

A METHODOLOGY TO ASSESS THE COST-BENEFIT POTENTIALS OF CLIMATE OPTIMAL TRAJECTORIES

M. Niklaß¹, V. Grewe², R. Ghosh¹, B. Lührs¹, F. Linke¹, A. Schmitt³, T. Luckova³, V. Gollnick¹

¹German Aerospace Center (DLR), Institute of Air Transportation Systems, Hamburg, Germany

²German Aerospace Center (DLR), Institute of Atmospheric Physics, Oberpfaffenhofen, Germany

³German Aerospace Center (DLR), Institute of Flight Guidance, Brunswick, Germany

Abstract

Impacts of commercial aircraft operation upon the environment, which are caused primarily from emissions of carbon-dioxide, nitrogen-oxides and the formation of contrails, are matter of growing concern, as aviation is one of the fastest growing industrial sectors worldwide and the awareness of its effects is expanding. To reduce the impact of air traffic emissions on global warming, different technological, operational as well as regulative approaches are conceivable. Two of the most promising mitigation strategies are tactical and strategic concepts of air traffic operations, which optimise flight trajectories with respect to climate and economy. Here we present a methodology to assess and to compare the cost-benefit potential of both of them, including aircraft and engine design, route planning, calculation of emissions, climate temperature response and operating costs, as well as ATM compatibility checks. As the introduction of new strategies may impact the air transport system as a whole and provoke benefits and drawbacks in different fields, the assessment is based on a holistic systems design approach, including systems analysis and concept design.

1. INTRODUCTION

Compared with other transport sectors, commercial aviation has experienced an over-proportional growth of transport volumes over the last decades. During the period between 2000 and 2012 the global air traffic, as measured by revenue passenger kilometres (RPK), grew by 61 % [1].

Air traffic operations impact the environment locally and globally in several ways. At airport vicinity, the main impacts are noise, air quality degradation and land use. On a global scale aviation affects climate through the emission of carbon dioxides (CO₂), nitrogen oxides (NO_x), water vapour (H₂O) and aerosols. Nitrogen oxides influence the formation of tropospheric and lowermost stratospheric ozone (O₃) and the depletion of methane (CH₄), both being important greenhouse gases (GHG). The emission of water vapour and aerosols trigger the formation of contrails in cold and moist areas, which reduce both the incoming solar and outgoing thermal radiation.

All these non-CO₂ emissions are characterised by a lifetime, which is much shorter than that of CO₂, and are highly dependent on chemical and meteorological background conditions. Therefore their climate impact largely depends on emission location (altitude h , latitude φ , longitude λ) and time (time of the day and season). Contrails, for instance, will disappear within a few minutes if the ambient air is not super-saturated with respect to ice.

Air traffic is the main direct anthropogenic source of emissions above the planetary boundary and caused 3.5% of the global anthropogenic radiative forcing (RF) in the year 2005, excluding the impact of induced cirrus cloudiness [2]. With a predicted annual growth rate of 4.7 % [1], which

largely outpaces the estimated annual fuel efficiency improvement rate of 1-2 % [3], the environmental effect of aviation will continue to grow. Shaping this growth in a climate friendly way is a major challenge of aviation research and the core of this work.

Different technological, operational as well as regulative approaches are conceivable to reduce the impact of air traffic emissions on global warming. There is a wide spectrum of possibilities, such as new operational concepts, climate optimal trajectories, alternative fuels, modification of aircraft design, new configurations, and mandatory regulations (see figure 1).

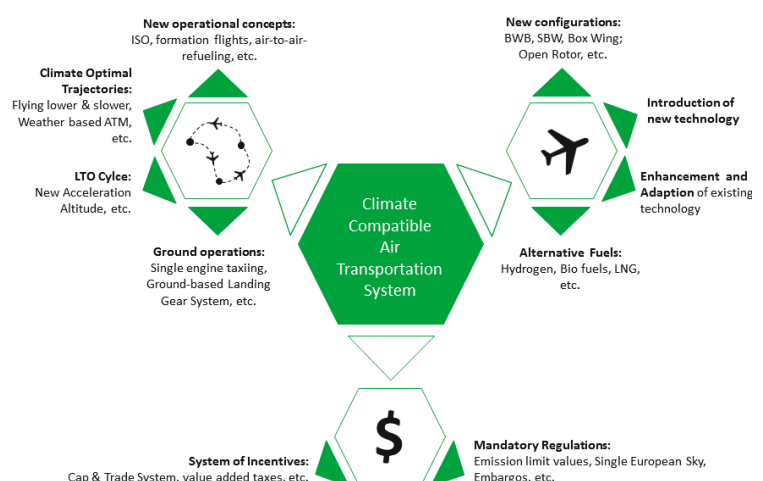


FIG 1. Overview of different operational (left), technological (right) and regulative concepts (bottom) to mitigate the climate impact of aviation.

Most of these mitigation strategies are minimizing the climate impact of one forcing agent, but the optimisation of one agent, e.g. contrail avoidance, may provoke a drawback of another, e.g. CO₂ emission due to an increase in fuel burn. Furthermore, there are many interdependencies between the main stakeholders of the air transport system (ATS). Hence, promising strategies that provide advantages in certain domains (e.g. climate impact) may influence the whole ATS and cause penalties in other domains (e.g. capacity of the air traffic management, ATM). On that score a multi-disciplinary and multi-perspective system design approach is necessary to assess the cost-benefit potentials of different mitigation strategies.

Such a systems design approach is developed within the DLR project WeCare (Utilizing Weather information for Climate efficient and eco-efficient future aviation). Among the objectives of the project is to compare cost-benefit potentials of a tactical and a strategic optimisation of air traffic operations.

The framework of the methodology is based on systems design, which is briefly introduced in Sect. 2. An overview of the climate impact of different forcing agents and individual mitigation strategies is given in Sect. 3. Sect. 4 introduces the basic ideas of tactical and strategic optimisation of air traffic operation with respect to climate and economics. The system design approach and the simulation process, as developed within the DLR project WeCare, is presented in Sect. 5.

2. SYSTEMS DESIGN (GENERAL APPROACH)

The ATS, as a complex system, includes the stakeholders manufacturers, aircraft operators, airports, and air navigation service providers (ANSPs) [4,5]. Despite their dependencies amongst themselves, there are also several interrelations between stakeholders and surrounding external factors, such as politics, economics, environment, and technology [6]. Hence, every change of sub-systems or external factors (e.g. introduction of new technologies/regulations) may impact the ATS as a whole and provoke advantages and disadvantages in the different fields that need to be balanced. Thus, the identification and quantification of main driving interrelationships between stakeholders and external factors is essential for the assessment of different mitigation strategies. This requires large inter-disciplinary expertise due to the complexity of the ATS.

To analyse and conceptualise the ATS in a holistic way Ghosh et al. (2014) introduced a theoretical framework of **systems design** with an integrated approach to participatory futurology, including systems analysis of the ATS and concept design [6]. That theoretical concept serves as framework for the methodology of this paper and is visualised in figure 2.

Systems analysis “focuses on a problem arising from the operations of a sociotechnical system, considers various responses to this problem, and supplies evidence about the costs, benefits, and other consequences of these responses” [7]. Carrying out systems analysis also means questioning the goals of the decision maker per se (“How should the future

be?”). Systems analysis clearly distinguishes between problem-deduced cases (development of desirable “futures” by finding and quantifying of issues/problems; scenario pull) and technology-induced cases (technologically possible future; technology push). This distinction is most important at the beginning of any process [6]. The focus of this paper, as described in section 1, is essentially a problem-deduced case.

