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A Concept for Multi-Criteria Environmental Assessment of Aircraft Trajectories

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Abstract: Comprehensive assessment of the environmental aspects of flight movements is of increasing interest to the aviation sector as a potential input for developing sustainable aviation strategies that consider climate impact, air quality and noise issues simultaneously. However, comprehensive assessments of all three environmental aspects do not yet exist and are in particular not yet operational practice in flight planning. The purpose of this study is to present a methodology which allows to establish a multi-criteria environmental impact assessment directly in the flight planning process. The method expands a concept developed for climate optimisation of aircraft trajectories, by representing additionally air quality and noise impacts as additional criteria or dimensions, together with climate impact of aircraft trajectory. We present the mathematical framework for environmental assessment and optimisation of aircraft trajectories. In that context we present ideas on future implementation of such advanced meteorological services into air traffic management and trajectory planning by relying on environmental change functions (ECFs). These ECFs represent environmental impact due to changes in air quality, noise and climate impact. In a case study for Europe prototype ECFs are implemented and a performance assessment of aircraft trajectories is performed for a one-day traffic sample. For a single flight fuel-optimal versus climate-optimized trajectory solution is evaluated using prototypic ECFs and identifying mitigation potential. The ultimate goal of such a concept is to make available a comprehensive assessment framework for environmental performance of aircraft operations, by providing key performance indicators on climate impact, air quality and noise, as well as a tool for environmental optimisation of aircraft trajectories. This framework would allow studying and characterising changes in traffic flows due to environmental optimisation, as well as studying trade-offs between distinct strategic measures.

Keywords: air traffic management; environment; climate impact; trajectory optimisation; climate impact mitigation; climate-optimized trajectories; environmental impact mitigation; air quality; environmental performance; ATFM; advanced meteorological service

1. Introduction

Consideration of environmental aspects in en-route flight planning is generally not operational practice apart from the economic goal to minimise fuel use and hence to reduce CO_2 emissions. Note that non-operational, i.e., research-related optimization tools include estimates for climate impacts in route optimization (e.g., [1]). However, only recently climate impact indicators were considered in more detail, which take into account more than mere emission amounts, for example contrail occurrence and ozone changes from NO_x emissions [2–8]. The reasons for this include a low TRL (technology readiness level) of a flight planning method that considers a multi-criteria environmental impact assessment and remaining uncertainty on strategic metrics of environmental impact to motivate environmental flight planning.

Aircraft trajectory optimisation has already started in the 1960s [9] while during the last decades development of approaches has been strongly supported by increasing capabilities of high performance computing. Optimisation tools exist that incorporate more detailed aircraft performance data, that consider meteorological data, e.g., wind and humidity, and that perform a full 4D optimisation. In common practice, route optimisation is driven by cost minimisation, hence those environmental aspects which translate into cash operating costs (COC), are taken into account. E.g., emissions of carbon dioxide enter into route optimisation as they directly correlate to fuel consumption. Other environmental impacts enter in COC optimisation through charges, e.g., noise or nitrogen oxide (NO_x) emissions near an airport in case of associated airport charges.

However, besides CO_2 climate impact, air traffic contributes to anthropogenic warming also by non-CO_2 impacts which are strongly dependent on the location, altitude, and time of emission. Overall, air traffic emissions contribute to anthropogenic warming by around 5% through CO_2 and non-CO_2 impacts [10,11] including contrail cirrus. Aviation stakeholders, European and national authorities implemented a series of initiatives that comprise in their workprogrammes the intention to make future aviation sustainable, e.g., the European Commission implemented under its Framework Programmes, CleanSky Joint Technology Initiative (JTI), 'green' aeronautical projects and SESAR2020 Joint Undertaking (JU). Previous research has shown that changing aircraft trajectories to avoid climate sensitive regions has the potential to reduce the climate impact of aviation [12]. Studies which focus on individual impact types e.g., [2,3,13–15] presented trade-offs between climate-optimised and cost-optimised trajectories for various regions of the earth (cross-polar, North Atlantic, Pacific traffic). More recent studies similarly exploited benefit and costs of contrails avoidance by analysing an aircraft trajectory [16] or tested route optimisation for climate optimisation [17].

Current daily operational flight planning has no information on environmental impacts of cruise emissions and a trajectory optimisation based on a climate impact assessment is not performed. Just recently individual aspects of climate impact from aviation were included in research-related optimisation tools (see above). The European project REACT4C [18] went a step beyond and focused on climate-optimised routing strategies primarily in the North Atlantic airspace using climate impact information in a flight planning tool [18,19]. Under current day ATM (Air Traffic Management) constraints and operational boundary conditions trajectories were optimised delivering cost-optimal and climate-optimal routes and vertical flight profiles that follow the existing air transport route system and include step climbs where appropriate. Based on a detailed weather classification [20] five representative days for winter and three days for summer were selected to calculate climate cost functions for these individual days. These climate cost functions comprise the impact of a local emission on global climate change and are used in a traffic simulator to optimise the traffic flow with respect to climate impact. The results from REACT4C [7,21] indicate, in a one day case study of a zonal weather pattern in winter, a large mitigation potential with a reduction of the climate impact of around 25% at a cost increase of about 0.5% for westbound trans-Atlantic flights, but lesser potential for eastbound flights.

In this paper we want to go another step forward, combining the climate and cost optimisation of REACT4C with an environmental optimisation near airports, regarding noise and regional air quality. Here, we use the term climate change function or environmental change function for a measure which quantifies environmental impact associated with aviation emission as a function of location and time of emission. This concept replaces the term climate cost function from earlier studies, by expanding the scope from climate to environment, using change instead of costs to emphasize units used being, e.g., climate impact measured as surface temperature change per kilogramm emission. The project ATM4E (Air Traffic Management for Environment, SESAR2020 (SESAR Joint Undertaking, European Research Programme, Exploratory research) explores the feasibility of such a concept for a multi-criteria, multi-dimensional environmental assessment of ATM operations working towards environmental optimisation of air traffic operations in the European airspace [22].

The objective of this paper is (1) to present a concept for multi-criteria environmental assessment of aircraft trajectories, which relies on a set of environmental change functions (ECFs). These ECFs represent environmental impact of an aviation emission due to changes in air quality, noise and climate impact. (2) We introduce meteorological (MET) data products which represent environmental impact at given location and time, so called environmental change functions, which we consider as advanced meteorological information which should be made available via ATM information infrastructure. We demonstrate as well how these individual change functions can be mathematically combined in order to yield an overall objective function, required for trajectory optimisation. Finally, (3) we perform a trajectory optimisation under cost-optimal conditions, providing environmental performance data for the assessment of aircraft trajectories using prototype ECFs. We present the overall approach to apply such environmental optimisation framework to the European ATM Network. For a single-flight we generate a Pareto front comparing fuel-optimal with climate-optimized solution. Section 2 describes methods available at start of ATM4E and general ideas. Section 3 describes how these methods are further developed in ATM4E to develop a concept of environmental change functions (ECFs). In Section 4 case studies for Europe are presented, while Section 5 presents options to integrate advanced MET services in future ATM. Section 6 discusses results and concludes this study.

Within ATM infrastructure, e.g., SESAR in Europe, meteorological data and information is often considered as part of the system infrastructure being called MET information system. We use this convention in a similar way in this study. Individual criteria of environmental performance can also be considered as distinct dimensions in an optimisation problem, which is why we also use the term multi-dimensional environmental assessment.

2. Models and Methods for Environmental Assessment

In this study we present a concept which aims at evaluating the environmental impact of aircraft trajectories on the environment, climate, air-quality, and noise, through an extensive modelling approach that incorporates large number of processes. Existing methods to calculate environmental impact of aviation emission and aircraft trajectories are integrated in the multi-criteria, multi-dimensional assessment, in order to evaluate the implications of environmentally-optimised flight operations to the European ATM network, considering climate, air quality and noise impacts.

2.1. Climate Impact of Aviation

Aviation emissions change the atmospheric concentration of chemical components and hence disturb the radiative balance in the atmosphere and subsequently contribute to climate change. The specific impact of aviation emissions depends on time and location of emission due to influence of e.g., background conditions, radiation and other meteorological parameters.

2.1.1. Climate Change Functions

For the environmental assessment concept we use a measure which connects aviation emission directly to with its environmental impact. This concept was applied to climate impact assessments in earlier studies [18], by using the initial cost function concept [19] which relied on cost functions pre-calculated with the comprehensive general circulation model EMAC [23] in a Lagrangian approach under specific meteorological conditions.

