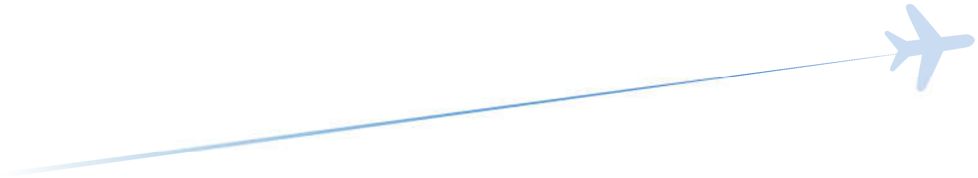

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Copyright Statement

ATM4E

AIR TRAFFIC MANAGEMENT FOR ENVIRONMENT

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The purpose of this document is the publication of the final project results from ATM4E.

Abstract

The overall aim of ATM4E was to explore the scope for the potential reduction of air traffic environmental impacts in European airspace on climate, air quality, and noise through optimization of air traffic operations.

Based on results from the previous project REACT4C a concept for the utilization of so-called algorithmic Environmental Change Functions (ECFs) in the planning of environmental-optimized flights has been developed and demonstrated. In conjunction with comprehensive meteorological data including different atmospheric parameters, these functions enable the instantaneous calculation of the climate impact caused by the engine emissions released at any point in the four-dimensional space (latitude, longitude, altitude, time). European traffic scenarios were analyzed to understand the extent to which environmental-optimized flights would lead to changes in air traffic flows and create challenges for ATM. The findings of the project were used to derive a roadmap that is consistent with SESAR2020 principles and objectives, which considers the necessary steps and actions that would need to be taken to ultimately introduce environmentally-optimized flight operations in European airspace.

The algorithmic ECFs which use MET data readily available at the flight planning phase, have been shown to give reasonable representations of detailed ECFs, and this enables operational implementation. Results of a comprehensive case study investigating the potential of environmental-optimized flight planning on a single day in Europe show many cases where reductions in the climate impact of order 10's of % can be achieved for an increased fuel burn of order of a few percent. Importantly, the reduction in climate impact has been shown to be large for some flights (for example, where relatively small deviations in flight route lead to avoidance of contrail formation) but are much less for others; therefore, a large fraction of the overall mitigation potential lying in the climate-optimization of European air traffic can already be gained by focusing on a limited number of "critical" flights only. It has also been found that environmental-optimized flight planning on a large scale in Europe could lead to imbalances in the demand-capacity situation in specific parts of the airspace assuming that capacity is managed and provided as it is today. Accommodating these traffic flow changes is a challenge the European ATM Network would have to overcome, if environmental optimization plays an increasing role in flight planning in the future.

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1 Executive Summary

The main objective of the ATM4E project was to explore the feasibility of a concept for environmental assessment of ATM operations working towards environmental optimisation of air traffic operations in the European airspace. Advances have been made by making progress in individual Work Packages. Specifically, progress has been made on provision of Environmental Change Functions as an advanced MET service (WP1), on planning of environmental-optimized trajectories in Europe (WP2), on verification of overall mitigation potential (WP3) and assessment and exploitation of project results (WP4).

Regarding the first objective, which was to establish a multi-dimensional Environmental Change Function (ECF) concept, by combining algorithm-based climate impact ECFs (including the non-CO2 climate impacts of aviation) with local air quality (LAQ) impact (for key pollutants) and perceived noise, algorithmic ECFs (aECFs) were developed; a novel set of aECFs was provided for the selected case study period. Regarding the local environmental impact, a methodology for LAQsS and Noise ECFs was developed and refined using different scenarios for a specific airport.

The second objective was to plan flight trajectories which mitigate the environmental impact for characteristic meteorological situations based on different air traffic management (ATM) constraint assumptions and optimization strategies and to investigate to what extent the resulting changes in traffic flows lead to particular challenges for ATM when such optimization is performed (WP2). A multi-phase concept for the integration of climate, LAQ and noise has been designed and implemented, considering three consecutive flight phases (take-off, cruise, and landing). Finally, the optimization campaign has been initiated and, for the first time, the entire traffic of a characteristic winter day (18 December 2015) has been environmentally optimized in four dimensions with different ATM and optimization strategies. It is the first time that algorithmic Climate Change Functions have been used in such a wide-ranging optimization, indicating a mitigation potential of more than 20% climate impact for a 1 % fuel penalty for the case study performed.

The third objective was to verify the algorithmic Environmental Change Functions and to evaluate environmentally-optimized routes in a future atmosphere in a comprehensive climate-chemistry modelling allowing a proof of concept of climate-optimisation with daily route analysis (WP3). From implementation of algorithmic climate change functions in a comprehensive climate-chemistry model, which includes an aircraft routing module, a one year simulation of air traffic, with associated emissions and chemical and radiative impact, has been performed. It was shown that using aECFs for identifying climate optimal routes, leads to a reduction of overall climate impact of aviation missions.

Finally, a roadmap was developed with recommendations and an implementation strategy for the environmental optimization of aircraft trajectories in close collaboration with aviation stakeholders (WP4). This roadmap presents the next steps towards establishment of climate-optimized routing in Europe. It became clear that benefits for the environment need to be represented in performance indicators to demonstrate these benefits in a quantitative way, in order to create an incentive for environmentally optimized trajectories. Second, next steps need to investigate robustness of identified routing options, and quantifying the associated uncertainties, and translate this to a concept for measuring and providing this information.

One of the main conclusions from the ATM4E project is a proof of concept: It has been established that information on the climate impact of aviation emission can be provided to flight planning systems by the use of environmental change functions (ECFs). In a case study for the Europe airspace, a mitigation potential of 10% climate impact reduction has been found for a large set of flights. Individual flights can have a significantly higher mitigation potential. In the view of the project team the implementation of such routing would need quantitative performance indicators in order to be able to demonstrate benefits for environment (Key performance area KP05) and consequently in order to gain the confidence of the stakeholder community. Finally, it has also been found that environmental-optimized flight planning in a large-scale domain such as Europe could lead to imbalances in the demand-capacity situation in specific parts of the airspace assuming that capacity is managed and provided as it is today. From conclusions and lesson learnt, next steps on research and development activities are proposed, which include enhancing the technology readiness level, enlarging and expanding the concept of environmental change functions, comprising a measure of robustness for ECFs allowing for robust decision making. Additionally, a large-scale test via simulation of life-trials would assess the decision and verification chain, while an expansion of performance data and economic incentives are required, as well as a network flow management analysis to detect changing traffic flows.

2 Project Overview

2.1 Operational/Technical Context

Beyond the desire to minimise fuel use and hence CO_2 emissions, currently the consideration of environmental aspects in en-route flight planning has not been operational practice. The reason for this is a low TRL of a flight planning method that considers a multi-dimensional environmental impact assessment and a lack of scientific understanding to motivate environmental flight planning. ATM4E contributed directly to the European ATM Master Plan which aims at enabling "the delivery of safe, cost-efficient and environmentally responsible Air Vehicle & ATM operations, systems and services", as it addresses the most-relevant research questions in order to realize environmentally responsible Air Vehicle & ATM operations. Furthermore, ATM4E addresses high-level environmental SES targets, being primarily to enable a 10% reduction in the effects that flights have on the environment (compared to 2005) and extends the original focus (flight efficiency only) to the consideration of the overall environmental perspective.