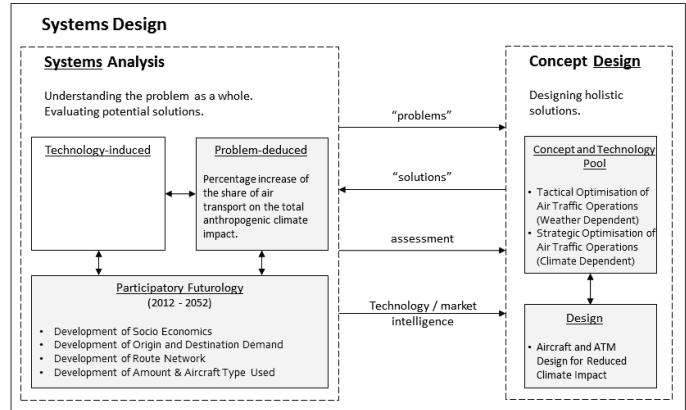


FIG 2. Systems Design with an integrated approach to participatory futurology, including systems analysis of the ATS and concept design according to [6]

Contrary to systems analysis, which focusses more on the detection and quantification of future problems (*percentage increase of the share of air transport on the total anthropogenic climate impact*), **concept design** creates solutions under divergent drivers. In the present case, there are conflicting drivers on microscopic and macroscopic level. On a microscopic level, different cause-effect principles and perturbation lifetimes of individual forcing factors have to be considered. On a macroscopic level, there are contradictory objective functions, for instance, between fuel burn and climate impact minimisation, which may result in economic penalties.

Following up the concept design, the effectiveness of newly developed strategies and technology perspectives are in turn analytically evaluated. The iteration between systems analysis and concept design, which pursue different ways of thinking, is essential for the assessment and development of innovative and holistic solutions [6]. *With regard to the present paper, there is a need to investigate the consequences of the introduction of climate optimal trajectories for each stakeholder. Some conceivable research questions are listed below:*

Is there a need to modify the airspace structure (e.g. free flight)? Do climate optimal trajectories influence the air traffic management (e.g. ATM work load)? Is there any impact on aircraft operators (e.g. airline flight schedule, fleet size and economics)?

3. CLIMATE IMPACT OF AVIATION (PROBLEMS) AND MITIGATION STRATEGIES (CONCEPT POOL)

As mentioned before, aviation affects the global climate by contrail induced cloudiness (CIC) and changes of the atmospheric composition, which impact terrestrial radiation

balance and radiative forcing. Consequently, the resulting temperature change alters the earth-atmosphere system towards a new state of quasi-equilibrium. Figure 3 shows estimates for the cumulated radiative forcing caused by aviation since pre-industrial times until 2005.

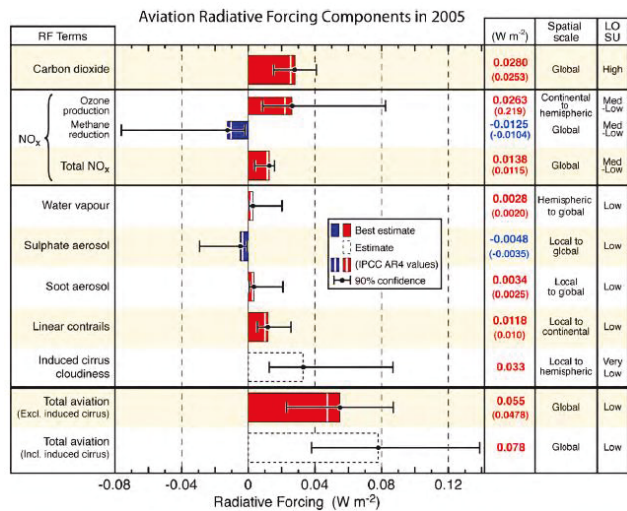


FIG 3. Radiative forcing components from global aviation, evaluated from preindustrial times until 2005. Bars represent updated best estimates or an estimate in the case of contrail-induced cloudiness (CIC) [2]

Carbon Dioxide (CO₂)

CO₂ emissions, which are directly proportional to fuel burn for kerosene fuelled aircraft, affect the climate through absorption and re-emission of terrestrial infrared radiation. CO₂ has a low chemical reactivity which results in a long perturbation lifetime (between 30 and several thousand years) and a homogeneous dispersion in the atmosphere. Hence, the climate impact of aviation CO₂ is almost independent of the locus of emission [8].

To reduce fossil CO₂ emissions different approaches are conceivable, such as intermediate stop operations on long range routes [9,10], alternative fuels [11], enhancements of fuel efficiency, and optimal routing. Fuel efficiency of aircraft, for instance, can be improved by novel engines (e.g. open rotor), by modification of aircraft design (e.g. optimisation for lower flight altitudes and speeds), or new aircraft concepts, such as laminar wings or blended wing body, just to name a few [12]. Aircraft routing can be optimised by the use of weather forecasts (e.g. wind-optimised flight trajectories) [13,14] and by an enhancement of the airspace structure (e.g. Single European Sky) [15] and the air traffic management (e.g. free flight) [16].

Water Vapour (H₂O)

Even though H₂O, which is the most effective and important GHG in the atmosphere, contributes about two third to the natural greenhouse effect, the climate impact of subsonic H₂O emissions without consideration of contrail formation is comparatively small. Though the amount of emitted H₂O can be accurately estimated (directly proportional to fuel burn),

the scientific understanding of its impact is still considered poor because of natural variability [17]. The relative impact of H₂O increases with altitude: the higher the altitude, the longer the lifetime and lower the background concentrations [8,18]. Due to a lack of major loss processes in the stratosphere, H₂O emissions of supersonic commercial aircraft with flight levels between 450 and 650 are more important. Alternative fuels, like hydrogen or methane fuels, have higher water vapour emission indexes (EI_{H_2O}) than kerosene (0.029 kg/MJ). So, their use is neither a mitigation option for H₂O, nor for contrail formation [19].

Nitrogen Oxides (NO_x)

Nitrogen oxides have a high chemical reactivity and very low atmospheric concentrations. Hence, NO_x emissions affect the climate through O₃ formation and CH₄ depletion; there is no direct terrestrial absorption at these wavelengths. While the reduction of CH₄, which is a long-lived greenhouse gas like CO₂, results in a global negative radiative forcing, the increase of the chemically reactive gas O₃ causes a warming. This O₃ warming is locally concentrated at northern hemisphere mid latitudes [20]. On average, the total climate impact of aviation NO_x is expected to be dominated by O₃ and therefore leads to a global warming of the atmosphere; though the precise magnitude is uncertain [21,22].

The amount of aviation NO_x results from the product of fuel consumption and the engine type-specific emission index EI_{NO_x} , which depends on ambient conditions, engine and combustor design, flight speed and power setting [23]. While fuel burn is minimised at stoichiometric combustions resulting in high flame temperatures, high EI_{NO_x} values are caused by long residence times at high combustion temperatures. This trade-off triggered a more rapid increase of total aviation NO_x emissions than of total fuel consumption over the last few decades [24].