For climate impact, one way to generate these ECF is to provide them as an annual mean change function, which are then climatological climate change functions (Section 2.2). Another option is to generate them individually for a specific weather situation, or in conjunction with linking specific weather situation to an archetypical weather pattern as done for the North Atlantic Flight corridor within REACT4C, by deriving them from meteorological key parameters. A third option is to derive algorithmic ECFs (aECFs) which estimate the ECFs based on readily available MET info, i.e., temperature, humidity, vorticity, and background concentrations (meteorological key parameters). In ATM4E we propose and test the applicability of aECFs (Section 3.2), as algorithms allow online generation of ECF from meteorological forecast data which is crucial for future implementation. These climate change functions are calculated for aviation emissions having a direct or an indirect climate impact. Carbon dioxide, water vapour, particulate matter and contrail induced cloudiness (CiC) are among those having direct radiative and climate impact. Emissions with indirect radiative impact are nitrogen oxides (NO_x) and particles. Hence, these ECFs are varying with location (position and altitude) and time and date of emission. We refer to average temperature response (ATR) as climate metric, but do not refer to other possible climate metrics, in order to improve readability of the paper. ATR is computed by averaging the surface temperature response during the considered period, assuming sustained emissions with respective routing strategy applied during the whole period. We present results for two distinct periods, 20 and 100 years. However alternative climate metrics can be used in our overall concept in a similar way.

We expand the model concept to comprise various efficient methods to derive ECFs from standard meteorology data, after a brief description of climatological ECFs (Section 2.1.2) and archetypical ECFs (Section 2.1.3) eventually leading to ECFs derived by an algorithm from meteorological standard data (Section 3.2).

2.1.2. Climatological Environmental Change Functions

Climatological ECFs describe the impact of aviation emissions as a function of location only; they are thus simpler than full weather dependent ECFs as they do not depend on the time of the emission. The time dimension is instead replaced by an annual mean. We use the climate response model AirClim [24,25] to compute annual mean response functions. The impact of regional emissions on global mean near surface temperature changes is investigated by releasing specific aircraft emissions for CO_2, H_2O and NO_x of each flight level into AirClim's emission regions of corresponding height. The climate impact in terms of ATR_{20} or ATR_{100} (Average Temperature Response over years) is normalized by the emissions in corresponding flight level to generate climatological emission-based climate change functions [17]. Annual mean climatological ECF for total, CO_2 and non-CO_2, climate impact of aviation emission are shown in Figure 1 for aircraft specific emission indices on flight level FL310, exemplarily. From a conceptual point of view, we suggest to include all known non-CO_2 impacts in corresponding climate change function, in order to assess total aviation climate impact. In our feasibility study of an assessment and trajectory optimisation, we have specifically included the following non-CO_2 impacts: nitrogen oxides influencing ozone, methane with direct and indirect (primary mode ozone) together with contrail cirrus, as well as water vapour. Hence, neglecting soot direct and indirect radiative impacts, as well as aerosol and cloud effects.

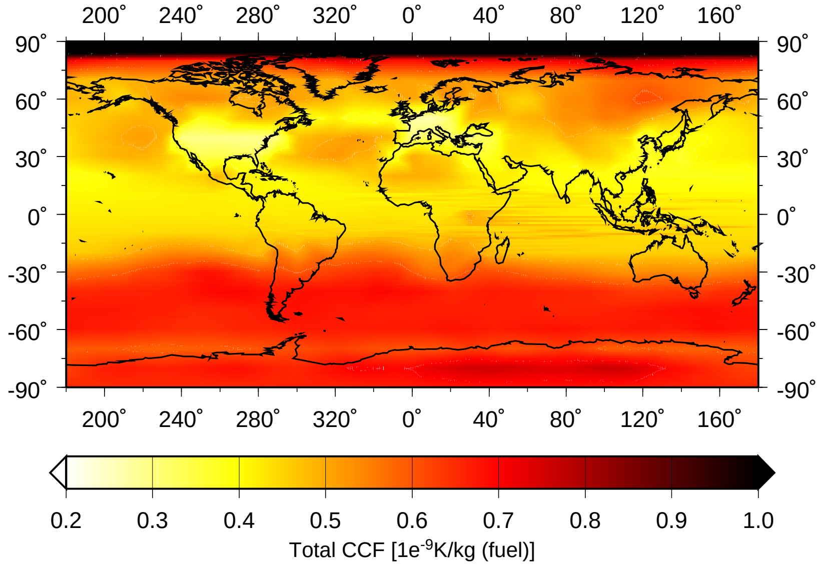

Figure 1. Climatological (annual mean) ECFs (environmental change function) for climate impact of total aviation emission as ATR_{100} per kg fuel on FL 310. Following aircraft specific emission indices were used: EI_{H_2O}=1.25 kg/kg, EI_{NO_x}=17.8 g/kg,0.15 km/kg.

2.1.3. Archetypical Weather Pattern in North Atlantic Flight Corridor

As the time dimension is not considered in climatological ECFs, their use might lead to a loss of optimisation potential. Thus we provide weather dependent ECFs for a set of specific weather patterns that are typical for the North Atlantic and that occur frequently. Within the European research project REACT4C such climate change functions were calculated for specific weather situations with a comprehensive climate-chemistry model [18,19,26]. Specifically, such weather-dependent climate change functions were calculated for a set of eight archetypical weather patterns, to study relationship between meteorology, fate of emissions and resulting climate impact of aviation emission. The selected pattern represents natural variability on synoptical scale and use atmospheric indices, North-Atlantic-Oscillation (NAO) and Atlantic Oscillation (AO), for characterisation of weather pattern [20].

2.2. Local and Regional Environmental Impacts

Within this study we expand the model concept to comprise additionally local impacts, air quality and noise issues, introducing environmental change functions (ECF), as well as an efficient method to derive ECFs from standard meteorology data. Aircraft operations near the ground produce an assortment of gaseous and particulate air contaminants that affect local air quality levels and potentially human health. Atmospheric concentrations found at surface level depend on emission strength but also on synoptic situation and associated physical and chemical mechanisms active in a specific region. In a polluted background atmosphere, aviation can contribute to exceedance of air quality limits, while in an unpolluted background atmosphere aircraft operations will cause less exceedances of air quality limits.

In addition, aircraft operations increase noise levels especially in localities over which aircraft are climbing out of and descending into airports. Noise is recognized from the WHO (World Health Organization) as a threat to human health and is probably the most significant concern for the residents of communities neighbouring airport. Minimizing the number of people significantly disturbed by aircraft noise is one of ICAO's main priorities and one of the industry's key environmental goals.

2.2.1. Local Air Quality Modelling

The contribution of aircraft emissions to local air quality (LAQ) issues, is examined using the EUROCONTROL Open-ALAQS tool that was developed in the context of the SESAR Project. Open-ALAQS, as one of the models approved for use by the ICAO Committee on Aviation Environmental Protection (CAEP), follows ICAO guidance on Airport Air Quality Modelling (ICAO Doc 9889, [27]). It is able to provide gridded emission inventories of key air pollutants (e.g., NO_X, PM) for all airport sources (e.g., auxilliary power units, ground support equipment, landside traffic).

Open-ALAQS uses a comprehensive approach recommended by ICAO to calculate aircraft emissions. In this advanced movement-based approach, the actual aircraft type/subtype and engine combinations as well as performance-based parameters like speed, altitude and ambient conditions (model-dependent) are required in order to obtain results with a high level of certainty. The Times-In-Mode (TIM) and thrust values used in Open-ALAQS are based on fixed-point profiles derived from the Aircraft Noise and Performance Database (ANP2.1). The fuel flow as well as the EI used in the calculations for a very large number of aircraft engines are derived from the ICAO Exhaust Emission Databank combined with the FOCA databank for pistons (and potentially FOI for turboprops).

Coupled with the Lagrangian particle dispersion model AUSTAL2000, the official reference model of the German Regulation on Air Quality Control (Technische Anleitung zur Reinhaltung der Luft, TA Luft), Open-ALAQS can also calculate the spatio-temporal distribution of the resulting concentrations. The resolution of the model outputs can be defined by the user depending as a function of desired accuracy and computational constrains.

In this study, a 500 m $\times$ 500 m $\times$ 100 m resolution was selected. More specifically, a regular 50 km $\times$ 50 km grid with a resolution of 500 m located around the airport reference point is used for the LAQ assessments. The horizontal grid was designed to cover both, arrival and departure procedures at the same time with one ECF. The size of the domain was selected according to typical values of operational procedures. For example, the typical descent angle of 3 degrees and 3000 ft altitude (it is commonly assumed that above this altitude aircraft operations have no impact on LAQ) result in a horizontal distance of 17.5 km. Adding a typical runway length of 4 km yields 21.5. Therefore, a conservative estimate (including rounding up and reserves) leads to a 25 km radius around the airport reference point. This can also be approximated by 50 km $\times$ 50 km. The vertical resolution is 100 up to 1000 m (or approximately 3000 ft) which is a typical value for airport local air quality impact assessments as it generally covers operations below the mixing zone height, assumed to be at 3000 ft altitude above ground level [28].

For each point on the grid an LAQ simulation is performed. Although the emitted quantity remains constant (1 kg) the environmental impact is expected to vary for each point. The environmental impact is calculated by combining the concentration increment with the number of people exposed to the calculated concentration levels to provide an environmental impact information for a specific location and time of emission, which is a measure of how a local specific aviation emission impacts environment, here local air quality.

The necessary meteorological information is derived from METAR data preferably from local meteorological stations. Although METAR data do not usually provide direct information on atmospheric stability, it is possible to estimate the required parameters using algorithmic procedures based on the available METAR variables [29].