The main objective of the ATM4E project is to explore the feasibility of a concept for environmental assessment of ATM operations working towards environmental optimisation of air traffic operations in the European airspace. The project aims to integrate existing methodologies for assessment of the environmental impact of aviation, in order to evaluate the implications of environmentally-optimized flight operations to the European ATM network, considering climate, air quality and noise impacts.

The proposed solution is based on an advanced MET service which enables flight planning tools to assess environmental impacts of a flight trajectory during the planning process. This MET service provides environmental impacts associated with an aviation emission by environmental change functions (ECFs) as improved information and enhanced awareness on the flight environment for each individual environmental impacts. Specifically, ECFs on climate impact provide a quantitative information on how strong an aviation emission impacts on climate change, measured e.g. in an average global temperature response over the next 20 years. Similarly, ECFs on local effects provide a measure how much the population is impacted by an emission released at a specific point and time, e.g. regarding particulate matter or nitrogen oxides (NO_x). 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.

2.2 Project Scope and Objectives

ATM4E project scope is to explore the feasibility of a concept for environmental assessment of ATM operations working towards environmental optimisation of air traffic operations in the European airspace.

The first objective is to establish a multi-dimensional environmental change function (ECF) concept, which will include air quality impact (for key pollutants) and perceived noise in addition to CO_2 and non-CO_2 climate impact. This constitutes a new metric for environmental impacts (WP1).

The second objective is to plan flight trajectories which mitigate the environmental impact for characteristic meteorological situations based on different ATM constraint assumptions and optimization strategies and investigate to what extent the resulting changes in traffic flows lead to particular challenges for air traffic management when such optimization is performed (WP2).

The third objective is to evaluate environmentally-optimized routes in a future atmosphere in a comprehensive climate-chemistry model allowing a proof of concept of climate-optimisation with daily route analysis (WP3).

Finally, a roadmap is developed with recommendations and an implementation strategy for the environmental optimization of aircraft trajectories in close collaboration with aviation stakeholders (WP4).

Within the scope of this project the term "change function" is used for multi-dimensional functions which describe a specific quantitative impact of aircraft operations, e.g. climate-impact of contrail formation per flight kilometre, impact on air quality per specific emission of NO_x and particulates or noise impact as 4-dimensional functions, depending on geographic position, altitude and time of flight.

2.3 Work Performed

ATM4E explored the feasibility of a concept for environmental assessment of ATM operations working towards environmental optimisation of air traffic operations in the European airspace with a structure composed of five workpackages.

The project therefore investigated the impact of environmental optimisation of aircraft trajectories in different phases of flight by investigating changes in traffic flows over Europe. This was realized by combining the meteorology and climate science expertise with knowledge on air traffic management and flight operations, more specifically flight planning and network management, as well as with fundamental mathematical and optimization competencies reflected by the different consortium members.

ATM4E was the logical follow up of the EU Framework Project REACT4C which aimed at the development of "a simulation framework for investigating climate change mitigation options for air traffic routing by avoiding climate sensitive regions" [35] and focused on flights over the North Atlantic. REACT4C demonstrated a concept of optimizing flight trajectories based on common elements and modelling infrastructure and tested its application on simulated transatlantic flights [34-[37]. Many further advances would be required to test the REACT4C methodology in an operational setting.

ATM4E expanded the REACT4C change functions to include local environmental impact elements (noise and local air quality), and to investigate the application of the concept to the European airspace, taking into consideration geographical specificities in terms of demand, capacity, weather and environment. Such Environmental Change Functions provide information on the environmental impact of an emission at a specific position, altitude and point in time. A conceptual framework for applying 4D trajectory optimization which uses this information to take into account environmental considerations during flight planning was developed in ATM4E. This required a customization of the necessary analytical tools. This concept was then applied to a set of scenarios covering different optimization strategies and different points in time within the European airspace. The R&D positioning of ATM4E was from "idea to application", further refining the application of the concept defined in REACT4C to the European airspace. Figure 1 indicates how the ATM4E project built upon the findings of REACT4C and further improved the optimization of trajectories for environment which was developed. Work performed in the workpackages is described in detail below.

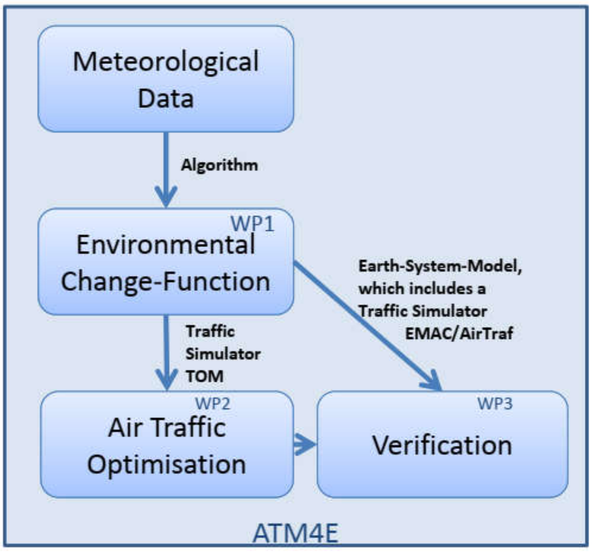


Figure 1 Workflow and workpackages of ATM4E

2.3.1 Work Package 1 – Environmental Change Functions

Work package 1 focused on the production of Environmental Change Functions (ECFs) to be used throughout ATM4E. This novel type of meteorological information service provides to airspace users spatially and temporally resolved information on sensitivity of the atmosphere at the specific point and time to environmental impacts. An ECF informs whether the environmental impact of an emission in this region is strong or weak. Work package 1 objectives were:

- To provide Climate Change Functions (CCFs) as predictors for the global climate impact of localized air traffic emissions
- To derive a reliable algorithm-based ECF for use in weather prediction models
- To include noise levels and local air quality impacts
- To integrate impacts via environmental metrics considering local impacts versus global impacts

The work was divided into four tasks. **Task 1.1 (Provision of CCFs)** was primarily a technical task transferring data generated with a comprehensive chemistry-climate model for algorithm-based ECF analysis (D1.1) [1] enabling to establish a link between meteorological parameters, like temperature, relative humidity and geopotential, towards climate impact measured as an average change of temperature over the next 20, 50 or 100 years.

Task 1.2 (Provision of environmental change functions for air quality and noise impact): The concept of deriving local scale environmental change functions for local air quality and noise was a novel undertaking by ATM4E and required new and detailed simulations and sensitivity studies to be undertaken to identify the role of key parameters (D1.2) [2]. The work resulted in a first set of environmental change functions for local air quality and sensitivity experiments examining the role of key parameters (such as wind speed and direction). Similarly, a new set of 5-dimensional (x, y, z, engine thrust and speed) noise ECFs were developed for specific airports based on numerous sensitivity tests.

