A NOTE ON HOW TO INTERNALIZE AVIATION'S CLIMATE IMPACT OF NON-CO2 EFFECTS

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Abstract. In the Paris Agreement 2015 (COP21, CMP11), the world's leaders have confirmed that there is a need for fundamental changes of existing patterns of production and consumption to mitigate global warming, which affects the livelihood of an increasing amount of people worldwide. Changes of these patterns involve significant economic costs, but polluters can refuse to pay their pollution costs adequately due to the absence of market prices for environmental public goods. In order to create financial incentives for pollution reduction, policy makers are paying closer attention to instruments of environmental economics.

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 should be imposed for operators of aircraft when flying through them. 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 reduction of global warming and even 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 an US-route and benchmarked against climate-optimized trajectories.

Keywords: climate mitigation concept, internalization, cost-benefit assessment, air transportation modeling, optimal control

INTRODUCTION

The degradation of the environment affects the livelihood of a growing number of people and all living beings. But polluters have little incentives to voluntarily internalize their pollution costs, as they can take the position of a free rider: they 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. If they are invited to share these costs, they may give an incorrect answer and understate their preference for the public good – including a zero willingness to pay as an extreme case – due to expectations that the availability of the good will be ensured by those with a higher willingness to pay. This might lead to under-provision of the good and cause market failure. For the competing demands on the environment a zero price cannot bring about an optimal allocation. Scarcity and degradation of public goods call for the introduction of prices. Internalization can be pursued through a variety of instruments of environmental policy like government regulation, tradeable permits (cap-and-trade systems), taxes or charges (Siebert, 2008).

Anthropogenic global warming 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. Inter-dependencies between aviation and climate change are complex and non-linear, and the amount of emissions is not equal to its climate impact. Approximately two-thirds of aviation-induced global warming is expected to be caused by non-CO_2 effects like the emission of nitrogen oxides (NO_x) and the formation of contrail induced cloudiness (CiC), which are highly sensitive on chemical and meteorological background conditions. Consequently, their climate response largely depends on emission location and time. NO_x emissions, for example, have a larger impact on climate when released at higher flight levels as more ozone can be produced during a longer time period due to an increase of atmospheric residence time (Schumann, 2012). Therefore, environmental policy making should change the focus on climate impact mitigation instead of emission reduction only.

The crucial questions are then (i) how to include aviation's climate impact of non-CO_2 effects adequately into an environmental policy measure and (ii) what is a reasonable 'shadow price' for global warming. The study at hand focuses on the first question.

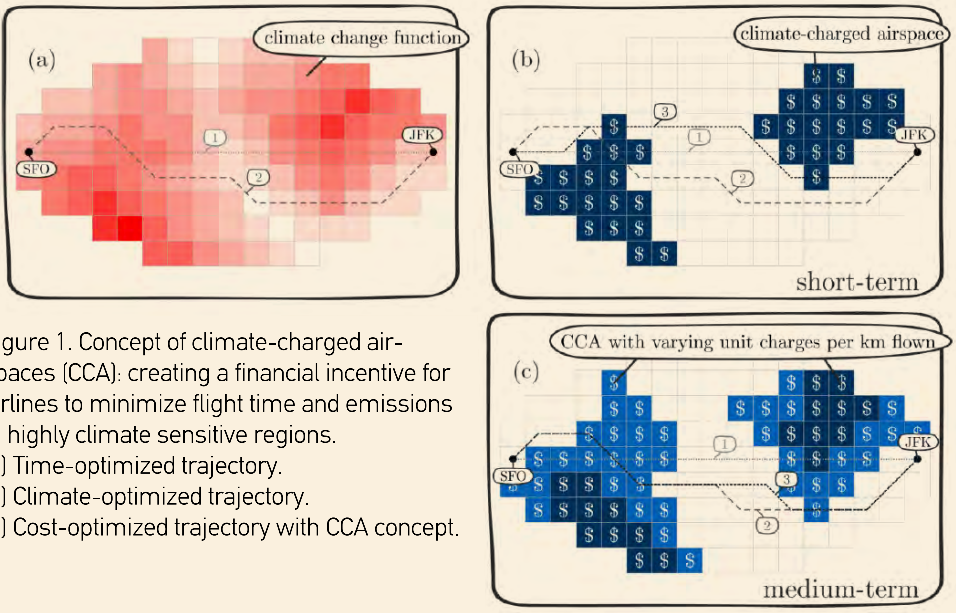

Figure 1. Concept of climate-charged airspaces (CCA): creating a financial incentive for airlines to minimize flight time and emissions in highly climate sensitive regions.
(1) Time-optimized trajectory.
(2) Climate-optimized trajectory.
(3) Cost-optimized trajectory with CCA concept.