2.2.2. Modelling of Noise Levels in Airport Vicinity

The impact of a single aircraft movement to the population around the airport can be estimated using single event noise metrics such as the maximum noise level (LMax), the sound exposure level (SEL) of an event, and the effective perceived noise level (EPNL) of an event. In the context of this study, the SEL, an indicator of the total noise level of an event that takes into account both the magnitude and duration of a noise event, is used.

The multi-airport noise impact assessment model STAPES (SysTem for AirPort noise Exposure Studies) is used to evaluate the noise levels produced and their associated environmental impact. STAPES is compliant with the best practice modelling guidance provided by both ECAC Doc.29 3rd Edition and ICAO Document 9911 and are used to effectively determine single event noise levels.

It is recommended for use within ICAO CAEP policy assessments, and this recommendation was endorsed by the CAEP Steering Group in June 2009. Moreover, it was designed to cover a large part of European airports and the population exposed to significant noise levels within the ECAC region (approximately 90% within the EU).

Following a similar methodology as for LAQ, separate simulations are performed for a set of points defined to simulate an aircraft flight path, for which the Noise-Power-Distance (NPD) relationship and the lateral adjustments are known. The NPD as well as the performance profiles (e.g., speed and thrust values as a function of the aircraft's location) data are taken from the Aircraft Noise and Performance (ANP) database which is hosted and maintained by EUROCONTROL on behalf of ICAO. It provides the necessary noise and performance characteristics for noise models, based on data supplied by aircraft manufacturers for specific airframe engine types, for a wide range of civil aircraft types.

The effect of source-receiver geometry on sound propagation as well as corrections to account for the effects of non-reference speed, engine installation effects (lateral directivity), lateral attenuation, finite segment length and longitudinal directivity are taken into account in the simulations as recommended in ECAC Doc.29. We note that, the selected configuration is designed to define a simple source-receptor relationship and is only intended to be used as proxy to actual sound event levels for the purpose of demonstrating the concept of noise ECFs. Definitive proof of concept would require considering different aircraft/engine types, non-reference atmospheric conditions, the actual aircraft geometry and flight parameters (e.g., bank angle, power settings, speed, weight).

2.2.3. Generation of Local Impact Metric Using Population Data

The environmental impact is calculated by combining the LAQ and noise results with the number of people exposed to the calculated NO_x/SEL levels. A basic LAQ metric is the emitted amount of respective component relevant for air quality, e.g., nitrogen oxides of particulare matter, under specific atmospheric height (3000 and 5000 feet). For trace compounds however, final metric proposed is a population-weighted value that is mapped back (distance, altitude) to the source to provide a measure of how a specific aircraft movement impacts local environment (within a 30 km radius from the airport reference point).

The population-weighted SEL is calculated using the centroid of each population grid cell as receptor point. The simulation is repeated for each point separately until the whole domain is covered. The environmental impact for each simulation (and therefore for each "emission point") is calculated by summing all population-weighted concentration/SEL values within the reference area.

2.3. Trajectory Optimisation Module (TOM)

In this study the stand-alone model Trajectory Optimisation Module (TOM) is used for trajectory management and optimisation receiving input data on air traffic (city pairs), standard MET data and algorithmic ECFs on environmental impacts. TOM applies optimal control techniques in order to determine continuously optimised four-dimensional aircraft trajectories. The general optimal control problem statement is shown in Equations (1)–(7):

$$\text{minimize} \quad \mathcal{J}\left(t, \mathbf{x}(t), \mathbf{u}(t)\right) = c_{\Upsilon} \cdot \Upsilon\left(t_0, t_f, \mathbf{x}(t_0), \mathbf{x}(t_f)\right) + c_{\Psi} \cdot \int_{t_0}^{t_f} \Psi\left(\mathbf{x}(t), \mathbf{u}(t), t\right) \, \mathrm{d}t \quad (1)$$

$$\text{subject to} \quad \dot{\mathbf{x}}(t) = f(\mathbf{x}(t), \mathbf{u}(t), t) \quad (2)$$

$$\mathbf{x}(t_0) \in [\mathbf{x}_{\text{min},0} \, ; \, \mathbf{x}_{\text{max},0}] \quad (3)$$

$$\mathbf{x}(t_f) \in [\mathbf{x}_{\text{min,f}} \, ; \, \mathbf{x}_{\text{max,f}}] \quad (4)$$

$$\mathbf{x}(t) \in [\mathbf{x}_{\text{min}} \, ; \, \mathbf{x}_{\text{max}}] \quad (5)$$

$$\mathbf{u}(t) \in [\mathbf{u}_{\text{min}} \, ; \, \mathbf{u}_{\text{max}}] \quad (6)$$

$$\mathbf{p}(t) \in [\mathbf{p}_{\text{min}} \, ; \, \mathbf{p}_{\text{max}}] \quad (7)$$

The aircraft's state variables (position, speed, mass, accumulated emission masses) are described by $\mathbf{x}(t)$. Moreover, $\mathbf{u}(t)$ denotes the aircraft's control variables (relative thrust, acceleration, heading) and the path variables $\mathbf{p}(t)$ are used in order to reflect flight envelope limitations (pressure, Mach number, calibrated air speed, relative lift coefficient). The objective function $\mathcal{J}$ (see Equation (1)) consists of two parts: (1) a penalty function Υ which is evaluated at the the initial (index 0) and final point (index f) of the trajectory and (2) the temporal integral over a penalty function Ψ along the trajectory. By varying the weighting factors c_{Υ} and c_{Ψ}, both penalty terms can be traded against each other. Identifying a control input $\mathbf{u}(t)$ which minimises the objective function $\mathcal{J}$ while satisfying the dynamic constraints (see Equation (2)) yields the optimal trajectory. The dynamic constraints are mainly characterized by the aircraft's equations of motion. Based on EUROCONTROL's *Base of Aircraft Data* (BADA) 4.2 aircraft performance models, a point-mass model with variable aircraft mass and three degrees of freedom is assumed [30]. Additionally, the dynamic constraints cover the estimation of aircraft emissions, which in case of NO_x are determined based on *Boeing Fuel Flow Method 2* [31,32], in case of CO_2 and H_2O emissions constant emission indices are used. Depending on the use case, further control, state and path limitations can be defined (see Equations (3)–(7)). A more detailed description of TOM is given by [33].

2.4. Verification of Algorithmic ECFs and Environmental Impacts

For verification purposes a module for aircraft trajectory assessment and optimisation has been integrated in a global climate-chemistry model working interactively during atmospheric calculations. Second, for verification purposes this module AirTraf is compared to another trajectory calculation model FAST.

2.4.1. AirTraf Calculation of Optimal Solution

AirTraf is a module which has been integrated in a global climate-chemistry model working interactively during atmospheric calculations. AirTraf (version 1.0) [34,35]) was developed as a verification tool for climate optimised routing strategies by analysing individual routing options for given city pairs. AirTraf is a submodel of the ECHAM/MESSy Atmospheric Chemistry (EMAC) model [23,36] (ECHAM5 version 5.3.02, MESSy version 2.52) and simulates global air traffic (online) which is able to simulate aircraft trajectories under individual optimisation criteria. An aircraft performance model and International Civil Aviation Organization (ICAO) engine performance data [37] are used. A global air traffic plan (any arbitrary number of flight plans) is used and both short- and long-term simulations are performed taking into account the individual departure times. The Genetic Algorithm (ARMOGA version 1.2.0) [38,39]) is used for the flight trajectory optimization. The GA optimises flight trajectory with respect to a selected routing option, taking account of the local weather conditions for every flight, and finds an optimal trajectory including altitude changes. Selecting a routing option means that aircraft trajectories are calculated which aim to minimise selected optimisation criteria: great circle (flight distance), flight time, fuel use (CO_2), impacts due to emissions of NO_x, H_2O, contrails formed and their radiative impact. Hence, our objective function is a combination of environmental impacts described by algorithm based ECF and associated economic costs, e.g., cash operating costs.

Once the optimal flight trajectory is found, which minimises the selected objective function, fuel use and emissions are calculated by the total energy model based on the BADA method [40] and DLR fuel flow method [41]. AirTraf outputs three dimensional emission fields of NO_x and H_2O emissions, as well as fuel use and flight distance as performance parameters. Comparing performance parameters of distinct optimisation criteria (route options) provides quantitative information which can be used in a cost-benefit-analysis. The details of the AirTraf submodel and its validation are given in [35]. Verification procedures of the aECFs using EMAC/AirTraf are presented in Section 3.4.

2.4.2. Verification in FAST and EMAC/AirTraf

The flight details and trajectories from AirTraf are used in the International Civil Aviation Organization (ICAO)'s Committee on Aviation Environmental Protection (CAEP) approved aviation emissions model, the Future Aviation Scenario Tool (FAST) [42]. This model has been extensively used in ICAO-CAEP activities, EU Framework Projects (TRADEOFF [43], QUANTIFY [42] and REACT4C [15] and the Intergovernmental Panel on Climate Change (IPCC) assessment [44]. FAST is a global 3D model that uses fuel flow data from the aircraft performance model, PIANO [Simos, 2008] and is able to support movements of different aircraft/engine types and configurations, mission distances and cruise altitudes. The model has a horizontal resolution of 1×1 degrees with a vertical g according to flight levels at intervals of 1000 ft. FAST uses flight details similar to those applied by AirTraf and its resulting optimised trajectories, to calculate fuel and emissions. The results are evaluated and verified against those calculated by AirTraf. Comparison of results from both independent trajectory models allows to evaluate and verify performance parameter and associated uncertainty of European traffic sample.