Task 1.3 (Derivation of algorithmic ECFs) was also an entirely innovative undertaking by ATM4E. The climate impact of aviation CO_2 depends only on the amount of CO_2 emitted, with no dependence on where it is emitted and can be directly derived from fuel use. By contrast, non-CO_2 climate impacts (e.g. contrails, ozone formation due to engine NO_x emissions) are highly dependent on the location and time of emissions and the prevailing weather conditions. Previous work in REACT4C developed climate change functions (CCFs) for non-CO_2 climate impacts, using detailed chemistry-climate model simulations. In an operational setting, i.e. in the framework of a routinely flight planning, it is not feasible to perform such detailed calculations, because of limitations in computing time. ATM4E investigated the potential of using simple relationships between standard MET data that is available during flight planning, and the climate change functions, to allow the rapid generation of so-called algorithmic environmental change functions (aECFs) for use in flight planning. ATM4E generated aCCFs for three classes of non-CO_2 climate effects (NO_x impacts on ozone and methane, the direct impact of aircraft water vapour emissions and persistent contrails) by extensive tests of the ability of different standard MET variables to explain the more detailed climate change functions, guided by an understanding of the controlling physical and chemical processes (D1.3) [3]. The derived algorithmic climate change functions captured many of the major horizontal and vertical variations found in the detailed climate change functions, and hence established the feasibility of the technique. The final chosen algorithms met the ATM4E requirements which require a trade-off between sufficient accuracy and the necessity for simplicity for use in an operational environment and were delivered for use by Work package 2. It was recognised that further refinements of the algorithmic environmental change functions in terms of their accuracy and applicability could be achieved; this would be best done after experience had been gathered in their use in an air traffic management setting, so that a clearer understanding of the trade-offs between accuracy and simplicity could be achieved.

Task 1.4 (Development of multi-dimensional environmental impact metrics for ECFs) reported the development of multi-dimensional environmental impact metrics (D1.4) [4]. This addressed a vital and innovative part of the ATM4E methodology which was the development of a framework for the integration of ECFs covering climate, noise and local air quality. To illustrate the concept of environmental impact assessment, this task considered a case study for an air traffic sample over Europe applied on a candidate day using real weather conditions. To illustrate climate optimization, the most mature of these areas under consideration, a case study was presented for a single-flight trajectory, using prototype algorithmic environmental change functions . For local air quality the increase of atmospheric NO_2 concentrations was selected as an environmental performance indicator, and performed sensitivity tests for different air quality indicators, e.g., using either daily or hourly peak concentrations. For noise impacts a conceptual approach was presented. Such an assessment framework allows the use of an optimisation under individual objective functions and weighting factors (representing the perceived relative importance of each component of the environmental change functions), to support the decision-making process at the flight-planning level.

2.3.2 Work Package 2 – Environmental-optimized routing impact on ATM

Within work package 2, environmental-optimized trajectories for a European air traffic scenario were calculated. To enable such environmental-optimized flight-planning the novel concept of algorithmic ECFs developed in WP1 had to be integrated in the flight planning process. Additionally, the implications which environmentally-optimized flight planning would have on the European ATM network were analysed. The underlying workflow is shown in Figure 2.

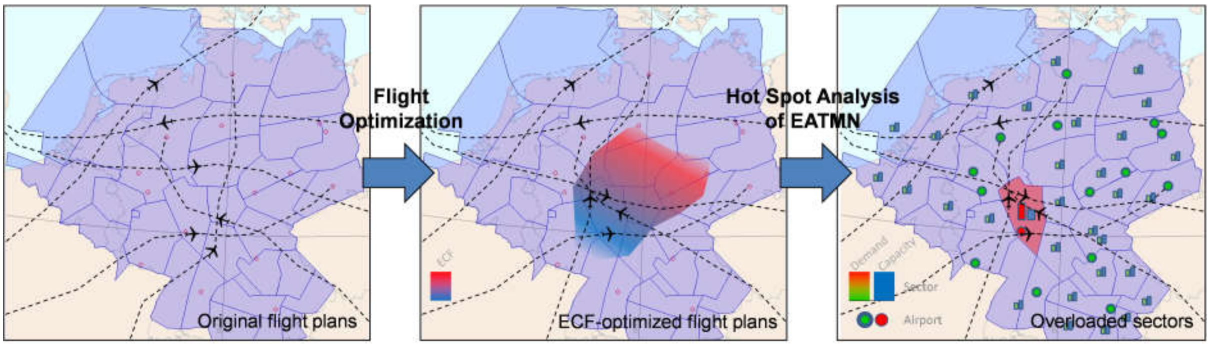


Figure 2: Flight optimization and hot spot analysis in European ATM Network. Original flight plans (left) and ECF optimized paths (middle & right) are shown. ECF (middle) indicates areas of warming (red) and cooling (blue). Overloaded sectors (right) are highlighted (red) together with demand (color-coded from green to red) and capacity (in blue) for individual sectors with climate optimized flight plans.

In preparation for this, air traffic data for Europe has been processed and filtered. For this purpose, different candidate days were identified which ensure an adequate balance between traffic load (high traffic load desired) and ATM Network disturbance (low amount of regulations desired); out of these, a reference day for the optimization study was selected based on meteorological considerations. For this reference day, a filtered dataset of flight movements was statistically analysed and provided to the Project Partners (D2.1) [5].

In a second step, the environmental impact of the selected air traffic scenario was determined by reproducing all flights with an aircraft trajectory calculator which simulates the release of engine emissions along the trajectory. The resulting amounts of carbon dioxide, water vapour and nitrogen oxides were finally provided in a 4D-grid depending on their location, altitude and time. The potential forming of contrails caused by these flights was estimated and added to the data set(D2.2) [6].

Tool implementation and adaptation activities were conducted. In particular, the Trajectory Optimization Module (TOM) was improved and qualified for the simulation and optimization of the large air traffic scenario identified in the first phase of the project. For this purpose, software interfaces between TOM and ECMWF meteorological data as well as Climate Change Functions from the REACT4C project as verification baseline were adapted. The interpolation routine was extended by the temporal dimension in order to allow for a full 4D optimization. Additionally, code parallelization has been implemented such that the optimization process became much faster and large scenarios can be handled more efficiently.

A concept for the integration of climate, local air quality and noise aspects into one combined optimization problem was proposed and implemented into TOM, while focussing on climate aspects first. Furthermore, requirements to the models for local air quality providing the respective terms for the environmental change functions were defined with respect to lateral and vertical resolution as well as coverage in close cooperation with WP1. For verification purposes in WP3, a comparison exercise was set up which allows for a comparison of different aircraft performance and emission models involved in the project in order to better understand differences and uncertainties of particular aircraft performance models.

The optimization campaign was conducted and, for the first time, the entire traffic of a characteristic winter day (18th December 2015) was environmentally optimized in four dimensions with different ATM and optimization strategies. It is the first time that algorithmic Climate Change Functions were used in such a wide-ranging optimization. The comprehensive trajectory data and the multitude of optimizations per route using different weights for the 3 environmental impacts (climate, local air quality and noise) and monetary costs allow for various interesting assessments. Results were discussed based on selected examples and the entire process is documented in the corresponding deliverable (D2.3) [7].

Finally, the ATM network effects were studied by identifying so called air traffic flow management hotspots. Prior to the analysis, the Network Flow Environment (NFE) had to be adapted in order to include the relevant network infrastructural data which have been valid on the reference day. Furthermore, an interface allowing for an efficient processing of the environmentally optimized traffic scenarios had to be developed. Relative differences of the demand-capacity-ratios of each capacity-afflicted airspace element for fuel- and climate-optimized trajectories are compared to the reference traffic sample. This indicator allows for an easy identification of air traffic flow management hotspots and new visual functionalities were included in the Network Flow Environment to plot standardized color-coded hotspot mappings for the European airspace. This enables to directly compare the implications of different sets of trajectories with given system capacities.