During cruise NO_x emissions are emitted by subsonic aircraft in the upper troposphere (UT) and lower stratosphere (LS). In these regions the lifetime of NO_x is higher than on ground, the removal rates of both NO_x and O₃ lower and the radiative forcing of O₃ is at a peak [25,26]. Therefore the climate impact of NO_x emissions can be reduced by operational changes in cruise flight altitudes towards lower flight levels [27,28]. Technologically, the implementation of different systems, such as lean-burn combustion, inter-cooling, and cooled cooling air, is under consideration to reduce the amount of aviation NO_x emissions [12]. A good example for a significant technological reduction of NO_x emissions at low altitude and cruise is the twin annular premixing swirler (TAPS) combustor of the GENx engine for B787.

Contrail Induced Cloudiness (CIC)

Condensation trails (contrails) are visible line-shaped cirrus clouds which are formed in the wake of aircraft by the mixing of hot and moist exhaust gases with sufficiently cold ambient air, as described by the Schmidt–Appleman criterion (SAC) [29]; see figure 4. If the ambient air, during flight, is super-saturated with respect to ice, contrails accumulate ambient water vapour, grow, spread, and evolve into natural looking

contrail-cirrus clouds; otherwise they dissolve quickly [30,31]. The accumulation of H_2O within contrail-cirrus clouds changes the water budget of the surrounding atmosphere and may influence the optical properties of natural clouds [32]. Ice super-saturated regions (ISSR) are rather thin in height (in the order of 500 m), have an average horizontal dimension of less than 100 km, and occur mainly in the upper troposphere [32,33,34]. In addition to the dependency of local atmospheric conditions there are further factors of influence on the formation of contrails, such as aircraft design aspects (propulsion efficiency η) and fuel parameters (amount of water vapour emission; EI_{H_2O}) (see figure 5) [35]. Schumann (2000) showed for individual meteorological situations that aircraft with higher η (higher SAC threshold temperature; compare fig. 4 and 5) cause contrails whereas other aircraft with lower fuel efficiency caused none [36].

Contrary to the physics of the contrail formation process, which is well understood, the present knowledge of the global climate impact of CIC is still poor and matter of current research. The RF of CIC depends on lifetime, optical thickness, level of coverage, geographic location, altitude, time of day and season (contrails form more likely at lower altitudes in winter than in summer), and the presence of lower clouds [19]. Even though contrails may cool the atmosphere during the day, especially over the ocean (cool and dark surface) and during morning and evening (high solar zenith angles), they have a total warming effect in the same order of magnitude as CO_2 indicated by RF [37,38]. Therefore, it is beneficial to the climate to investigate potential contrail mitigation strategies:

“An aircraft cannot fly without burning fuel, but it has the possibility to avoid the production of contrails by choosing its flight level and path” [39].

For the reduction of the environmental effect of CIC, the path length of flight through ISSR has to be minimised. Thus, one approach could be a general (*strategic*) shift of the cruise altitude to higher (LS is far drier than UT) or lower flight levels (ambient temperature has to be above SAC threshold temperature) in which the presence of ISSRs is increasingly unlikely [40,41]. With this approach a strategic vertical change of several thousand metres is required to achieve strong contrail mitigation on a global scale; even though small vertical deviations of 1000 ft (one flight level up or down) [39] or small lateral changes [42,43] are expected to be sufficient to avoid local ISSR. In lieu thereof, flight trajectories can also be climate-optimised through small *tactical* changes in vertical and lateral direction under consideration of actual weather information (e.g. precise position and extent of ISSRs) [39].

Aerosol Particles

In addition to gaseous emissions, aircraft jet engines emit solid aerosol particles (e.g. soot and metal particles) and precursors of volatile particles, such as sulphur species, chemi-ions and unburned hydrocarbons [8]. They affect the atmosphere via reflection and absorption of radiation, participation in atmospheric chemical reactions, transformation into cloud condensation nuclei, and modification of radiative properties of natural cirrus clouds (e.g. form, size, and amount of cloud particles) [44,45].

Therefore, the technological reduction of all kinds of particle (especially soot emissions) and particle precursor emissions will contribute to the mitigation of aviation induced cloud changes [46].

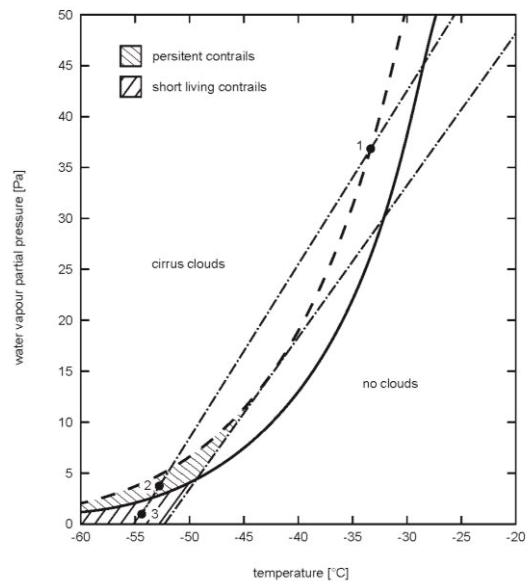


FIG 4. Principle of contrail formation and persistence according to [45] and [47]. Bold curves represent the water vapour saturation pressure over liquid (full) and ice water (dashed). The dash-dotted line marks the phase trajectory of the mixture of hot and moist exhaust gases and cold ambient air. Contrails form when the mixing line cuts the line of water saturation (point 1). The tangent to water saturation marks the warmest temperatures for which contrail formation is possible (threshold condition). The points 2–3 represent different contrail conditions as observed: 3: short-lived, 2: persistent. Contrails are persistent when ambient conditions are in-between threshold mixing line, ice, and liquid saturation.

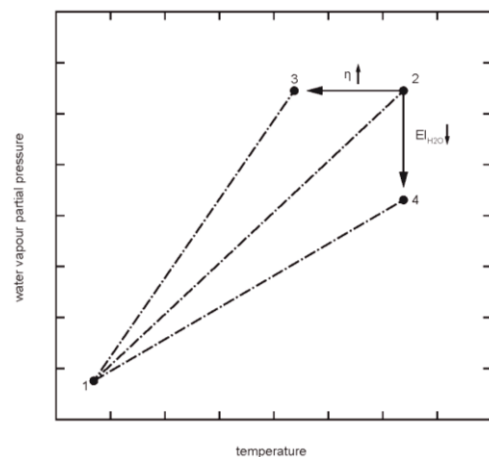


FIG 5. Influence of propulsion efficiency η and emission index of water (EI_{H_2O}) on the steepness G of the mixing line. Increasing η (less heat emission) and increasing EI_{H_2O} (more humidity) causes more contrails (increase of G), with contrail formation at lower altitudes and higher ambient temperatures. Point 1 marks ambient conditions; points 2–4 represent different engine exhaust conditions: 2: hot and moist, 3: less hot, 4: less moist.