CONCEPT OF CLIMATE-CHARGED AIRSPACES (CCA)

In order to create an incentive for airlines to minimize flight time and emissions in highly climate sensitive regions, we suggest to impose a climate charge for operators of aircraft that fly in these areas (see figure 1); contrary to approaches that propose an environmental charge for CO_2 and/or NOx emissions. An airspace j should be levied with an environmental unit charge U_{cj} per kilometre flown, d_j , if its climate sensitivity with respect to aircraft emissions[1] exceeds a specific threshold value C_{thr}:

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

Thus, cost-minimizing airlines will re-route their flights to reduce the climate charges and hence their cash operating costs[2]. In this manner, climate impact mitigation coincides with the cutting of costs. The operator of an aircraft can decide individually for each flight according to individual 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 (trajectory 3 in fig. 1). Consequently, dealing with 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. CCA could be defined and monitored by air traffic control instead.

The certainty of the climate benefit of optimized trajectories is highly dependent on the quality of CCF and their correctness. Thus, existing uncertainties in climate impact modelling could lead to optimized trajectories – according to prevailing CCF_i of different agents i – that might turn out to be either over- or underestimated with respect to their climate mitigation potential. In order to be environmental effective a resilient handling of these uncertainties is necessary. Therefore, the implementation of the CCA concept focuses in a first step only on those areas that are likely highly sensitive to climate (short-term, see fig. 1b). But its implementation can be adapted to current level of scientific understanding (LOSU) at any time (medium-term, see fig. 1c) by introducing varying unit charges U_{cj} for different levels of climate sensitivities.

Ideally, the total shadow price of a single flight ($\Sigma_i U_{cj} d_j$) should equal all its external costs associated with climate change. This means compensating actual economic, environmental and health damage. But by estimating socio-economic costs, concurrently, also the level of uncertainties rises,

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[1] The climate sensitivity of an area is expressed here by total climate change functions (CCF_{tot}) characterizing the environmental impact caused by non-CO2 effects of aircraft's emissions at a certain location and time.

[2] According to Eurocontrol (2016), many airlines choose to fly longer – at times when fuel costs are relatively low – and re-route their flights over Europe away from more expensive airspace areas to minimize costs.

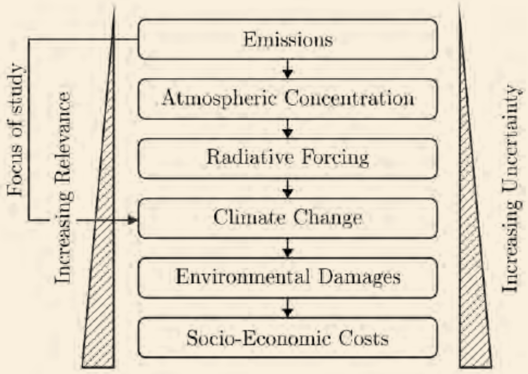

Fig. 2. Cause-effect chain from emissions to socio-economic costs according to Fuglestvedt et al. (2010)

due to the currently low state of understanding and the simplifications made during modelling, see fig. 2. The main object of this work is, however, to evaluate the concept of CCA, not to estimate the exact value of the charge in terms of money. Thus, in order to reduce uncertainties, the shadow price calculation is limited to climate change in terms of average temperature change (ATR).

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)*. *TOM* minimizes a cost functional J while satisfying dynamic constraints as well as state (i.e. maximum speed), control (e.g. thrust limit) and path limitations (e.g. maximum pressure altitude). A comprehensive description of TOM is given by Lührs et al. (2016) and Niklaß et al. (2015).

A. Calculation of optimized trajectories with respect to climate and economy

For benchmark purposes, a multi-objective optimization with regard to climate and monetary costs is performed within this study. Therefore, monetary costs (COC) and climate change functions (CCF) are integrated into TOM's cost functional J_{COT}. The Pareto optimal set is found by varying the weights of monetary (c_Y) and climate (c_Ψ) 'costs' with $c_Y+c_\Psi=1$ and $c_Y,c_\Psi \in [0,1]$. A trajectory is optimal with regard to monetary costs, if $c_Y=1$, and optimal with regard to climate, if $c_\Psi=1$.

Climate Change Functions: CCF(x,t) are computed by Niklaß et al. (2016) with the climate response model AirClim and expressed as average temperature response integrated over a time period of 100 years (ATR100) per unit emission. CCF$_i(x,t)$ are calculated individually for $\mathrm{CO_2}$, $\mathrm{H_2O}$, NO_x (ATR$_{100}$ per unit emission), and CiC (ATR$_{100}$ per flown unit distance).