For the first time, the implications of environmentally optimized European air traffic on the ATM network were investigated in detail. Two aspects make this investigation outstanding: First completeness of the air traffic sample and second the way the optimisation is performed, which allows a full 4D trajectory optimization with different optimization strategies. The corresponding deliverable (D2.4) [8] contains first results. Due to the multidimensional character of the ATM network demand and capacity situation, a lot more specific analyses can be conducted aiming at a more detailed and distinguished picture of when and where demand-capacity imbalances might occur, if environmental-optimized flights are filed on a large scale in Europe.

2.3.3 Work Package 3 – Verification of environmental impact reduction from ECFs

Work package 3 focused on the verification of both the algorithmic Environmental Change Functions (aECFs) and the potential to reduce environmental impacts by applying environmental change functions. It was verified with a comprehensive chemistry-climate model if, and to what extent, climate-optimized trajectories identified using the novel ECF concept developed in ATM4E, resulted in an overall climate impact mitigation. Work package 3 objectives were:

- To evaluate environmental impact reduction by avoiding climate sensitive regions (e.g. contrails).
- To verify effectiveness of algorithm based ECF with a coupled Earth-System-Model.

There work was divided into four tasks. **Task 3.1 (Definition of the verification procedure)** was primarily defining in detail (D3.1) [9] the individual aspects of verification and the procedure. This includes a detailed description of the models used, the model set-ups, scenario definition and the benchmark for verifying the individual aspects.

Task 3.2 was a more technical task which focused on the **implementation of algorithmic environmental change functions**, developed in WP 1, in the EMAC Earth-System Model (M3.1). The climate change functions for CO_2, H_2O, NO_x and contrails were implemented and tested successfully. As foreseen in the project plan, the contrail climate change functions were developed at a later stage in WP1 due to their complexity. A prototype, the potential occurrence of persisting contrails (potential contrail coverage), was implemented, tested and used for some of the verification procedures.

Task 3.3 was dedicated to **air traffic climate simulation** aiming at the verification of the algorithmic climate change functions. The Earth-System-Model EMAC, which was enhanced in task 3.2 with the capability to predict the climate impact of a local emission, i.e. by the algorithmic climate change functions, was applied to simulate the air traffic flow in a cost optimal and climate optimal manner (with respect to the algorithmic climate change functions). The difference in the atmospheric composition and climate variables (D3.2) [10] is used to verify the effectiveness of algorithmic climate change functions. Additionally, long-term simulations were performed to derive climatology of the algorithmic climate change functions and compare them to literature. An air traffic climate simulation is performed based on the contrail prototype algorithmic climate change functions, which effectively leads to the avoidance of contrails in the simulation.

Task 3.4 summarised the **verification of algorithmic climate change functions**based on the results from task 3.3 and a comparison of the calculated algorithmic climate change functionsclimatology with literature. The effectiveness of aECFs in reducing the environmental impact was derived by analysing results from WP2 and comparing them to literature. Since the different air traffic flow simulators applied in WP2 and WP3 are crucial for the verification of the effectiveness of aECFs, a detailed verification of the calculated aircraft trajectories was performed. These verification procedures and results are described in (D3.3) [11].

2.3.4 Work Package 4 – Assessment and exploitation

Work package 4 focused on exploitation and implementation of project results. As the challenge of developing climate-optimized aircraft trajectories in an efficient ATM environment is a highly inter-disciplinary task involving a large group of stakeholders, this was organized in a dedicated work package.

Task 4.1 organised **stakeholder exchange** comprising organisation of external experts advisory board activities, with meetings and webinar.

Task 4.2 identified **intermediate solutions** and proposed an **implementation strategy** for optimising ATM operations for the environment. It provided an overview on other possible metrics and to assess the overall impact of climate-optimised trajectories in the context of these additional impacts, in order to be able to reflect user preferences (D4.1) [12]. It provided recommendations for intermediate solutions to minimising the total impact (D4.2) [13].

Task 4.3 provided **a roadmap** for how these solutions can be made more robust in the future.to reduce environmental impacts by applying environmental change functions (D4.2) [14].

2.3.5 Work Package 5 – Management

Work package 5 performed the overall project management, including financial, legal and administrative management of ATM4E. In **task 5.1** a detailed project management plan was developed, updated and implemented (D5.1) [15] as part of overall project coordination. **Task 5.2** organised regular project meetings and project reports. Major project results are summarized in the final project results report (this document) as a basis for the final project close out meeting (D5.2) [16]. Finally, **task 5.3** performs the administrative management.

2.4 Key Project Results

2.4.1 WP1 Environmental Change Functions

The key project results from WP1 were the generation of algorithmic Environmental Change Functions (aECFs) that enabled the testing of the major component of the ATM4E methodology in Workpackage 2. The underlying concept was to use detailed calculations of the main environmental components of aviation (climate change, local air quality and noise) to derive aECFs. These allowed a rapid calculation of the environmental impacts using standard MET forecast data at the flight-planning stage. This recognised that the computational demands of state-of-the-art techniques preclude their use in an operational environment for the foreseeable future.

The climate change functions (CCFs) and their algorithmic counterparts (aCCFs), recognise that the climate impact is made up of both CO_2 and non-CO_2 components; ATM4E considered ozone and methane changes from NO_x emissions, water vapour emissions and persistent contrail formation. These are highly dependent on the location of emissions and the prevailing weather conditions, and so can vary strongly along a given flight trajectory. The climate effect was quantified as the global impact of the local emissions. A metric is required to place the climate effect of CO_2 and non-CO_2 on a common scale, particularly because the persistence of the climate effect varies between the effects. CO_2 causes a long-lived perturbation to the climate system while at the opposite extreme, individual persistent contrails may last only hours. Several choices of metrics are available, and within ATM4E one particular metric was chosen, which is the average temperature response over a 20-year period (ATR20) due to a given emission, assuming a given future air traffic scenario. ATM4E used detailed CCFs derived in the EU Framework 7 REACT4C project using a sophisticated chemistry-climate model, to achieve the innovative step of deriving aCCFs.

For the local air quality and noise impacts, the domain of impact was taken to be local, and generated during the take-off and landing flight segments. The impact at a given location was weighted by the population affected. ECFs for these components had not previously been produced prior to ATM4E and hence had to be generated, prior to the generation of aECFs for delivery to Workpackage 2.

For the selected day of the case study in Europe aECFs were generated [5]. The development of the water vapour and nitrogen oxide emission aCCFs, followed a four step procedure described in detail by [21] and [25] using the approach shown in Figure 3. First, a pre-selection of atmospheric parameters is made which includes wind characteristics, temperature, humidity, geopotential height, rain rates, incoming solar radiation, and ozone concentration. In total several hundred parameters were pre-selected. Second, a correlation analysis is performed, which identifies the most relevant parameters (around 30 to 50) among those that explain the structures seen in the REACT4C CCFs. From these, 4 correlations are identified as having the highest statistical significance.