TAB 1. Overview of previous studies on climate optimal trajectories

	Sausen et al. (1998) [40]	Fischer (2009) [28]	Grewe et al. (2010) [62]	Sridhar et al. (2011) [42]	Schumann et al. (2011) [64]	Schwartz (2011) [61]	Koch (2013) [52]	Chen et al. (2014) [55]	Grewe et al. (2014) [63]	Ng et al. (2014) [66]	
✓	✓	✓	-	-	✓	✓	-	-	-	-	Strategic optimization of flight trajectories
-	-	-	✓	✓	-	-	✓	✓	✓	✓	Tactical optimization of flight trajectories
-	-	-	-	-	✓	✓	-	-	-	-	Adaption of aircraft design
✓	✓	✓	(✓)	✓	-	✓	-	(✓)	-	-	Assessment for global route network
-	-	-	-	-	✓	✓	(✓)	✓	(✓)	(✓)	Consideration of financial impacts
-	✓	✓	-	✓	✓	✓	✓	✓	✓	✓	Consideration of global temperature change
-	✓	✓	-	(✓)	-	✓	(✓)	✓	(✓)	(✓)	Consideration of temporal and regional dependency of perturbations of different forcing agents

4. CONCEPT DESIGN (SOLUTIONS)

The climate impact of non-CO₂ emissions is highly dependent on atmospheric background conditions and therefore sensitive to the locus and time of the emission (Sect. 3). Hence, the transfer of this knowledge in the route-planning and aircraft design process offer the potential to reduce the overall aviation net climate impact for a given transport volume.

As mitigation strategies of individual atmospheric forcing agents vary greatly from each other, the optimisation of one agent, e.g. fuel burn, may provoke a drawback of another, e.g. amount of emitted NO_x . Thus, a proper consideration of the different cause-effect principles and perturbation lifetimes is essential to attain optimal trajectories with respect to climate. In order to achieve this, grids of **climate cost functions** Ψ_i (*climate penalty functions*) of different forcing agents i (e.g. for NO_x , H_2O , and contrails) can be used as interfaces between climate-chemistry modelling and route-planning software. The superposition of these climate cost functions enables the quantification of the net climate impact of different aircraft emissions at any flight point (time and locus) and hence its minimisation through operational route changes (see figure 6). In dependency of expertise and goal and scope of analysis the level of detail of climate cost

functions differ significantly, e.g. in the number of dimensions, which range from 1D (single dependency of altitude h) [48] to 4D (dependency of longitude λ , latitude φ , altitude h , and time t) [47,49].

As illustrated in figure 6, optimal trajectories with respect to climate cause detours, which may result in monetary penalties. Hence, there is a need to trade-off these contradictory objective functions. This can be realised by introducing an **overall cost function** J_{total} (*overall penalty function*), which is defined in equation 1 as sum of the products of monetary weighting factor c_Y and monetary cost function Y , and climate weighting factor c_ψ and path integral of climate cost functions $\Psi_i \cdot ds(t)$ of all species.

$$J_{total} = c_Y \cdot Y(m_{Fuel}, t, s(t)) + c_\Psi \cdot \sum_{i=1}^n \int_{s_0}^{s_f} \Psi_i(\lambda, \varphi, h, t) \cdot ds(t)$$

The **monetary cost function** γ (*monetary penalty function*) is depending on mission fuel m_{Fuel} , time-dependent costs (e.g. for maintenance and crew), and path-dependent costs, such as overflight charges.

The largest amount of emission per flight is emitted during the cruise phase at altitudes which are particularly sensitive to climate. The longer the cruise phase, the greater the flexibility for lateral route changes. Thus, long-range flights offer the largest mitigation potential by trajectory optimisation.

As there are several restrictions, such as fixed airspace structures and air traffic management procedures, flight trajectories cannot be modified at will. For this purpose climate optimal trajectories differ mainly in the kind (lateral and/or vertical) and amount (few major or several minor changes) of re-routing. Hence, they can be clustered in strategic (*climate-based*) and tactical (*weather-based*) concepts of air traffic operations.

The following paragraphs provide an overview of the basic ideas of these concepts on the one hand, and climate based aircraft designs on the other. A summary of the results of

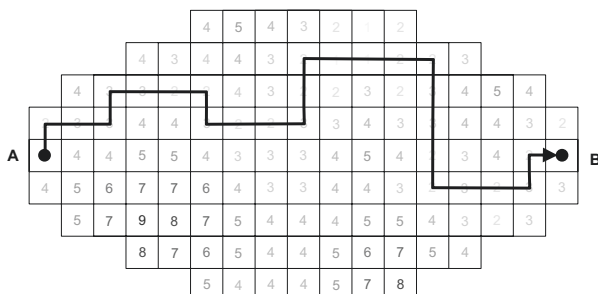


FIG 6. Schematic sketch of a 2D grid of climate cost functions $\Psi(\lambda, \varphi)$. The bold curve represents the path $s(t)$ of the optimal trajectory with respect to climate from A (origin) to B (destination). Figures symbolise the intensity of climate impact.

selected studies, which devoted their work to the analysis of climate optimal trajectories, is given in Tab. 1.

Strategic Optimisations of Air Traffic Operations

Since H_2O , CH_4 and O_3 and CIC show a high altitude dependency, a strategic change of the cruise flight altitudes is a potential operational mitigation option. Sausen et al. (1998) analysed the contrail mitigation potential by shifting air traffic globally up and down by 1 km [40]. Fichter et al. (2005) demonstrated a high RF reduction potential of non- CO_2 emissions for a cruise altitude shift to lower flight levels and vice versa [41]. Flying higher (*through LS*) is not applicable globally, as tropical tropopause exceeds maximum flight levels of subsonic aircraft. Any reduction of cruise altitude results in an increase of drag and in an increase of the fuel flow. Flying lower would therefore come along with reduced flight speeds, off-design operations of current aircraft and subsequently to an increase in cash operation costs (COC). Therefore, Koch et al. quantified the cost-benefit potential of flying lower and slower for a world fleet of current long-range aircraft, which allows the trade-off between climate impact reduction and economical penalties [50,51,52]. According to their results, it is possible to mitigate the fleet average temperature response (ATR, global mean surface temperature response integrated over 100 years) by 4.7 % without additional financial costs or by 41.8 % for a 10 % increase in COC (compare figure 7) [51,52].

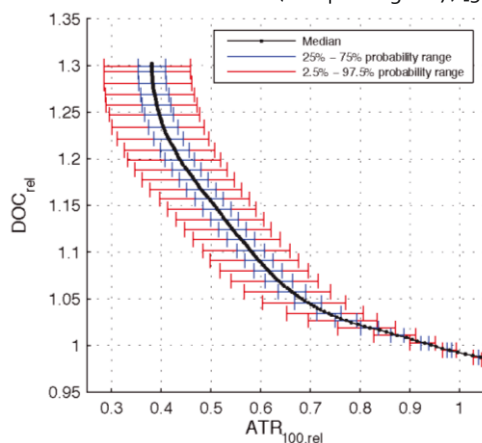


FIG 7. Cost-benefit-potential (DOC vs. ATR) of flying lower and slower for A330-200. The Pareto front is resulting from altered cruise conditions on a global route network containing all conducted flights of this aircraft type in 2006 [52].

Tactical Optimisations of Air Traffic Operations

In place of a strategic change of the cruise altitude, the climate impact of aviation can be reduced by avoiding climate sensitive regions for all components through several tactical, weather-dependent changes in cruise altitudes and lateral routing. As weather-dependent optimisations are assumed to require more frequent flight level changes, there will probably be a rise of COC due to an increase of ATM workload.

Most studies about weather optimised flight routing focus on the correlation between ISSRs (contrail) avoidance and fuel penalties [39,42,53,54,55,56]. Schumann et al. (2011), for instance, optimised the climate impact of contrails and CO_2

fuel consumption of flight trajectories by enhancing contrails during day time (cooling) and by avoiding contrails during night (warming) through flight level changes of typically 2000 ft (610 m) up or down [54]. Chen et al. (2014) optimised flight trajectories with respect to fuel consumption and environmental cost of climate impact reduction, expressed as monetary social cost of carbon, and demonstrated the influence of weather forecasts accuracy on the environmental net benefit [55].