Monetary Cost Functions: The economic impact of a flight trajectory is described by the share of cash operating costs (COC) calculated as function of mission time (t_f-t_0) and mission fuel (m_0-m_f). COC are derived from Liebeck et al. (1995) and scaled to 2012 US dollars with the average US inflation rate of average consumer prices (IMF, 2014).

B. Implementation of climate-charged airspaces (CCA)

Climate charges, C_{cj}, are expressed for a flight through an climate-charged airspace j in analogy to en-route and terminal charges:

$$C_{cj} = U_{cj} \cdot \left(\frac{\mathrm{MTOW}}{k_1}\right)^{k_2} \cdot I_{AC} \cdot d_j \tag{2}$$

where d_j is defined as the distance traveled in CCA$_j$, MTOW as maximum take-off weight of an aircraft and $I_{AC} \in [0,1]$ as incentive factor for climate-friendly technologies. It is conceivable to link I_{AC} with prospective $\mathrm{CO_2}$ and NO_x certification standards for cruise as are currently being discussed for $\mathrm{CO_2}$ by ICAO (2016).
Cost-optimized trajectories are obtained by minimizing the cost functional $J_{\mathrm{CCA}}=f(\mathrm{COC},C_{cj})$.

EXPECTED RESULTS

The feasibility of the CCA concept is evaluated for an U.S. route from San Francisco (SFO) to New York (JFK). Therefore, optimized trajectories (minimization of J_{COT} and J_{CCA} with varying climate charges U_{cj}) are identified with TOM and benchmarked against each other from a cost (increase of cash operating cost) and environmental (reduction of average temperature response) point of view.

Similar computations have been already performed by Niklaß et al. (2016) for climate-restricted airspaces (CRA, $U_{cj} \rightarrow \infty$) with varying threshold values. As shown in figure 3, the introductions of CRAs allow climate impact mitigation efficiencies in the same order of magnitude as COT. But, however, a large volume fraction of the airspace has to be closed to achieve high climate impact reductions (see figure 4). ATR can be reduced, for instance, by 10% on the route from Lisbon, Portugal (LIS) to Miami, USA (MIA) for a cost increase of less than 1% by closing 26.6% of the North-Atlantic airspace in-between 8,500 and 12,500m of altitude. Similarly high efficiencies are expected also for climate charged areas, but with the advantage of being more operationally feasible.

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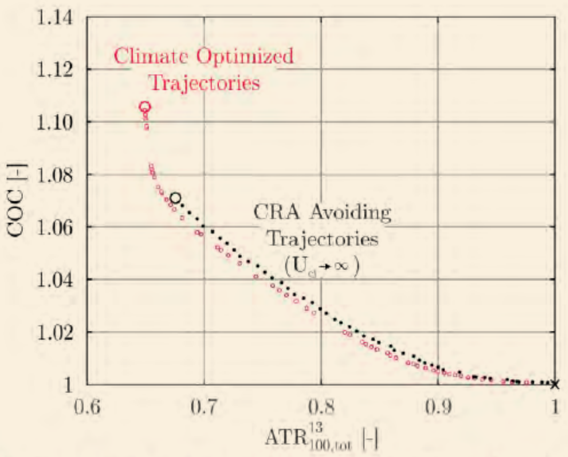

Fig. 3. Average temperature response (ATR) and cash operating costs (COC) for climate-optimized trajectories (COT, red) and CRA avoiding trajectories ($U_{cj} \rightarrow \infty$, black, solid) (Niklaß et al. 2016).

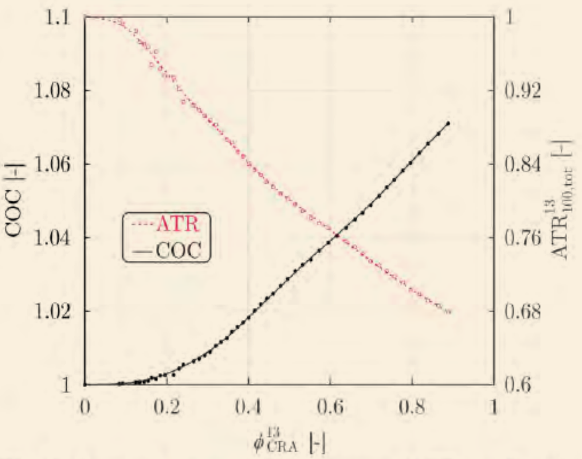

Fig. 4. Average temperature response (ATR, red) and cash operating costs (COC, black, solid) as function of the restricted volume fraction of upper airspace ($\phi^{13}_{\mathrm{CRA}}, U_{cj} \rightarrow \infty$) (Niklaß et al. 2016).

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