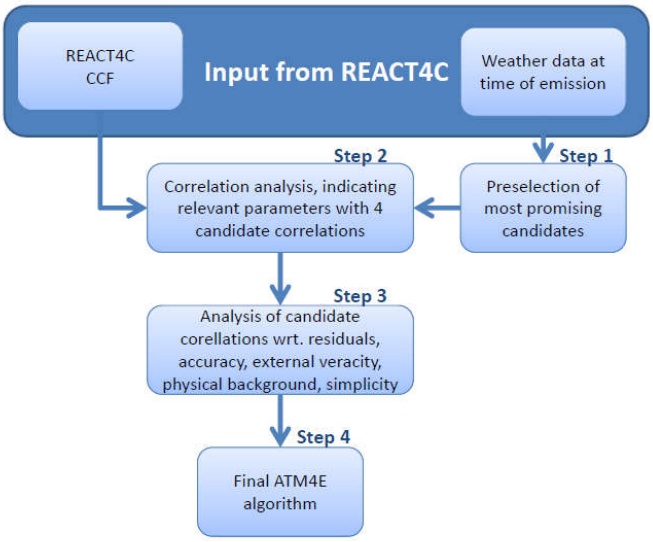


Figure 3 Schematic of the production of the algorithmic Climate Change Functions from the original REACT4C climate change functions

For water vapour, the aCCF was based on a meteorological parameter known as potential vorticity (PV), which depends on both winds, and the vertical variation of temperature. In the context of ATM4E, PV effectively discriminates whether a flight is occurring in the troposphere (where water vapour is short-lived and has a low impact on climate) or in the stratosphere (where it is longer-lived and has a greater impact). The PV captures the variation of tropopause height with latitude and longitude; such variations are largely dictated by the prevailing weather pattern.

For NO_x, the warming effect on ozone was characterised by two parameters – one is the local temperature at aircraft altitude (since chemical processes are dependent on the temperature) and the other is the “geopotential” which is closely related to wind patterns and hence helps characterise how the NO_x emissions are moved by the winds. The cooling effects of the methane reductions were also captured by a relationship that includes geopotential and the amount of incoming solar radiation at the top of the atmosphere.

The algorithms explain roughly 60%, 40% and 20% of the variability in the CCFs for water vapour, the NO_x-O_3, and NO_x-CH_4, respectively. Hence the water vapour algorithm well explains climate impacts of a local water vapour emission, whereas the quality decreases for the NO_x-O_3 aCCF, and especially the NO_x-CH_4 aCCF. Figure 4 presents an example of the CCFs and aCCFs for water vapour.

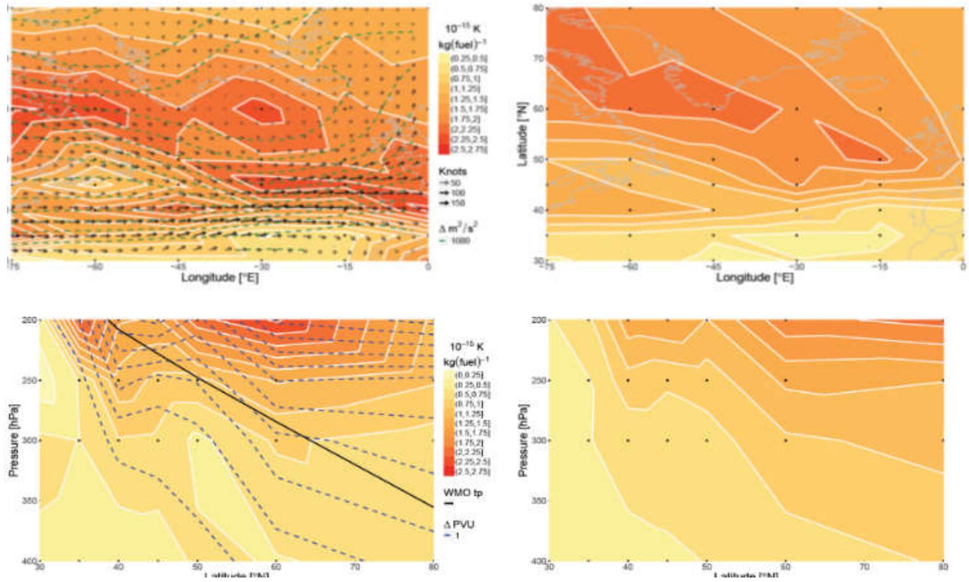


Figure 4: Water vapour CCF (left) and aCCF (right) for 12 UTC, 200 hPa, REACT4C Weather Pattern 1 50[36] as a function of latitude and longitude (top row) and latitude and pressure (bottom row), Wind speed is indicated by arrows (top left, only) and the geopotential by green isolines (left only). The black line indicates the location of the tropopause.

For persistent contrails, their formation depends sensitively on atmospheric conditions – typically over Europe, such conditions occur around 15% of the time, but these conditions vary rapidly with height and location and depend on the prevailing weather conditions. An added complication is that contrails impact both the "longwave" infrared radiation emitted by the Earth and atmosphere (causing a warming effect) and reflect solar radiation back to space (causing a cooling effect) so that the net effect is a residual of these; it can be of either sign, depending on conditions and time of day of contrail formation. A number of important parameters that determine the contrail climate impact (such as ice particle size and shape, contrail width and depth) could not be easily and quickly predicted from weather forecast data and so, for ATM4E assumed values for these. They provide a foundation for more refined work in the future.

aCCFs were derived separately for night-time contrails and day-time contrails, because the net contrail climate effect is hugely influenced by the time of the day. At night, contrails only warm via a positive LW forcing. During the day, contrails both cool by reflecting sunlight back to space and warm by trapping heat so that the net effect results from compensation between the two effects. The procedure that was followed was to (i) exploit detailed calculations from REACT4C which tracked the passage of air through regions of the atmosphere that support contrail formation, (ii) calculate the resulting radiative effect of these contrails using a physically-based model, and (iii) seek simple relationships between the contrail radiative effect and quantities easily available from the forecast MET data. For the feasibility purposes of ATM4E it was found that temperature (which strongly determines the amount of contrail ice content) and the outgoing infrared radiation, provided reasonable approximations to the climate effect. The forecast MET data also provide the information on the likelihood of contrail formation. Example aCCFs are shown in Figure 5 for FL390 for the case study day of 18 December 2015 at 0000, 0600 and 1200 (UTC). The evolution of both the location and magnitude of the contrail aCCF can be seen during the progression of the day as the weather situation evolves.