3. Environmental Change Functions for Aviation

In the context of this study we propose to expand current MET services by advanced meteorolgical data, which are relevant for environmental impact of aviation emissions (climate, air quality, noise). Such advanced MET service is provided to flight management via the interface of an ECF, preferably an aECFs.

3.1. Environmental Change Functions-Multi-Criteria Impact Assessment

In this study we expand a modelling concept for climate-optimisation which has been developed in a feasibility study for the North Atlantic [18,19] to a concept for a multi-criteria environmental impact assessment, covering climate, air quality and noise impact, simultaneously. For this purpose we also define a concept how to establish an interface between ATM and environmental impact information, which further develops the so-called climate cost function approach presented in [18].

A flowchart (Figure 2) shows how standard MET information is complimented with algorithmic ECFs in order to be made available for trajectory optimisation, as advanced MET information service. Performance assessment of aircraft trajectories then comprises environmental performance data beside performance data, e.g., on fuel and time efficiency.

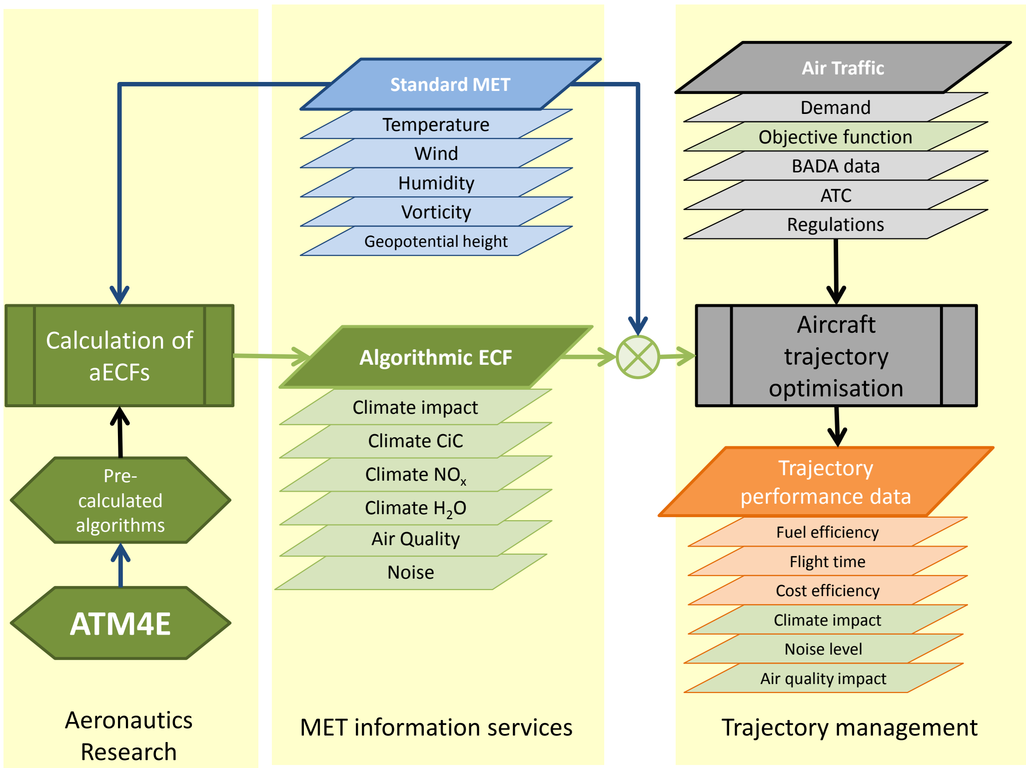

Figure 2. Flowchart of Environmental Assessment of aircraft trajectory management using ATM4E algorithmic environmental change functions (aECF) concept, with elements newly introduced by ATM4E highlighted in green.

For the impact function which describes environmental impact of an aviation emission, we use first order approximation from a Taylor series. This mathematical description can be transformed to represent our overall objective function for trajectory calculation in this study by a penalty function approach as shown in [18]. As environmental impact of aviation emissions depends strongly on meteorological conditions, comprising physical and chemical parameters, provision of this advanced information is integrated as MET information service for the specific application of environmental performance. From an ATM perspective, such MET components need to be verified before integration of such information in a common ATM infrastructure can take place, as is described in Section 3.4. We can formulate objective function for environmental assessment in Equation (8). In the first term enter cash operating costs (COC) multiplied by a weighting coefficient. In the second part of the penalty function ECFs are integrated over flight time. Central element of mathematical formulation are the ECFs which relate e.g., emission with its associated environmental impact, and which are advanced MET information required for environmental assessment.

$$\mathcal{J} = c_{\Upsilon} \cdot \mathrm{COC}(t_{\mathrm{mission}}, m_{\mathrm{fuel,mission}}) + \int_{t_0}^{t_f} \sum_i (c_{\Psi,i} \cdot \mathrm{ECF}_i(\mathbf{x}, t) \cdot \dot{r}_i)\, \mathrm{d}t \quad (8)$$

$$i \in \{\mathrm{CO_2}, \mathrm{H_2O}, \mathrm{NO_x}, \mathrm{CiC}, \mathrm{LAQ}, \mathrm{noise}\} \quad (9)$$

$$\dot{r}_{\mathrm{CO_2}} = \dot{m}_{\mathrm{CO_2}} \quad (10)$$

$$\dot{r}_{\mathrm{H_2O}} = \dot{m}_{\mathrm{H_2O}} \quad (11)$$

$$\dot{r}_{\mathrm{NO_x}} = \dot{m}_{\mathrm{NO_x}} \quad (12)$$

$$\dot{r}_{\mathrm{CiC}} = v_{\mathrm{TAS}} \quad (13)$$

$$\dot{r}_{\mathrm{LAQ}} = \dot{m}_{\mathrm{NO_x}} \quad (14)$$

In this mathematical formulation ECFs are provided in intensive units, on a per emitted amount basis. Climate impact ECFs are given in a typical climate metric, e.g., ATR, per mass or kilometre flown. Local and regional impacts are provided as emitted amount below a certain atmospheric height, e.g., 3000 ft, or as local air quality change, i.e., degradation of air quality per emitted amount.

3.2. Algorithmic Weather-Dependent Environmental Change Functions

Climate change and environmental change functions show a strong dependence on meteorological situation on a synoptical scale, hence they are weather-dependent. For that purpose high-quality meteorological information can be used for an accurate generation of such weather-dependent ECFs, which then reflect specific meteorological situation. As described in the methods section, different approaches to determine these weather-dependent ECFs exist, i.e., either using MET information to classify synoptical situation according to archetypical weather patterns, as performed within earlier studies [26]. Alternatively, algorithmic ECFs can be developed by using directly spatially and temporally resolved standard MET information available, e.g., provided by a System Wide Information Management (SWIM) as implemented within SESAR, to derive environmental change associated to aviation emission as 4-dimensional functions. Algorithms are used to establish such link between meteorological key parameters and associated environmental impact, which were identified from comprehensive analysis of environmental impact at a specific location and associated prevailing meteorological conditions. Hence, we define the term algorithmic ECF (aECF) in order to describe such algorithms wich enable to calculate ECF from basic MET information.

Development of such algorithms require fundamental understanding of atmospheric processes, statistical analysis and high-quality synoptical scale meteorological information, in order to identify and validate robust relationships, e.g., [45], which need to be in a next step integrated as interactive MET information product in ATM tools. Such aECFs rely on meteorological parameters, e.g., atmospheric temperature, relative humidity, geopotential height, potential vorticity, or boundary layer height, combined with e.g., atmospheric concentration and transformation of key chemical species as well as radiation.

In order to illustrate the concept of aECFs, we present atmospheric mechanisms relevant for contrail formation and associated climate impact, and how this translates to an aECF. Persistent contrails form in air which is sufficiently cold and which is supersaturated with respect to ice, i.e., where the humidity with respect to ice is above 100%. These cold ice-supersaturated regions are usually associated with rising air, and have been found to occur around high pressure ridges, in association with ascending air masses in low pressure systems and the jet stream, as shown in previous studies [46–49]. Once contrail form they cause a radiative effect which can be described following the radiative forcing concept. The radiative forcing of contrails is dependent on many factors; factors such as lifetime and optical depth may be linked to the weather situation in which they occur, thus potentially allowing the computation of the ECFs [3]. For example, long-lived ice-supersaturated regions have been shown to occur in slower moving air [50]. Additionally, the contrail radiative forcing depends not only on conditions at time of contrail formation, but depends as well on the advection of the contrail and its position relative to the (time-evolving) terminator between daytime and night time. For contrails the idea of an aECF is to combine key aircraft and engine parameters, e.g., aircraft type, fuel composition and engine exit temperature, together with key meteorological parameters, to determine environmental change associated to a kilometre flown at that specific location and time due to contrail climate impact. By linking such aECF to MET information available, the trajectory optimisation tool calculates for each point a corresponding ECF, resulting in a four-dimensional ECF (given in climate impact per flown kilometre) available online for use, analysis and trajectory optimisation within an ATM decision support system. Presented approach can be applied similarly to other environmental impacts of aviation emission, e.g., water vapour and nitrogen oxides climate impact.