The EU FP7 Project REACT4C (Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate) extended previous work by considering an increased number of forcing factors (CO_2 , NO_x , H_2O , soot, CIC) [43,49,57,58]. On basis of 4-D climate cost functions they optimised the transatlantic air traffic with respect to climate and economy. As optimised flight trajectories depend on each other, their approach includes conflict avoidance to ensure an optimal traffic flow for the in all sectors, as illustrated in figure 8.

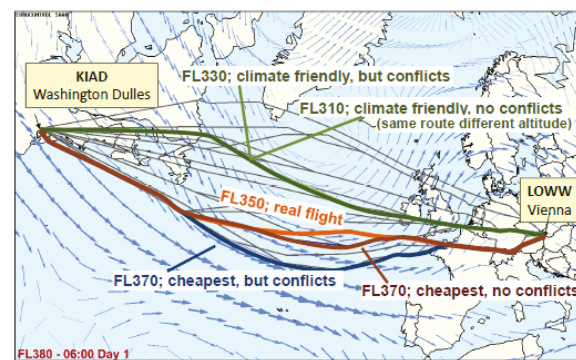


FIG 8. Optimised trajectories with respect to climate and economy taken from Grewe et al. (2014) [47]. The light brown trajectory represents the real flight at that day between Washington Dulles (KIAD) and Vienna (LOWW). Optimal trajectories with respect to economics are given in blue (conflicts) and dark brown (no conflicts). Optimised trajectories with respect to climate and economy are shown in green (trajectories with and without conflict avoidance differ only in cruise altitude). Arrows represents the wind field at flight level 380.

Climate based Aircraft Design

Vertical changes of the flight trajectories cause performance losses of current aircraft. As aircraft are designed to maximise their earning capacity for a particular market, these performance losses would lead to a competitive disadvantage. Therefore, both tactical and strategic concepts of air traffic operations may result in the need for an optimisation of aircraft.

Antoine et al. [59], Schwartz et al. [60,61], and Koch et al. [51,52] suggested an aircraft re-design for the new design point (cruise speed and cruise altitude) to counteract the resulting performance loss of current aircraft *by flying lower and slower*. The optimisation of these aircraft was based on few key design variables, such as wing area, wing aspect and taper ratio, and wing sweep.

According to Koch (2013) the superposition of both, climate optimised flight routing and aircraft re-design, enables a reduction of the climate impact by 53.5 % for 10 % COC increase relative to current air traffic; respectively a mitigation by 32.3 % without any increase in COC; fig. 9 [52].

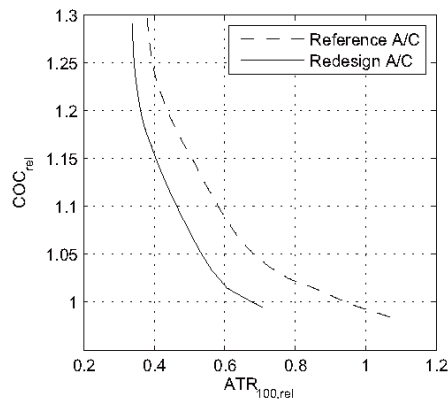


FIG 9. Pareto frontiers of climate impact reduction potential in terms of average temperature response ATR (for 100 years) and increased cash operated costs (COC) for the fleets of reference and redesigned aircraft A332 in 2006 [52]

Even though tactical concepts of air traffic operations are assumed to have more potential to mitigate the climate impact of aviation than strategic ones, it has not yet been proven [45]. For this reason the DLR project WeCare focuses on the comparison of these mitigation potentials.

4. EVALUATION METHODOLOGY (ASSESSMENT)

As described in the previous sections, a multi-disciplinary and multi-perspective systems design approach is necessary to assess the cost-benefit potentials of different mitigation strategies. Such an approach is developed within the DLR project WeCare (Utilizing Weather information for Climate efficient and eco-efficient future aviation), including aircraft and engine design, calculations of trajectories, emissions, climate response and operating costs, as well as ATM compatibility checks. Among the objectives of the project is to compare cost-benefit potentials of a tactical and a strategic optimisation of air traffic operations. WeCare's simulation process, as shown in figure 10, is split into an inner and an outer circle that are executed consecutively and

iteratively. In the first simulation loop (*inner circle*), the flight routing of current aircraft is optimised strategically (Concept A) and tactically (Concept B) with respect to climate and economics. In a second phase (*outer circle*) aircraft are re-designed to new design points for reduced climate impact.

In the following, the individual steps of this simulation process are outlined:

Reference traffic scenario

The reference traffic scenario of the study is defined as the actual air traffic of a single day between North America and Europe. The North Atlantic airspace is the busiest oceanic airspace in the world and highly sensible to climate, especially to NO_x emissions and CIC. The busiest day in 2012 of the North Atlantic airspace defines route network, aircraft types, flight frequency and flight departure times, as well as economic assumptions, such as crude oil price and costs for labour and fees.

Aircraft and Engine Design

The aircraft design and engine performance calculation is performed twice, initially at the beginning of the simulation process and secondly after the derivation of new design points.

In the first instance, aircraft models of selected aircraft types are generated. Therefore, geometry, structure, aerodynamics, and engine performance are modelled and calibrated according to the real aircraft. The resulting engine performance map, for instance, consists of thrust and fuel flow characteristics as well as emission indices (i.e. NO_x , CO, soot) as function of flight level and Mach number.

In the second instance current aircraft are optimised with respect to climate to newly derived design conditions of tactical and strategic concepts of air traffic operations. The re-design of aircraft includes optimisations of key design