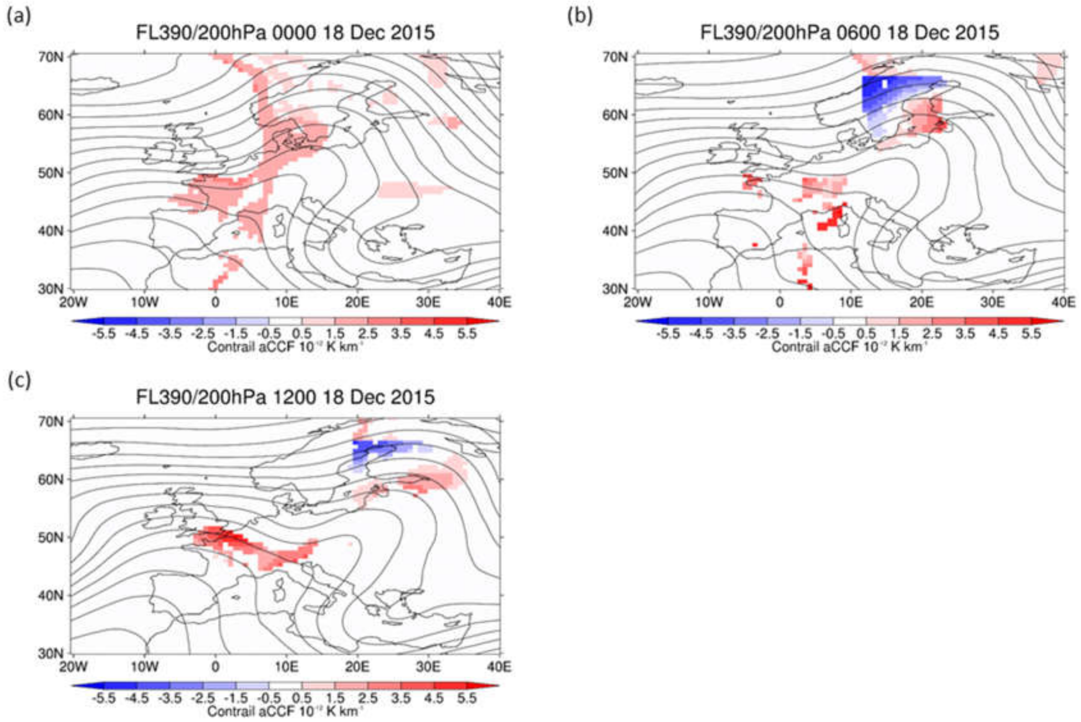


Figure 5: Contrail aCCF (colours) in 10^{-12} K km^{-1} and geopotential height (black contours) at a flight level of 39,000 ft (FL390) for the case study day of 18 December 2015 at (a) 0000 UTC, (b) 0600 UTC and (c) 1200 UTC. Positive values (red) indicate regions where aviation emission would cause a warming by contrails; while negative values (blue) indicate a cooling by contrails.

Local air quality (LAQ) ECFs are produced based on the simulations performed with Eurocontrol's Open-ALAQS model [38] coupled with the Lagrangian particle dispersion model AUSTAL2000 [39], the official reference model of the German Regulation on Air Quality Control (Technische Anleitung zur Reinhaltung der Luft, TA Luft).

The environmental impact is calculated by combining the LAQ results with the number of people exposed to the calculated NO_x levels. A basic LAQ metric is the emitted amount of respective component relevant for air quality, e.g., nitrogen oxides or particulate matter, under a specific atmospheric height. For trace compounds however, the final metric proposed for the ECF 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). An illustration of the calculated ECFs for two different airports (Hamburg and Madrid) is shown in Figure 6 together with the population density (number of people in each grid cell).

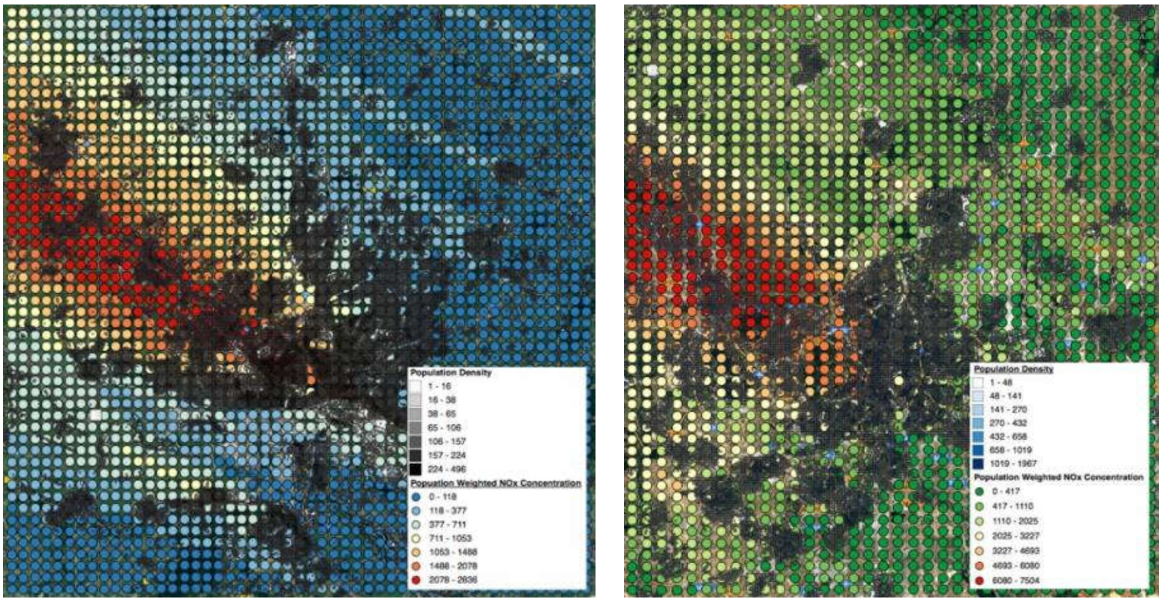


Figure 6: LAQ ECF for z=0m, Hamburg Airport (left), Madrid (right). The population density is superposed on the population-weighted NO_x concentration.

The modelling process for deriving ECFs for the noise generated from a single aircraft is centred on a customised version of Eurocontrol’s multi-airport noise impact assessment model STAPES (SysTem for AirPort noise Exposure Studies. The population around the airport is estimated as described above for LAQ ECFs. The core methods from STAPES are used in the context of this study to effectively determine noise levels from single aircraft movements.

Following a similar methodology as for LAQ, separate simulations are performed for a set of points defined to simulate an aircraft flight path. Single-event levels are calculated from the customised version of STAPES for different aircraft thrust (i.e. 15500, 17000, 21000) and speed (i.e. 270, 220, 165) settings according to the NPD distances provided in Eurocontrol’s ANP database. The results are then combined with population data to estimate the number of people affected by each noise level, 33-36dB noise level results are illustrated in Figure 7 for the case of Hamburg Airport.

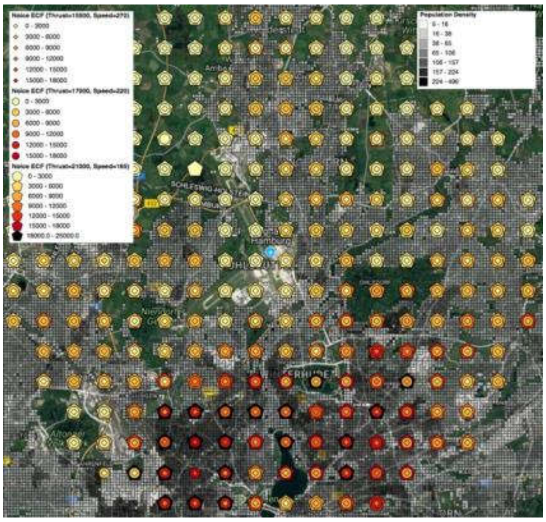


Figure 7: Example, for Hamburg Airport, of 5D noise ECFs. Single-event levels are calculated for different aircraft thrust and speed settings. The results are then combined with population data (shown in grey) to estimate the number of people affected by each noise level.

The information from each emission point of the defined grid provides the necessary input data for the noise ECFs used in ATM4E Work Package 2.

2.4.2 WP2 Environmental-optimized routing impact on ATM

The work in WP2 started with the identification of a representative reference day as a basis for the traffic optimization and analysis. December 18th, 2015 was chosen as reference day. This day is characterized by a high traffic volume, a low number of regulations (weather-, ATC-, and aerodrome related) as well as an interesting weather situation. The entire dataset which was exported from EUROCONTROL's Demand Data Repository 2 (DDR2) database after clean-up consists of 28,337 flights. As ATM4E focuses on the European airspace, it was decided to concentrate on intra-ECAC (European Civil Aviation Conference) flights only, reducing the dataset to 22,274 flights. Since the performance model which is used for trajectory calculation and optimization is based on EUROCONTROL's Base of Aircraft Data (BADA) 4.0, only flights which are covered by this database are considered, which decreases the number of flights which are taken into account to 13,512. Although this seems to be a large reduction of flights, the amount of considered available seat kilometres (ASK) only decreases by 8-9% [5] since especially large Airbus and Boeing aircraft are part of BADA 4.0. Lastly, flights which depart before or arrive after December 18th 2015 are filtered out leading to a final dataset of 13,276 flights (see Figure 8), in the following called "foreground"-flights. However, the flights which have been filtered out, are considered as "background"-flights within the hotspot analysis by using their original point profiles [5].