3.3. Local Impacts Environmental Change Function for Air Quality and Noise

The calculation of local and regional air quality (LAQ) ECFs is based on a methodology designed to evaluate the sensitivity of ground air quality levels to aircraft emissions. We note that only the Approach (AP), Take-Off (TO) and Climb-Out (CL) parts of the LTO cycle are considered. In our analysis, taxiing emissions are not examined as they depend on specific airport characteristics (e.g., airport size, design, capacity and infrastructure) as well as several operational restrictions related to Air Traffic Planning (runway sequencing, gate assignment etc.), and scope of aircraft optimisation are those flight segments which are in the air.

The approach followed is based on a standardized setup which includes a specific amount of a pollutant (e.g., 1 kg of NO_2) emitted at equidistant points on a 3D-grid of geographic position and altitude. Local meteorological data (METAR) preferably from airport stations close to the runway-are used to calculate the dispersion of the emissions for each simulation and thus the LAQ impact (i.e., the derived NO_x concentration increment) at receptor points in the vicinity of the airport. Together with information on affected population (by this degradation of air quality) an integrated measure of LAQ impacts on population can be calculated by the sum of all intersection points with the official EU population data given at a 1 km $\times$ 1 km resolution (GEOSTAT 2011) and the NO_x concentration gridded datasets. This new metric is then used as MET information to TOM to make available an airport-specific ECF for local air-quality, relating to particulate matter and nitrogen oxide emissions.

3.4. Verification of Algorithm Based Environmental Change Functions

Before these aECFs are used for trajectory optimization, a verification process is performed to ensure that the aECFs serve their purposes by comparing results from two distinct calculation procedures for the overall climate impact of an air traffic sample. The EMAC/AirTraf described in Section 4.5 is an appropriate simulation tool since it combines the Earth-system model EMAC with the air traffic simulation model AirTraf. In Figure 3, an overview of the aECFs verification procedure is presented. AirTraf model calculates aircraft trajectories choosing climate impact reduction based on aECFs as optimisation criteria, cost optimal and climate optimal. As part of this procedure, aviation emissions are calculated to yield overall climate impact by multiplication with the aECFs and integration over time (right leg arrow). Similarly, aviation emission are integrated as 3 dimensional flux fields to the atmospheric chemistry model [23], affecting the chemical composition of the atmosphere, identified with a specific tagging scheme [51,52] and changing radiative balance, respectively. Accordingly, with both approaches the Average Temperature Response (ATR) attributed to each emission specie is calculated. This verification procedure is performed to ensure that the overall ATR calculated based on the aECFs matches the ATR calculated from the calculated impact in the atmospheric chemistry model, hence allows to perform a proof of concept for aECFs.

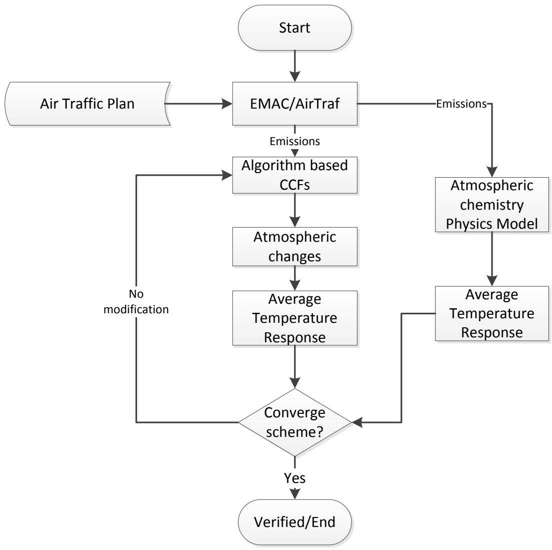

Figure 3. The aECFs verification procedure comparing climate impact metrics (ATR) calculated with two independent approaches.

4. Case Study: Environmental Assessment and Optimisation of Air Traffic in Europe

We apply above concept for a multi-criteria environmental assessment of aviation operations in a case study for the European airspace, in order to provide environmental performance data and in order to test feasibility working towards environmental optimisation of air traffic operations. Results are shown for a European traffic sample, together with a sensitivity study on environmental optimisation of an aircraft trajectory.

4.1. Selecting Reference Traffic Sample

The traffic data to be used for the optimization was selected taking into account both, ATM network as well as meteorological aspects. The objective was to choose a representative date that was on the one hand as unimpeded by ATM regulations as possible and on the other hand was dominated by weather patterns with a certain complexity for expecting interesting optimization results. Based on air traffic demand data of the year 2015 (obtained from EUROCONTROL's Demand Data Repository DDR2), first the busiest day of each month was selected in order to compile a list of candidate days. Based on this, two days per winter and two days per summer season each were down-selected under criteria of high numbers of flight movements while at the same time ensuring a low impact by messages from the Aeronautical Information Management (AIM). Messages in AIM contain e.g., Notices for Airmen (NOTAMs) and thus include restrictions that could have affected the flights on that day. During winter season (Oct-Mar), additionally a low number of Aerodrome regulations was made sure. The resulting four candidate days (28 August, 11 September, 27 February and 18 December 2015) were then evaluated based on meteorological considerations.

4.2. Meteorological Situation in Case Study 18 December 2015

For each day, contrail formation regions were identified using infrared satellite imagery and data from the ECMWF ERA-Interim re-analysis [53]. As indicator for photochemical activity in the atmosphere, the ozone production efficiency was determined with the ECHAM/MESSy atmospheric chemistry model. Additionally geopotential height was determined from ECMWF ERA-Interim re-analysis. As ECFs depend to a large extent on synoptical situation, particular focus was given on selecting candidate days for our case study. A meteorological situation is selected which represents a medium to high complexity of the meteorological environment which ATM is encountering. From the list of candidate days, 18 December 2015 turned out to be best suited as reference day for the optimization case study.

The 18th of December 2015 is selected as specific date for our case study. The day was characterised by a high-pressure ridge over Europe with the jet stream meandering for North (Figure 4). The wind shows some westerlies over Europe and contrail formation regions exist in particular at the end of the day over parts of Europe. From EMAC climate-chemistry simulations we find areas of high ozone production efficiency via photochemical radical reaction (H_2O) extending into the South of Europe. In the Northern part of Europe lower ozone production efficiency via this reaction channel can be observed. For the climate impact of nitrogen oxides a contrast between Northern and Southern parts of Europe is expected, due to differences in geopotential height, prevailing wind direction and photochemical activity.

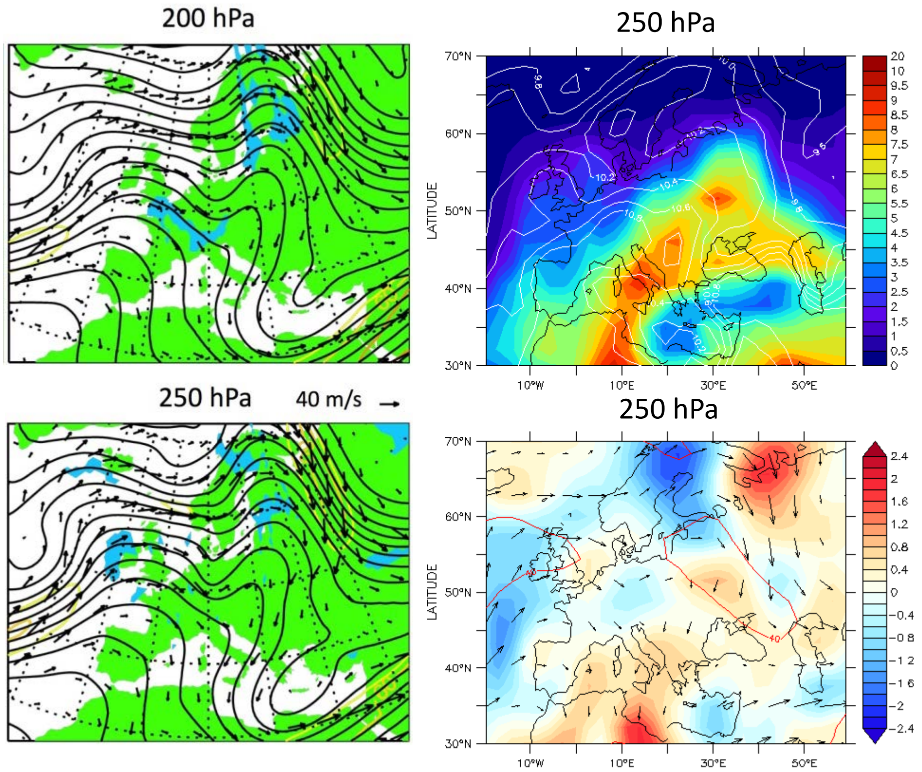

Figure 4. Synoptical situation on 18 December 2015: geopotential height, wind and contrail supersaturation (**blue**) in 200 hPa (**top left**) and 250 hPa (**bottom left**), ozone production efficiency (**top right**), and vertical motion [m/s] (**bottom right**) and location of jet (redline representing 40 m/s windspeed).

