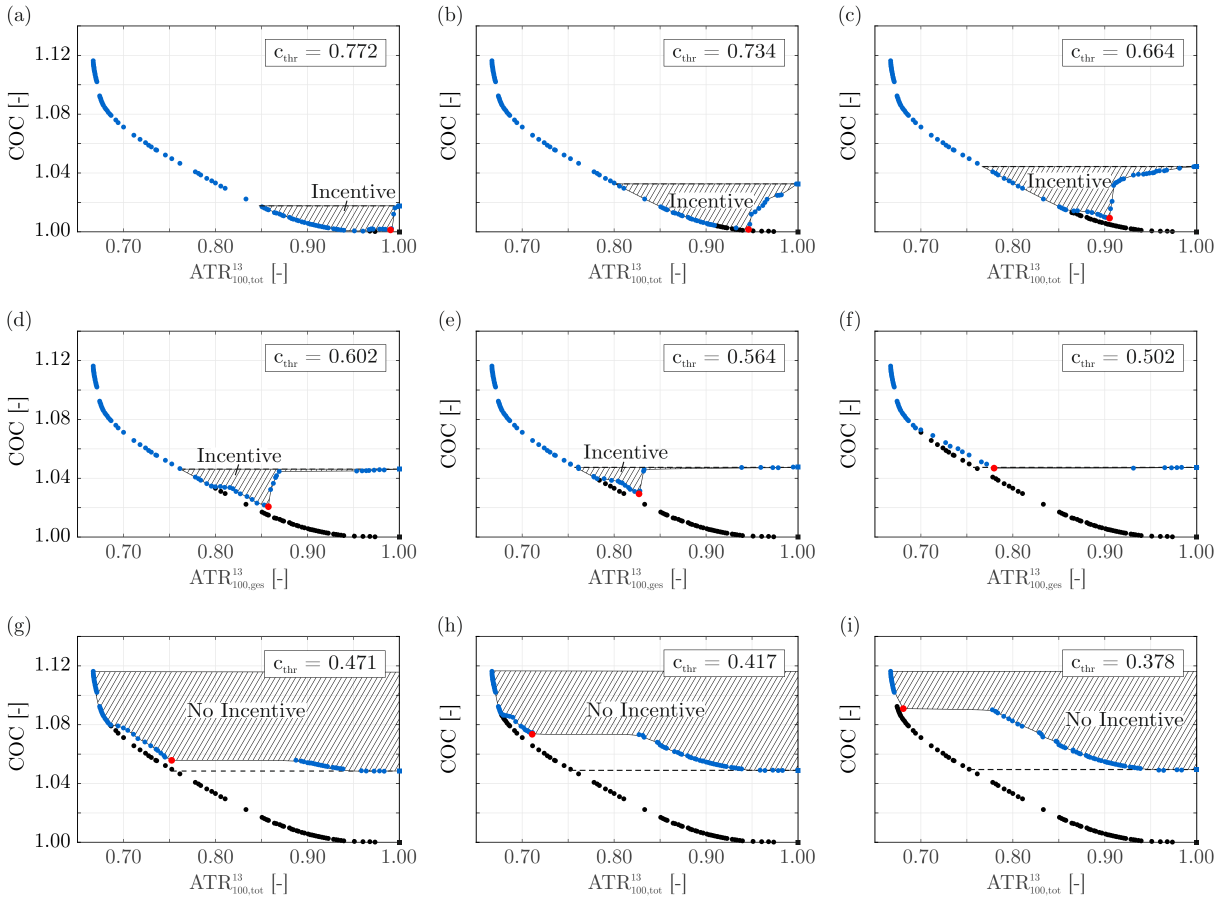

Fig. 9 Influence of the threshold value (c_{thr}) on the mitigation potential of climate-charged airspaces (CCA) for the transatlantic route LIS-MIA and a climate unit charge ($U_{c,j}$) of 0.5 $/ km

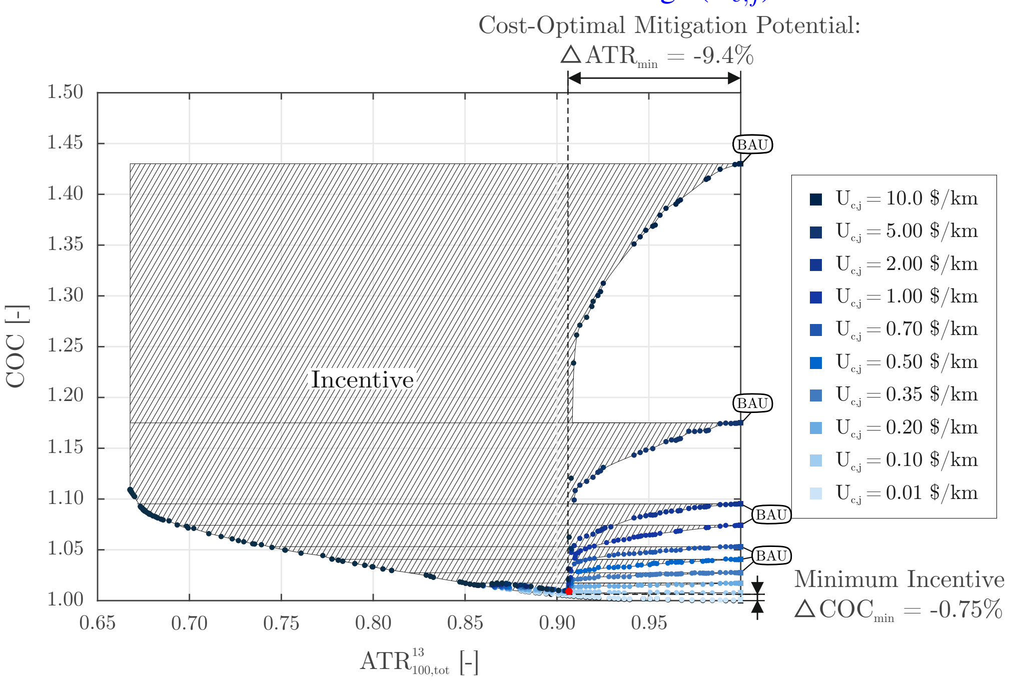

Fig. 10 Influence of the climate unit charge ($U_{c,j}$; shades of blue) on the mitigation potential of climate-charged airspaces (CCA) for the transatlantic route LIS-MIA and a threshold value (c_{thr}) of 0.664

In future publications an extension of this analysis is planned to network level as well as the integration of wind effects and airspace capacity constraints (i.e., step climb procedures) into the simulation. Furthermore, the authors want to analyze administrative efforts of the CCA concept for aircraft operators and supervising authorities.

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Contact Author Email Address

malte.niklass@dlr.de