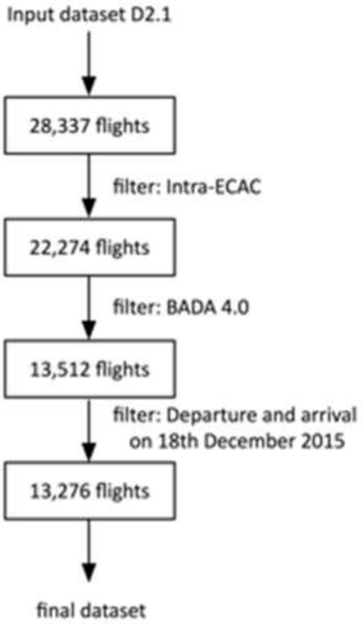


Figure 8: Applied filters on the ATM4E input dataset for Europe [5]

This resulting air traffic dataset has then been analysed with respect to its environmental impact. Specifically, CO_2, H_2O, NO_x emissions as well as formed contrails have been determined using a methodology comprising of so-called "reduced" emission profiles, which were derived from pre-calculated trajectories and emission distributions [6]. Table 1 lists the resulting aggregated values.

Table 1: Cumulated results of the environmental impact analysis [6]

Parameter	Amount
Total CO_2 emissions	1.4990e+08 kg
Total H_2O emissions	5.8773e+07 kg
Total NO_x emissions [NO_2]	7.1985e+05 kg
Total distance in contrail areas	6.7647e+05 km
Total air distance	1.4246e+07 km
Total ground distance	1.4166e+07 km
Total ASK	2.3622e+09 seat km
Average NO_x emission index	0.0150 kgNO_x/kgFuel
Relative air distance through areas with potential persistent contrail formation	4.75%
CO_2 per ASK	0.0635 kg/seat km
NO_x per ASK	3.0253e-04 kg/seat km

In a next step, the traffic sample described above has been environmentally optimized in four dimensions with different ATM and optimization strategies starting with the focus on the climate impact of the flights' en-route portion. For the calculation of these optimal trajectories the Trajectory Optimization Module (TOM) was applied. TOM is based on optimal control theory and determines the aircraft state as a function of time considering the aircraft's equations of motion and flight performance characteristics such that a cost function is minimized and specific constraints are fulfilled. It transforms the optimal control problem into a discrete nonlinear programming problem and solves it. The algorithmic Climate Change Functions (aCCFs) developed in WP1 have been implemented into the Trajectory Optimization Module (TOM), in order to allow for an on-line aCCF evaluation within the optimization process; the cost functional was adapted accordingly [7]. As an example, the results of the optimization for the flight between Lulea and Gran Canaria are shown in Figure 9 to Figure 11.

This flight is on rank 7 in terms of ASK in the traffic scenario. Pareto fronts distinguished by different radiative forcing agents (different colors) are depicted in Figure 9. Each point on a Pareto curve represents one of 100 optimization runs per route with a different set of weighting factors excluding those results that are not Pareto-optimal (a filter is applied to delete those from the curve). Hence, each point corresponds to the resulting optimized trajectory and shows the relative increase of the trip fuel (y-axis), representing operating cost, over the relative climate impact reduction (x-axis, here, averaged temperature response, ATR) with respect to the minimum fuel case (in the following called base case). In addition to the overall Pareto-front (blue), the individual contributions of CO_2 (black), H_2O (cyan), NO_x (red) as well as aviation-induced cirrus cloudiness (green) are shown in Figure 9. As can be observed from the overall Pareto front, the maximum ATR reduction potential is found to be approximately 58% corresponding with an increased fuel burn of about 4.5%. The Pareto front is characterized by a discontinuous behavior, which is caused by the reduction of the climate impact due to the avoidance of contrail sensitive regions.

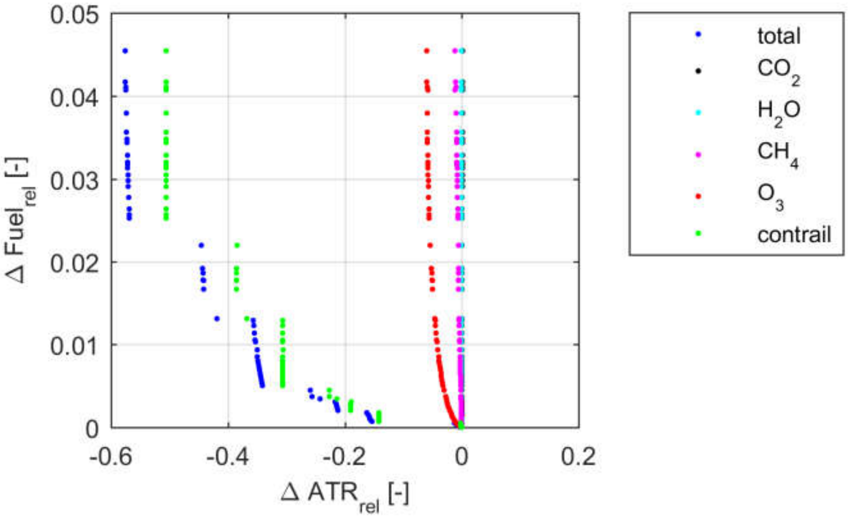


Figure 9: Pareto front of trip fuel increase over ATR reduction potential for the flight ESPA-GCLP

In comparison to the great circle trajectory (blue curve), the base case trajectory (black curve) is shifted to the southeast as a result of favourable wind conditions (see Figure 10, top right). Additionally, it can be observed that the base case trajectory crosses a contrail sensitive region (dark red region in Figure 10, bottom left).