4.3. Engine Emissions and Environmental Performance

The air traffic over Europe on the selected day is used as a reference scenario for the optimization task in ATM4E. Further assumptions are made to filter the traffic data for a better processability. As ATM4E focuses on the European airspace, only intra-ECAC (European Civil Aviation Conference) flights are considered and only flights that can be modelled with aircraft performance data from EUROCONTROL's Base of Aircraft Data (BADA) 4.0 are taken into account. This required simplification reduces the amount of available seat kilometres (ASK) in the data set by only 8–9%, since especially large commercial aircraft representing major parts of ASK are included in BADA 4.0. Lastly, flights which depart before or arrive after 18 December 2015 are filtered out leading to a final dataset of 13,276 flights (from originally 28,337).

In order to assess the environmental impact caused by the traffic sample and in order to prepare trajectory optimization, for the described reference flight set the overall performance parameters with respect to gaseous aircraft emissions, the provoked contrail formation and the overall climate impact are calculated. For this purpose, DLR's Global Air Traffic Emission Distribution Laboratory (GRIDLAB) is applied which contains a database of precomputed emission profiles for various aircraft types, mission ranges and load factors [54]. For the computation of these reduced profiles a numerical trajectory simulation tool is used. Aircraft mechanics are modeled by using simplified equations of motion also known as Total Energy Model and evaluating BADA model equations for aerodynamics, thrust and fuel flow to obtain the forces acting on the aircraft as well as the engine state relevant for emission calculation in each simulation time step [30]. Standard profiles are simulated assuming typical speed schedules for climb, cruise and descent. In cruise, step climbs are performed where required by monitoring and following the aircraft's optimum altitude profile. Emissions are modelled using the state-of-the-art Boeing Fuel Flow Method 2, which allows for the estimation of emission indices (EI) for the species NO_x, HC and CO derived from EIs for sea level conditions obtained from the Engine Emission Databank by the International Civil Aviation Organization (ICAO) [33], whereas species that are produced proportionally to fuel burn, i.e., CO_2, H_2O are calculated using constant EIs. Four-dimensional (longitude, latitude, altitude, time) emission inventories are generated by simulating every flight in the traffic scenario and determining the corresponding emission distribution. Figure 5 shows the NO_x emission distribution at 12:00 p.m. UTC of the European traffic sample. Regions with potential persistent contrail formation were identified with a method relying on the Schmidt-Appleman criterion [55], and the contrail situation at 12:00 p.m. UTC is depicted in Figure 5. From this criterion we calculate the distance flown under persistent contrail formation criteria shown in Table 1 by taking into account real weather conditions on that specific day, which corresponds to 5% of air distance in this representative traffic sample.

Table 1. Performance Parameter of European traffic sample: Cumulated emissions and distance in contrail areas on 18 December 2015. For climate impact uncertainty range is provided in parenthesis. For local air quality concentrations (LAQ) mean values together with maximum values n parenthesis are provided, on an daily and hourly (24 h/1 h) basis.

Parameter	**Name**	**Amount**
Air distance	flight km	1.42×10^7 km
Carbon dioxide emissions	CO_2	1.50×10^8 kg
Nitrogen oxides emissions	NO_x	7.20×10^5 kg
LAQ Nitrogen oxides emissions	NO_x (<3000 ft)	5.2×10^4 kg
LAQ Nitrogen oxides emissions	NO_x (<5000 ft)	7.1×10^4 kg
Water vapour emissions	H_2O	5.88×10^7 kg
Distance flown in contrail areas	km contrailing	6.76×10^5 km
Environmental performance indicators		
Total climate impact	ATR_{20}	$5.7 \times (4.1 - 7.0) \times 10^{-3}$ mK
Total climate impact	ATR_{100}	$16.7 \times (12.1 - 20.3) \times 10^{-3}$ mK
Ratio non-CO_2/CO_2	ATR_{20}	$20.0 \times (13.9 - 24.8)$
Ratio non-CO_2/CO_2	ATR_{100}	$5.8 \times (3.9 - 7.2)$
LAQ NO_x concentration (24 h/1 h)	NO_x (ground)	$0.01 \times (0.2)/0.3 \times (5.8)$ µg/m^3
LAQ NO_x concentration (24 h/1 h)	NO_x (<3000 ft)	$0.01 \times (0.4)/0.4 \times (10.6)$ µg/m^3
LAQ NO_x concentration (24 h/1 h)	NO_x (<5000 ft)	$0.01 \times (0.4)/0.3 \times (10.6)$ µg/m^3

Overall performance data of the traffic sample, comprising air distance travelled, cumulated emissions as well as the distance in contrail areas are listed for the chosen reference day. Among environmental performance data the overall climate impact has been evaluated for two distinct climate impact metrics. ATRs over 20 and 100 years have been calculated under the assumption of sustained emissions, which means that routing decision is similar on each day over the time horizon.

As a background greenhouse gas concentration scenario we used the representative concentration pathway with a moderate growth (RCP6). Ratios of climate impacts of non-CO_2 versus CO_2-impacts are calculated for ATR_{20} with 20.0, and for ATR_{100} with a lower value of 5.8. Uncertainty range provided refers to sensitivity study on seasonal cycle and annual mean ECFs. An overview of relative contributions to total climate impact is shown in Figure 6 for ATR over two distinct time horizon, 20 and 100 years, showing importance of individual non-CO_2 impacts versus CO_2. With regards to LAQ, emitted amounts of nitrogen oxides below 3000 and 5000 feet are calculated. For local air quality the increase of atmospheric NO_2 concentration is estimated using parametric study to investigate sensitivities assuming moderate advection of trace compounds and low atmospheric loss rate. We present mean and maximum values for several vertical layers, i.e., ground level, up to 3000 and 5000 feet. Mean NO_2 concentration is estimated to increase by about 0.3 to 0.4 μg/m^3, with maximum increase of hourly values in specific regions in the order of up to 10.6 μg/m^3.

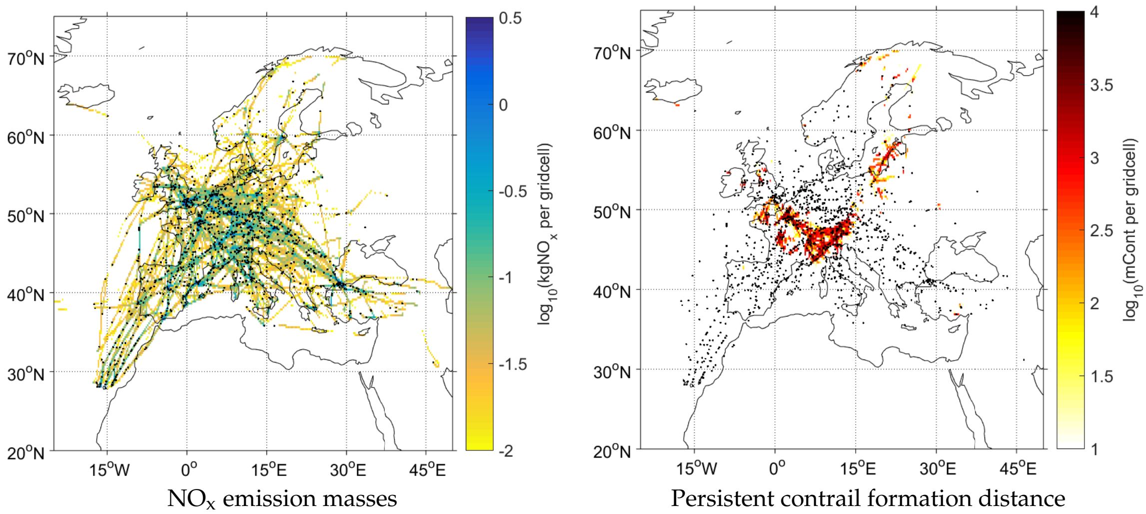

Figure 5. NO_x emissions (**left**) and persistent contrail formation distance (**right**) per gridcell (0.25° × 0.25°) integrated over a time period of 20 s on 18 December 2015, 12:00 p.m. UTC. Single aircraft are represented as black dots (1216 in total). Note that a low pass filter was applied to the distributions in order to visualise the prior flight path.

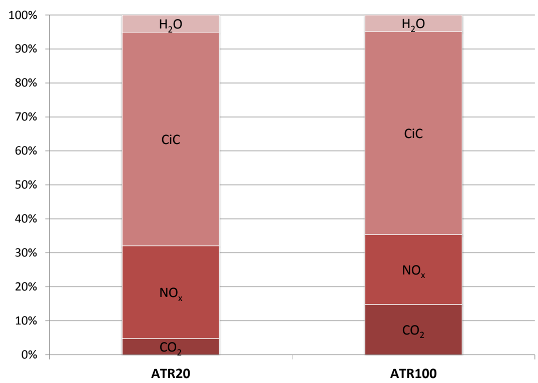

Figure 6. Environmental assessment of European traffic sample: relative contribution of individual climate impacts, CO_2, NO_x, contrail induced cloudiness (CiC), and H_2O, to overall climate impact for ATR_{20} and ATR_{100} on 18 December 2015.