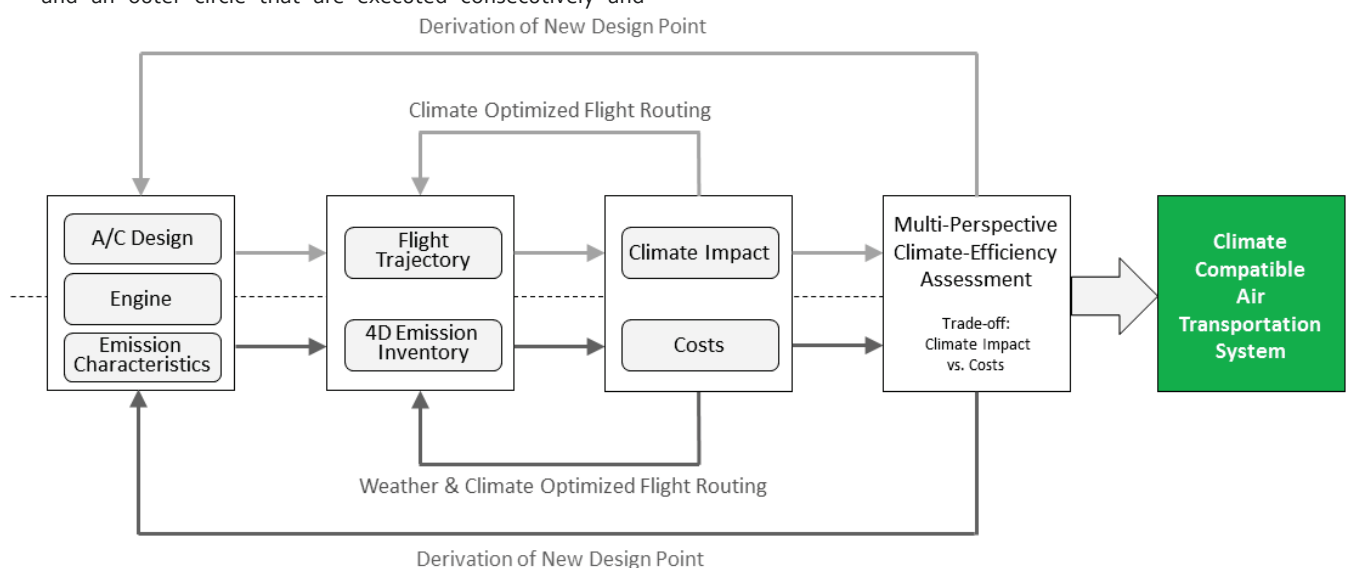


FIG 10. Simulation process as applied in the DLR project WeCare. The inner circle represents a tactical (*weather-based*) and strategic (*climate-based*) optimisation of air traffic operations with respect to climate and economics; the outer circle illustrates the technological adaption of aircraft to new design points for both concepts.

parameters, such as aspect ratio, taper ratio, and leading edge sweep angle of the wing and tail plane. Design constraints, payload range capabilities, and technology level are kept constant to provide a fair comparison between current and re-designed aircraft. Also, the engine performance model remains unchanged to ensure equal emission characteristics for the second assessment loop.

For the derivation of new design points the frequency distribution of cruise flight conditions (cruise flight level and cruise speed) with high cost-benefit potential (reduction of climate impact vs. increase of monetary costs) is calculated for both concepts.

Climate impact of reference traffic scenario

Before estimating the climate impact mitigation potential of tactical and strategic optimisation of air traffic operations, the reference climate impact of current air traffic has to be determined.

Therefore, route-planning and mission simulation tools are used to calculate optimal flight trajectories with respect to economics for all routes of the reference traffic scenario. Costs per flight are expressed by the metric cash operating costs, including cost for fuel, crew, maintenance, and fees (landing and navigation).

Climate cost functions for carbon dioxide, water vapour, nitrogen oxides, and contrails enable the quantification of the resulting climate impact (expressed in changes in global average temperature response; ATR) of each aircraft and route. These functions are calculated in a comprehensive global climate-chemistry model and allocate a corresponding climate response to an aircraft emission at a special location and time. The global mean surface temperature response integrated over 100 years, as the climate metric of choice, is derived from the quantified radiative forcing.

Optimisation of flight trajectories with respect to climate and economics

Flying lower and slower is the core idea of the **strategic concept** (Concept A), see figure 11. In consideration of climatological mean data, the climate impact of H_2O , CH_4 , O_3 and CIC is mitigated by a general change of cruise altitude and speed. For each route of the reference scenario the average temperature response and cash operating costs are calculated for varying cruise Mach numbers (Ma_{Cr}) and initial cruise altitudes (ICA_{Cr}) with the simulation chain described above to attain a Pareto front of the best combinations of ATR and COC changes (*exhaustive search optimisation*). To ensure that aircraft is capable to perform these flights, there is a check of the aircraft specific flight envelope limitations (buffeting and speed, altitude and stall limits).

The **tactical concept** (Concept B) tries to minimise both, the climate impact and cash operating costs of flight trajectories in consideration of typical weather situations by several minor trajectory changes in lateral and vertical direction. Contrary to concept A, in which the same strategic change of flight altitude and speed is performed every day, the

resulting tactical optimised flight trajectories differ every day in dependency of actual weather situation. Monetary (c_γ) and climate (c_ψ) weighting factors are changed incrementally to attain a Pareto front between climate reduction potential of tactical routing and increased COC, which is similar to concept A.

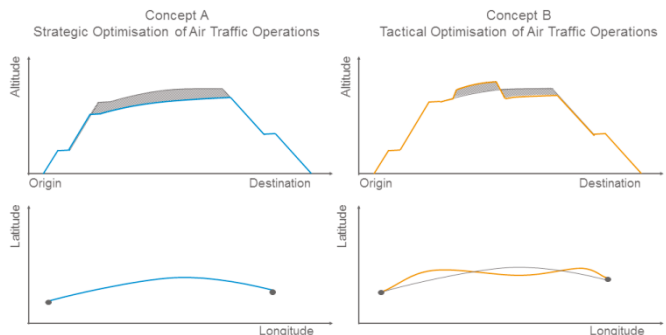


FIG 11. Strategic, climate-dependent optimisation of air traffic (left; same change in flight trajectory is performed every day) vs. tactical, weather-dependent optimisation (right; different flight trajectories for every day). The thin black lines represent the reference trajectories with minimal costs.

As the implementation of strategic and tactical route optimisation requires climatological mean data on the one hand, and actual weather situations on the other, separate climate cost functions for CO_2 , H_2O , NO_x and CIC are calculated in a comprehensive global climate-chemistry model for both concepts. To represent seasonal weather changes, the climate cost functions of concept B are calculated for several typical weather patterns; each of them represents a characteristic day of the year 2012. Since there are weather fluctuations during day, these climate cost functions have a time dependency contrary to those of concept A. Therefore, variations in the dimensions of the climate cost functions may occur, as it does, for example, for contrails: $\Psi_{A,Contrails}(\lambda, \varphi, h)$ vs. $\Psi_{B,Contrails}(\lambda, \varphi, h, t)$. This means, that an aircraft emission at a special location and time may cause a slightly different climate response for both concepts. To ensure comparability of the resulting mitigation potentials these deviations are quantified by climate specialists.

Multi-perspective climate-efficiency assessment

The assessment of strategic and tactical concepts of air traffic operations is based on the trade-off (Pareto frontiers) between climate impact reduction potential and increased operating costs: *How big is the climate impact reduction potential of concept A and concept B for an increase of x % of cash operating costs?*

On the one hand, the climate impact mitigation potential of tactical routing is assumed to exceed the mitigation potential of the strategic concept for a given aircraft, since climate sensitive regions for all components can be circuited more efficiently [45]. On the other hand, the climate potential of aircraft optimisation with respect to climate is higher for strategic concepts, as there a larger deviations between current and optimised design points of aircraft due to major changes in cruise altitude. For precisely that reason, the overall cost-benefit-potential of the superposition of route optimisation with respect to climate and economics, and

aircraft re-design has to be assessed for both concepts (*second loop of the simulation process*).

For tactical routing its net benefit is highly dependent on the accuracy of actual weather data. As it is unrealistic to have perfect forecast data (meteorological and air-chemistry information), it is conceivable that weather optimised flights pass climate sensitive regions or avoid insensitive ones at times. Therefore, the real net benefit of tactical routing based on forecast data is likely to be smaller than the estimated one.

Furthermore, the implementation of tactical routing depends on the flexibility of future ATM. Avoiding climate sensitive and preferring climate friendly regions causes more frequent vertical and lateral route changes, which may result in an increase of air traffic controller workload and may provoke new high density regions. To take these effects into consideration, the individual optimised flight trajectories are integrated into an overall air traffic simulation for conflict prevention. Accessorily, analyses are conducted to quantify additional work and expense of ATM.