4.4. Cost-Optimal Versus Climate-Optimal Trajectory Optimisation

Beside environmental assessment of aircraft trajectories, the framework can also be applied in an environmental optimisation by adapting corresponding objective functions used in TOM. For a flight from London Heathrow (LHR) to Istanbul (IST) aircraft trajectory was optimized under a series of objectives functions (Equation (8)), by varying individual weights from fuel optimal case to climate-minimal solution. ECFs used in this optimisation, are prototypes which were calculated from AirClim climatological mean ECFs. The resulting Pareto front is shown in Figure 7, together with trajectories from three distinct solutions, the reference case, and solutions for 1% and 5% percent fuel increase, resulting in a climate impact mitigation by reducing ATR by 12% and 25%, respectively.

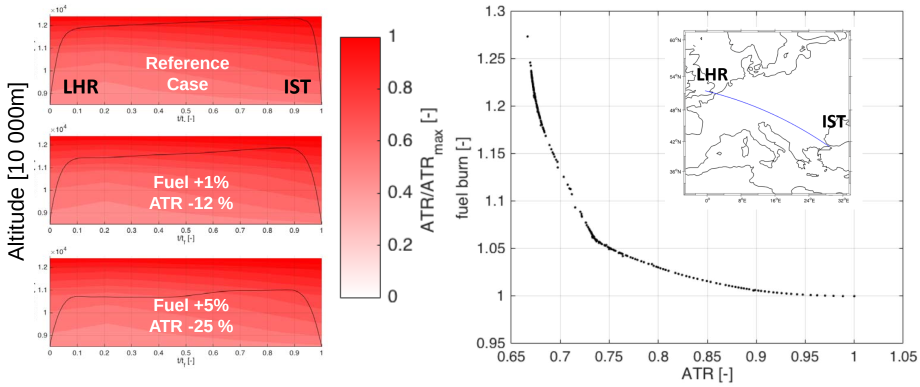

Figure 7. Evaluation of fuel-optimal versus climate-optimal solution, by using prototype ECFs for flight from London Heathrow (LHR) to Istanbul (IST) showing Pareto front (**right**). Trajectories (**left**) for reference case (**top**), fuel increase of 1% (**middle**) and 5% (**bottom**) with relative strength of total ATR shown as shading.

4.5. Application of ECF in General Circulation Model Interactively

Within the verification exercise in ATM4E the following objective function is developed:

$$f = (1-\alpha) \cdot Cost + \alpha \cdot K \cdot \sum_i ATR_i \tag{15}$$

where α varies between [0, 1] controlling the weight between the cash operating cost (COC) and the Average Temperature Response (ATR). The subscript i indicates emission specie, e.g., nitrogen oxides, water vapour or contrails. The coefficient K is calculated by Equation (16). The overall objective would be a summation of individual objective function by each emission species.

$$K = \frac{Cost_{clim\_opt} - Cost_{cost\_opt}}{ATR_{cost\_opt} - ATR_{clim\_opt}} \tag{16}$$

which represents the increase in cost attributed to per Kelvin reduction in ATR.

Once the aECFs are verified as described in Section 3.4, they are implemented for climate-optimisation of trajectories. In order to examine the effectiveness of the climate impact reduction achieved from the rerouted flights in ATM4E, another verification task has been assigned, the procedure of which is depicted in Figure 8. In this process, the experience gained from REACT4C [21] is used as a baseline. At the first place, trajectory optimization is performed based on the objective functions given in Equation (15). By varying the value of α, different levels of the importance are assigned to the cost and the climate impact. Accordingly, a Pareto Front with respect to the operating cost and the ATR is expected. In Equation (15), the coefficient K differs as different city pairs are concerned. Therefore, the factor K and α together influences the location of the data set on the Pareto Front.

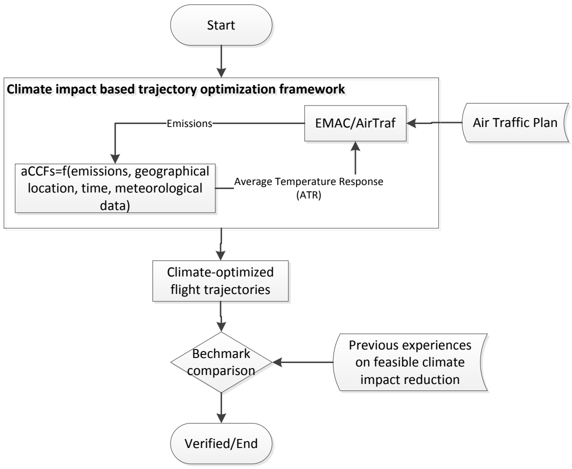

Figure 8. Verification of effectiveness in climate impact reduction using aECF-based optimised trajectories.

5. Development of MET Products on Environment

The ATM4E approach on environmental flight planning requires that verified advanced MET information are implemented in flight planning, providing the impact of a local emission on climate, air quality and noise. For that purpose ATM4E develops verified aECFs, which allow to provide among MET services both (standard) weather forecast information and advanced MET information, i.e., aECFs (Figure 9). This advanced MET information can be distributed with standard MET information, e.g., in a SWIM concept, while taking legislation into account in terms of objective function and flight planning. There is the possibility to implement algorithm-based environmental change functions into national weather forecast models, which then provide advanced information via services to users, allowing for an environmental flight planning, as well as short-term tactical adaptations to the aircraft trajectory. Having available ECFs during flight planning also offers the ability to environmentally assess the actually executed flight and to record the data for e.g., environmental legislative purpose.

It is proposed to use ECFs as interface between environmental expertise (derived from models) and air traffic management tools, in order to represent environmental impact in air trajectory models, instead of code integration in a flight planning tool. An interface (function) has the advantage that, first, complex and comprehensive systems and models, e.g., climate-chemistry model with coupled homogeneous and heterogeneous atmospheric chemistry, is used for ECF generation. Second, any updates due to scientific understanding or political decision, e.g., on time horizon of climate impact metric being considered, is integrated by simply replacing (mathematical formulation) of a specific aECF function.

Such advanced MET information offers the possibility to determine key performance indicators in the key performance area environment (KP05). Quantitative indicators providing information on climate impact, air quality impact and noise level can be derived by implementing aECFs in flight planning.

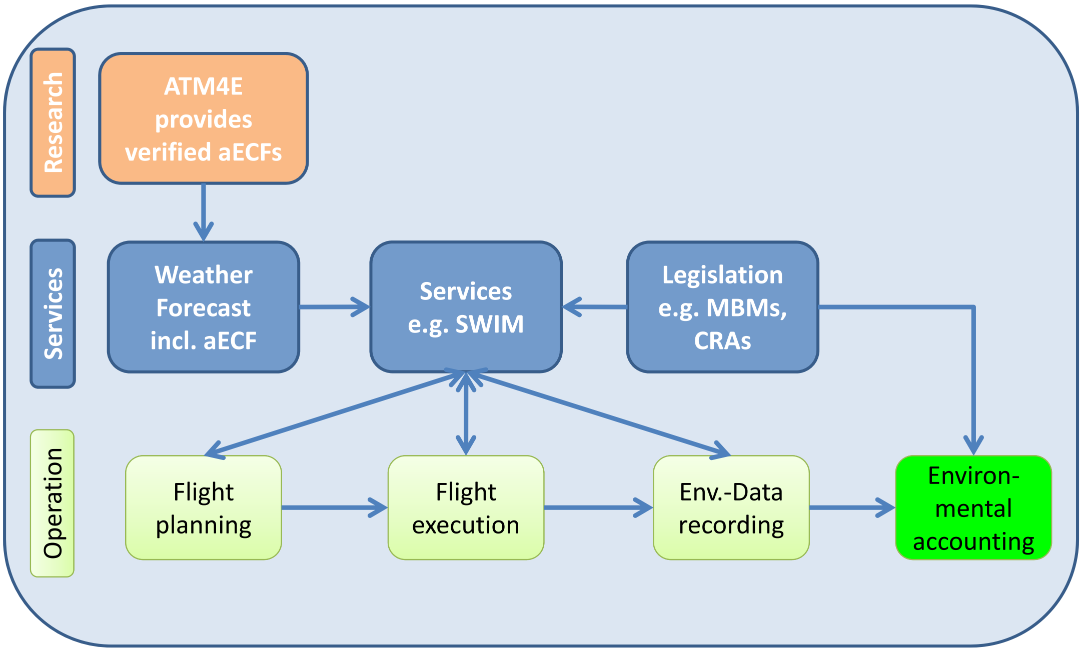

Figure 9. Overview on Air Traffic Management (ATM) infrastructure comprising environmental MET components as proposed by AMT4E (ATM for Environment).

6. Discussion

Development of algorithmic environmental change functions (aECFs) which consider actual weather conditions enables an environmental assessment of aircraft trajectories. Synoptical scale pattern determine regions with high and low sensitivity to aircraft emissions, hence determine climate change functions. Making available algorithms which establish linkage between MET information and environmental impact is a pre-requisite for an efficient generation of ECFs. Such a concept brings as advantage that consequently environmental assessment of aircraft trajectories are not limited to match weather pattern which correspond to archetypical pattern, but for each synoptical situation corresponding advanced MET data products on climate and environmental impact can be generated. Environmental performance data of European traffic sample in the case study (18 December 2015) showed that overall climate impact is composed of both CO_2 and non-CO_2 impacts, with non negligible non-CO_2 effects about 5–20 times higher than CO_2 impacts alone, depending on climate metric calculated. For longer time horizon this ratio tends to lower values, going down from about 20 to about 6, when comparing a time horizon of 20 and 100 years, respectively.

In terms of implementation of such concept described, additional environmental MET information data products need to be made available to ATM. Hence complexity of the ATM environment due to meteorology, needs to be transferred via MET information into the ATM infrastructure, making sure that ATM is having available high quality information for efficient flight planning. Within the SESAR 2020 Master Plan such information is made available system-wide via the SWIM infrastructure, where MET is one component in it, as is e.g., AIM information.

Trade-offs in optimisation for local and global impacts might be expected to be low, because standard local impact ECFs show a relatively weak overlap with climate ECFs. However, there are also dependencies between both optimisations, which only a multi-dimensional analysis is able to analyse. For example, a climate optimisation might lead to increased mission fuel, leading to an increased take-off weight which then affects emissions and local air quality. Addtionally, a vertical extension of atmospheric domain relevant for air quality, to altitudes higher than 3000 feet, results in a stronger overlap of both domains and hence again requires tools which are able to estimate associated trade-offs.

Current quantitative estimates rely on prototypic model simulations which were performed with a state-of-the-art climate-chemistry-model. A sensitivity analysis and Monte Carlo simulations [24] allow to provide estimates of remaining uncertainties. However, for future implementation steps it is crucial to continuously consider improved understanding on major processes, e.g., number of ice crystals formed in contrails and their radiative impact. Indirect aerosol effects are currently not considered in this set of ECFs, as quantitative estimates were considered to have a too large uncertainty. However, from a methodological point of view, they can be integrated in a similar way, once scientific advancements have been made and estimates with lower uncertainty will be available.

As explained in the case study, flights by aircraft not included in BADA 4.0 are filtered out. However, they can be considered as "background"-flights within a hotspot analysis, in order to estimate importance of these aircraft types and uncertainty in results achieved due to limiting analysis to only those aircraft types included in BADA 4.0.

Other studies also present concepts how to indicate mitigation potential of avoiding contrail forming regions, e.g., using optimal control theory with a point-mass aircraft model [16]. They presented an environmental benefit by climate optimisation for a single long-haul flight when using synoptical situation for localisation of contrail forming regions, in the order of 35% less radiative forcing due to CO_2 and contrails, for an increase of about 2% in fuel. Our estimates use ATR as climate metric, and are show a slightly lower benefit of about 17%. Main difference between both studies is that we were using prototypic ECFs for contrails, which lead to larger areas of contrail formation, which make it more difficult to completely avoid contrail formation. Additionally, our study is making the effort to integrate a larger set of environmental impacts at the same time and we perform trajectory analysis for a traffic sample representing European traffic on a typical day.

Modelling chain combines individual elements for assessment and validation of results, with high complexity requiring a joint roadmap how to design, develop and verify such advanced MET components and how their implementation in current ATM infrastructure can take place.

7. Summary and Conclusions

This paper presents overall concept for a multi-criteria environmental assessment framework relying on environmental change functions (ECFs), as is currently under development in the European project ATM4E which is part of Exploratory Research within SESAR2020 research programme. Models and methods required are described, which are used to quantify environmental impacts and plan aircraft trajectories. Concept of ECFs is presented in detail and methods how to generate are described. This comprises the concept how these impacts are transferred to a trajectory optimisation tool (TOM) for air traffic optimisation in the mathematical formulation of the objective function. We present a case study for a traffic sample over Europe which is applied on a candidate day using real weather conditions. Initial findings are presented using prototype ECFs. We provide an estimate for importance of non-CO_2 using ATR as climate metric, with a ratio of non-CO_2 to CO_2 impacts on climate between 6 and 20, for time horizon 20 and 100 years, respectively. From climate-optimisation of a single-flight trajectory, using prototype ECFs, an estimate of climate impact mitigation potential is calculated in the order of 12% and 25%, for fuel increase of 1% and 5% respectively. For LAQ we selected as environmental performance indicator in this initial case study the increase of atmospheric NO_2 concentrations, performing sensitivity tests for different air quality indicators, e.g., using either daily or hourly peak concentrations. We do not show quantitative results for noise here, but only present the conceptual approach. However, we are aware that for noise and noise annoyance mitigation a large set of dedicated measures exist, e.g., alternative approaches comprising vertical adaptations (continuous descent approach), curved approaches or curfew regulations, in order to address noise issues. Future studies need to analyse under which conditions the presented concept is able to capture these measures and quantify associated benefits.

The innovative aspect in this study is to present a quantitative assessment of environmental performance indicators for a trajectory optimisation of a European traffic sample, representing a comprehensive framework for a multi-criteria environmental assessment framework, which comprises both climate impacts and local and regional environmental impacts. Such an assessment framework allows to be used for an analysis of overall environmental performance of a set of aircraft trajectories, but also an optimisation under individual objective functions and weighting factors, to support strategic decision making in the sense of a decision support system.

A novel aspect is the combination with an Earth-System model for online verification of algorithmic environmental change functions and proposed routing strategies when minimizing environmental impacts. The application of an integrated air traffic submodel see Sections 2.3 and 3.4 and [35] will enable for the first time the online verification of environmentally optimised rerouting strategies in an Earth-System-Model. Here this approach is used to verify the algorithm-based climate change functions. However, many more applications can be envisaged. The pre-requisite is a climate impact proxy, which is based on information, available from weather forecast models. Alternative routing strategies for climate impact mitigation, such as e.g., avoiding night-contrails which warm the climate and which can be estimated with a relatively low uncertainty, can be analysed with this verification platform as well.

The concept presented here relies on identification and effective implementation of aECFs in flight planning tools as advanced MET services providing a flexible interface to comprehensive calculation of environmental impacts of aviation emissions. For establishing required set of individual aECFs representing individual effects of aviation climate and environmental impact, comprehensive assessments of atmospheric and environmental impacts are required. Such assessments require suitable atmospheric chemistry and physics modelling tools being applied. They subsequently need to consider and identify key atmospheric parameters in order to eventually provide mathematical formulation of aECFs, which can then be implemented in an expanded ATM aircraft trajectory optimisation tool.

This concept lays the basis for performing route optimisation in the European airspace using advanced MET information in the light of environmental assessment and optimisation of aircraft movements in Europe. Ultimately, this will lead to a strategic roadmap of how to implement such a multi-criteria and multi-dimensional environmental assessment and optimisation framework into current ATM infrastructure by integrating tailored MET components, in order to make future aviation sustainable.

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Author Contributions: Sigrun Matthes has defined the outline, conceived the study and wrote large parts of the paper; Volker Grewe conceived validation exercise; Katrin Dahlmann and Christine Frömming provided climatological and archetypical ECFs; Benjamin Lührs and Florian Linke designed and performed trajectory optimisation; Emma Irvine and Keith Shine conceived meteorological analysis; Feijia Yin and Hiroshi Yamashita performed validation developments; Ling Lim and Bethan Owen described verification with FAST; Stavros Stromatas presented modelling of local impacts, LAQ and noise.

Conflicts of Interest: All authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

aECF	Alogrithmic Environmental Change Function
AIM	Aeronautical Information Management
ASK	Available Seat Kilometres
ATM	Air Traffic Management
ATFM	Air Traffic Flow Management
ATM4E	ATM for Environment (SESAR2020 project)
ATR	Average Temperature Response

BADA	Base of Aircraft Data (EUROCONTROL)
CCF	Climate Change (cost) Function
CiC	Contrail Induced Cloudiness
DDR2	Demand Data Repository (EUROCONTROL)
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOC	Direct Operating Costs
ECAC	European Civil Aviation Conference
ECF	Environmental Change Function
ECHAM	European Centre Hamburg General Circulation Model
ECMWF	European Centre for Medium-Range Weather Forecasts
EI	Emission Index
EMAC	ECHAM/MESSy Atmospheric Chemistry model
ERA	European Reanalysis
ICAO	International Civil Aviation Organization
LAQ	Local Air Quality
MESSy	Modular Earth Submodel System
MET	Meteorological Information (as being part of ATM)
NOTAMs	Notices for Airmen
REACT4C	Reducing Aviation Emission by Changing Trajectories (FP7 project)
SESAR	Single European Sky Aviation Research
TRL	Technology Readiness Level

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