The implementation of strategic concepts (general change of cruise altitude and speed) can be handled easier from ATM's point of view; but flying lower, within the weather-creating layer of the atmosphere, increases the probability of inflight turbulences. Additionally, a reduction of the flight speed may be at odds with curfew regulation at destination airport and minimum buffer times and hence, may influence the flight schedule of airlines and fleet utilisation.

Further studies of WeCare focus on modelling the future evolution of global air transport until the year 2050, which is expressed by the development of four interacting key drivers (socio economics, demand between origins and destinations, route-network, and amount and aircraft type used). The scenarios that are created are used to quantify the cumulative global net impact of operational (e.g. flying slower, intermediate stop operations) and technological measures (e.g. launching a new aircraft) over time.

6. CONCLUSIONS AND OUTLOOK

DLR is developing within the project WeCare a methodology to assess the cost-benefit potential of climate optimal trajectories, including aircraft and engine design, calculations of trajectories, emissions, climate temperature response and operating costs, as well as ATM compatibility checks. The objective of the study is to improve a general understanding of cause-effect relationships between ATS and climate, and to identify and quantify the net benefit of different mitigation strategies.

As global air traffic is assumed to grow with an annual rate of 4.7 % [1], it is unlikely that the implementation of a single mitigation strategy is enough to take aviation in a more environmentally-friendly direction in the future. Climate-neutral growth can only be achieved by the combination of promising technological, operational and regulative mitigation strategies which are compatible to each other.

Upcoming work will implement and refine the methodology introduced here.

ACKNOWLEDGMENTS

The following partner institutions contribute to the DLR project WeCare (Utilizing Weather information for Climate efficient and eco-efficient future aviation).

- i. DLR – Atmospheric Physics
- ii. DLR – Air Transportation Systems
- iii. DLR – Flight Experiments
- iv. DLR – Flight Guidance
- v. DLR – Propulsion Technology
- vi. DLR – Simulation and Software Technology

LITERATURE

- [1] Airbus: Global Market Forecast. Future Journeys 2013 - 2032, 2013.
- [2] Lee, D.; Fahey, D.; Forster, P.; Newton, P.; Wit, R.; Lim, L.; Owen, B.; Sausen, R.: Aviation and global climate change in the 21st century. *Atmospheric Environment*, 43, 3520–37, 2009.
- [3] Intergovernmental Panel on Climate Change: Fourth assessment report - Climate change: Synthesis Report, 2007
- [4] Langhans, P.; Gollnick, V.; Stumpf, E.: A Holistic Approach To Evaluate The Air Transportation System. 26th Int. Congress of the Aeronautical Sciences (ICAS), 2008.
- [5] Weiss, M.; Gmelin, T.; Dzikus, N.; Sun, X.: Enhanced Assessment of the Air Transportation System. 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, 2011.
- [6] Ghosh, R.; Schilling, T.; Wicke, K.: Theoretical Framework of Systems Design for the Air Transportation System including an inherently quantitative Philosophy of Scenario Development. 29th International Council of the Aeronautical Sciences (ICAS), 2014.
- [7] Miser, H.: Handbook of Systems Analysis. Volume 1, 1981.
- [8] Intergovernmental Panel on Climate Change: Aviation and the Global Atmosphere. Summary for Policymakers, 1999.
- [9] Langhans, S.; Linke, F.; Nolte, P.; Gollnick, V.: System Analysis for an Intermediate Stop Operations Concept on Long Range Routes. *Journal of Aircraft*, 50, 1, 29–37, 2013.
- [10] Linke, F.; Langhans, S.; Gollnick, V.: Studies on the Potential of Intermediate Stop Operations for Today's Airlines. 16th Air Transport Research Society (ATRS) World Conference, 2012.
- [11] Stratton, R.; Wong, H. M.; Hileman, J.: Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels. Report No. PARTNER-COE-2010-001, 2010.
- [12] Green, J.: The potential for reducing the impact of aviation on climate. *Technology Analysis & Strategic Management*, 21, 1, 39–59, 2009.
- [13] Oliverira, R. F. de; Büskens, C.: Emission-optimal flight trajectories with weather hazard avoidance and 4D wind modeling. 3rd CEAS Air and Space Conference; 21st AIDAA Congress, 2011.
- [14] Sridhar, B.; Ng, H.; Linke, F.; Chen, N.: Benefits Analysis of Wind-Optimal Operations for Trans-Atlantic Flights. 14th AIAA Aviation Technology, Integration, and Operations Conference, 2014.
- [15] SESAR: The Roadmap for Sustainable Air Traffic Management. European ATM Master Plan, 2, 2012.
- [16] Mulkerin, T.: Free Flight is in the Future. Large-Scale Controller Pilot Data Link, Communications Emulation Testbed. *IEEE Aerospace and Electronic Systems Magazine*, 18, 23–27, 2003.
- [17] Miake-Lye, R.: Advancing the understanding of aviation's global impact. Report No. PARTNER-COE.2005-003, 2005.
- [18] Grewe, V.; Stenke, A.: AirClim: an efficient tool for climate evaluation of aircraft technology. *Atmospheric Chemistry and Physics*, 8, 4621–39, 2008.
- [19] Gierens, K.; Lim, L.; Eleftheratos, K.: A Review of Various Strategies for Contrail Avoidance. *The Open Atmospheric Science Journal*, 2, 1–7, 2008.

- [20] Grewe, V.; Dameris, M.; Fichter, C.; Sausen, R.: Impact of aircraft NO_x emissions. Part 1. Interactively coupled climate-chemistry simulations and sensitivities to climate-chemistry feedback, lightning and model resolution. *Meteorologische Zeitschrift*, 11, 3, 177–86, 2002.
- [21] Lee, D.; Pitari, G.; Grewe, V.; Gierens, K.; Penner, J.; Petzold, A.; Prather, M.; Schumann, U.; Bais, A.; Bernsten, T.; Iachetti, D.; Lim, L.; Sausen, R.: Transport impacts on atmosphere and climate: Aviation. *Atmospheric Environment*, 44, 4678–734, 2010.
- [22] Holmes, C.; Tang, Q.; Prather, M.: Uncertainties in climate assessment for the case of aviation NO. *Proceeding of the National Academy of Sciences of the USA (PNAS)*, 180, 27, 10997–1002, 2011.
- [23] Döpelheuer, A.; Lecht, M.: Influence of Engine Performance on Emission Characteristics. *RTO Symposium*, 1998.
- [24] Paassen, D. M. van; Ruijgrok, G. J. J.: *Elements of Aircraft Pollution*, 2005.
- [25] Wang, Z.; Chien, C.-J.; Tonnesen, G.: Development of a tagged species source apportionment algorithm to characterize three-dimensional transport and transformation of precursors and secondary pollutants. *Journal of Geophysical Research*, 114, D21206, 2009.
- [26] Lacis, A.; Wubbles, D.; Logan, J.: Radiative Forcing of Climate by Changes in the Vertical Distribution of Ozone. *Journal of Geophysical Research*, 95, 7, 9971–81, 1990.
- [27] Grewe, V.; Dameris, M.; Fichter, C.; Lee, D.: Impact of aircraft NO_x emissions. Part 2: Effects of lowering the flight altitude. *Meteorologische Zeitschrift*, 11, 3, 197–205, 2002.
- [28] Fichter, C.: *Climate Impact of Air Traffic Emissions in Dependency of the Emission Location and Altitude*, Dissertation. Manchester Metropolitan University, 2009.
- [29] Schumann, U.: On conditions for contrail formation from aircraft exhausts. *Meteorologische Zeitschrift*, 5, 4–23, 1996.
- [30] Schumann, U.: Formation, properties and climatic effects of contrails. *Comptes Rendus Physique*, 6, 549–65, 2005.
- [31] Sausen, R.; Isaksen, I.; Grewe, V.: Aviation radiative forcing in 2000. An update on IPCC, *Meteorologische Zeitschrift*, 14, 4, 555–61, 2005.
- [32] Burkhardt, U.; Kärcher, B.: Global radiative forcing from contrail cirrus. *Nature Climate Change*, 1, 54–58, 2011.
- [33] Spichting, P.; Gierens, K.; Leiterer, U.; Dier, H.: Ice supersaturation in the tropopause region over Lindenberg, Germany. *Meteorologische Zeitschrift*, 12, 3, 143–56, 2003.
- [34] Gierens, K.; Spichting, P.: On the size distribution of ice-supersaturated regions in the upper troposphere and the lower stratosphere. *Ann. Geophysicae*, 18, 499–504, 2000.
- [35] Jeßberger, P.; Voigt, C.; Schumann, U.; Sölch, I.; Schlager, H.; Kaufmann, S.; Petzold, A.; Schäuble, D.; Gayet, J. F.: Aircraft type influence on contrail properties. *Atmospheric Chemistry and Physics*, 13, 11965–84, 2013.
- [36] Schumann, U.: Influence of propulsion efficiency on contrail formation. *Aerospace Science and Technology*, 4, 391–401, 2000.
- [37] Meerkötter, R.; Schumann, U.; Doelling, D.; Minnis, P.; Nakajima, T.; Tsushima, Y.: Radiative forcing by contrails. *Ann. Geophysicae*, 17, 1080–94, 1999.
- [38] Schumann, U.: A contrail cirrus prediction model. *Geoscientific Model Development Discussions*, 5, 543–80, 2012.
- [39] Mannstein, H.; Schumann, U.: Aircraft induced cirrus over Europe. *Meteorologische Zeitschrift*, 14, 4, 549–54, 2005.
- [40] Sausen, R.; Gierens, K.; Ponater, M.; Schumann, U.: A Diagnostic Study of the Global Distribution of Contrails Part 1. Present Day Climate. *Theor. Appl. Climatol.*, 61, 127–141, 1998.
- [41] Fichter, C.; Marquart, S.; Sausen, R.; Lee, D.: The impact of cruise altitude on contrails and related radiative forcing. *Meteorologische Zeitschrift*, 14, 4, 563–72, 2005.
- [42] Sridhar, B.; Chen, N.; Linke, F.; Ng, H.: Design of Aircraft Trajectories based on Trade-offs between Emission Sources. 9th USA/Europe Air Traffic Management Research and Development Seminar, 2011.
- [43] Grewe, V.; Frömming, C.; Matthes, S.: Aircraft routing with minimal climate impact: The REACT4C cost function modelling approach. *Geosci. Model Dev.*, 7, 175–201, 2014.
- [44] Hendricks, J.; Kärcher, B.; Lohmann, U.: Effects of ice nuclei on cirrus clouds in a global climate model. *Journal of Geophysical Research*, 116, D18206, 2011.
- [45] Schumann, U.: *Atmospheric Physics. Background - Methods - Trend*. Heidelberg, 2012.
- [46] Kärcher, B.; Yu, F.: Role of aircraft soot emissions in contrail formation. *Geophysical Research Letters*, 36, L01804, 2009.
- [47] Grewe, V.: *Climate Impact of Air Traffic. Lesson*, TU Berlin, 2014.
- [48] Schwartz, E.; Kroo, I.; Waitz, I.: Metric for Comparing Lifetime Average Climate Impact of Aircraft. *AIAA Journal*, 49, 8, 1600–13, 2011.
- [49] Frömming, C.; Grewe, V.; Jöckel, P.: Climate cost functions as a basis for climate optimized flight trajectories, 10th USA/Europe Air Traffic Management Research and Development Seminar (ATM2013), 2013.
- [50] Koch, A.; Lührs, B.; Dahmann, K.; Linke, F.; Grewe, V.; Litz, M.; Plohr, M.; Nagel, B.; Gollnick, V.; Schumann, U.: Climate impact assessment of varying cruise flight altitudes applying the CATS simulation approach. 3rd CEAS Air & Space Conference; 21st AIAA Congress, 2011.
- [51] Koch, A.; Lührs, B.; Dahlem, F.; Lau, A.; Linke, F.; Dahmann, K.; Gollnick, V.; Schumann, U.: Studies on the climate impact mitigation potential of actual and future air traffic. An integrated cost-benefit assessment applying the CATS simulation approach. 16th Air Transport Research Society (ATRS) World Conference, 2012.
- [52] Koch, A.: *Climate Impact Mitigation Potential given by Changes in Aircraft Design and Operations. A Contribution to a Climate Compatible Air Transportation System*, Dissertation. TU Hamburg-Harburg, 2013.
- [53] Campbell, S.; Neogi, N.; Bragg, M.: An Operational Strategy for Persistent Contrail Mitigation. 9th AIAA Aviation Technology, Integration, and Operations Conference (ATIO) and Aircraft Noise and Emissions Reduction Symposium (ANERS), 2009.
- [54] Schumann, U.; Graf, K.; Mannstein, H.: Potential to reduce the climate impact of aviation by flight level changes. 3rd AIAA Atmospheric Space Environments Conference, 2011.
- [55] Chen, N.; Kirschen, P.; Sridhar, B.; Ng, H.: Identification of Flights for Cost-Efficient Climate Impact Reduction. AIAA Aircraft Noise and Emissions Reduction Symposium, 2014.
- [56] Ng, H.; Sridhar, B.; Chen, N.; Li, J.: Three-Dimensional Trajectory Design for Reducing Climate Impact of Trans-Atlantic Flights. 14th AIAA Aviation Technology, Integration, and Operations Conference, 2014.
- [57] Frömming, C.; Ponater, M.; Dahmann, K.: Aviation-induced radiative forcing and surface temperature change in dependency of the emission altitude. *Journal of Geophysical Research*, 117, D19104, 2012.
- [58] Matthes, S.: REACT4C - Climate Optimised Flight Planning. Knörzer, D.; Szodrich, J.: *Innovation for Sustainable Aviation in a Global Environment*, 2012.
- [59] Antoine, N.; Kroo, I.: *Framework for Aircraft Conceptual Design and Environmental Performance Studies*. AIAA Journal, 43, 10, 2100–09, 2005.
- [60] Schwartz, E.; Kroo, I.: Aircraft Design: Trading Cost and Climate Impact. AIAA Aerospace Sciences Meeting 47, 2009.
- [61] Schwartz, E.: *Aircraft Design for reduced Climate Impact*, Dissertation. Stanford University, 2011.
- [62] Grewe, V.; Plohr, M.; Cerino, G.; Di Muzio, M.; Deremaux, Y.; Galerneau, M.; de Saint Martin, M.; Chaika, T.; Hasselrot, A.; Tengzelius, U.; Korovkin, V.: Estimates of the Climate Impact of Future Small-Scale Supersonic Transport Aircraft - Results from the HISAC EU-Project, *The Aeronautical Journal*, 114, 199–206, 2010.