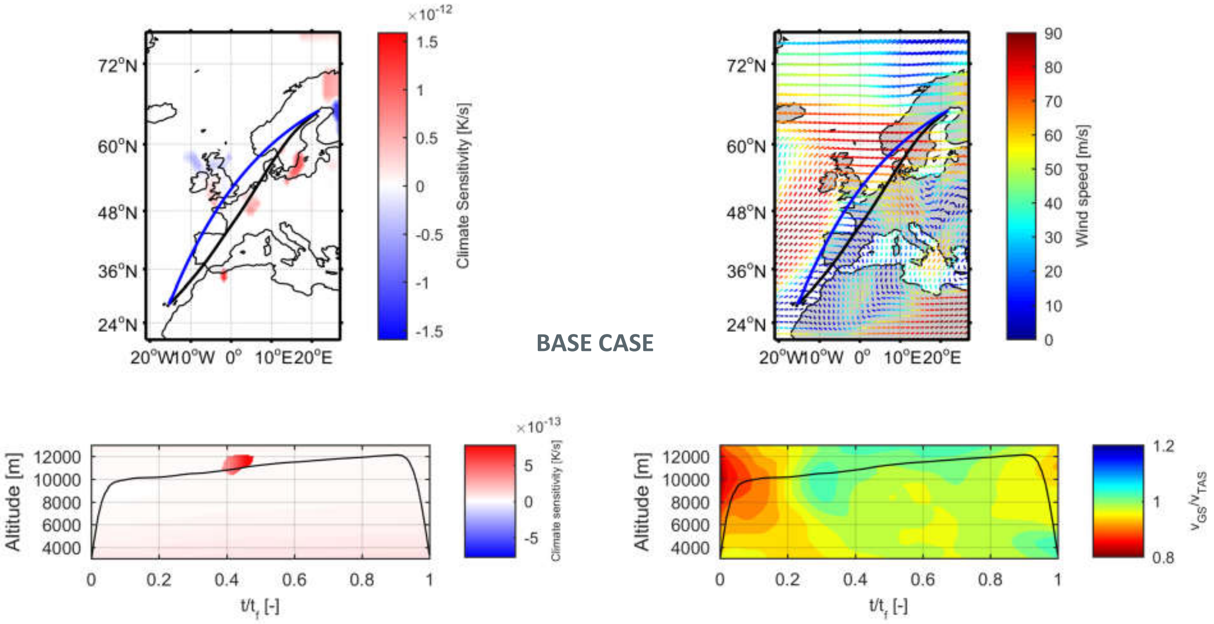


Figure 10: Horizontal map plots and vertical flight profile in the base case for the flight ESPA-GCLP (top left: map of climate change function evaluated at mean cruise altitude with mean aircraft parameters; top right: wind field evaluated at mean cruise altitude – blue curve represent great circle connection; bottom left: vertical section of overall climate change function along the trajectory; bottom right: section of ratio of ground to air speed showing head/tail wind situation along trajectory)

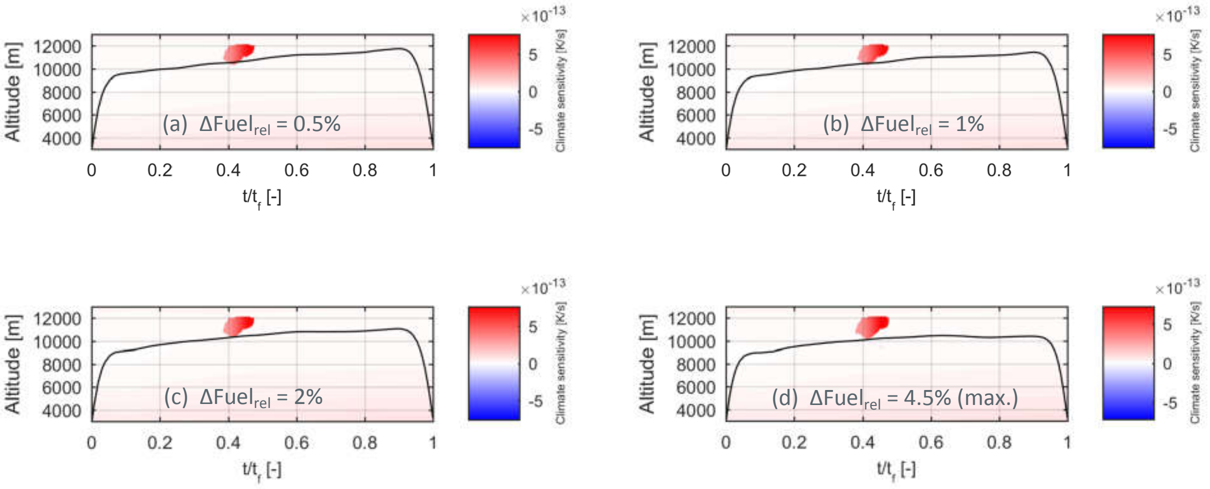


Figure 11: Vertical flight profiles for 4 different points on the pareto front corresponding to 4 different values of the relative fuel increase for flight ESPA-GCLP (top left: a – 0.5%, top right: b – 1%, bottom left: c – 2%, bottom right: d – 4.5%)

Figure 11 (a) to (d) indicate a continuously decreasing altitude if higher fuel penalties are accepted; due to low lateral aCCF gradients, trajectory changes occur predominantly in the vertical domain. In this example, the jumps in the Pareto front (see Figure 9) are caused by the shape of the contrail sensitive region: whenever only small variations of the trajectory lead to high changes of flight time spent in this region, discontinuous behavior may occur. For the minimum ATR trajectory the contrail sensitive region is even fully avoided (see Figure 11 (d)).

An aggregated assessment of the resulting optimized trajectories has been done leading to the Pareto-front in Figure 12. This Pareto-front is based on the most important 2000 routes within the European Airspace (intra-ECAC region) with respect to the available seat kilometres (ASK). They cover 35.5% of all routes within the optimization scenario. Optimized aircraft operations are performed on each individual route in order to achieve the maximum overall climate impact reduction for a given overall fuel penalty. This leads to a relationship between climate impact reduction and cost increase relative to the cost optimal base case, i.e. fuel optimal operation [11].

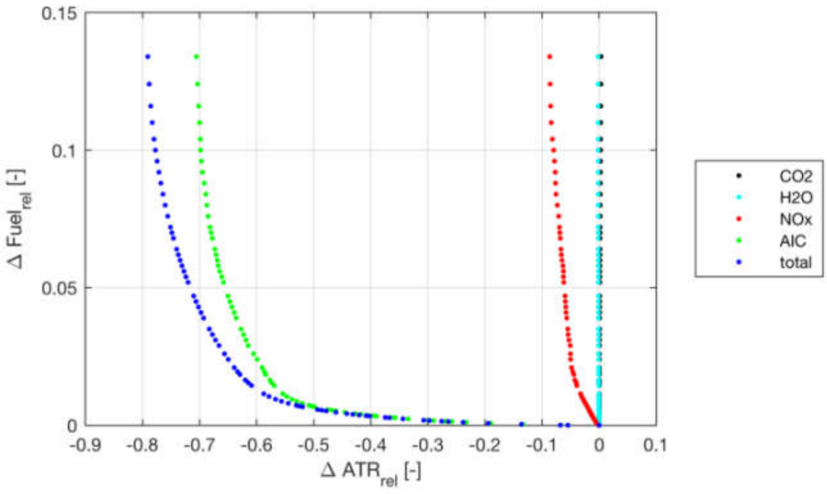


Figure 12: Overall pareto front (blue) for the top 2000 routes (in terms of ASK) of the European Airspace (intra-ECAC region) with the individual contributions of CO_2 (black), H_2O (cyan), NO_x (red) and aviation induced cirrus cloudiness (green).

The blue curve which represents the overall Pareto-front in Figure 12 can be interpreted in two ways: (1) for a given fuel penalty (y-axis) it yields the maximum climate impact reduction (x-axis) or (2) for a given climate impact reduction (x-axis) it yields the lowest possible fuel penalty (y-axis).

In the vicinity of the minimum fuel scenario which is located at the origin (0|0) of Figure 12, high climate impact mitigation efficiencies (climate impact reduction per fuel increase) can be observed, e.g. it indicates the possibility to reduce the climate impact by almost 60% for a fuel penalty of 1%. For higher fuel penalties, the climate impact mitigation efficiency is decreasing rapidly until it reaches saturation at a climate impact reduction of almost 80% with a corresponding fuel penalty of 13.5%.

Additionally, from Figure 12 it can be concluded, that the climate impact reduction for this particular day is essentially driven by contrail avoidance since the reduction in ATR caused by aviation induced cirrus cloudiness dominates the overall Pareto-front (green curve). The second largest effect is caused by the reduction of the climate impact of NO_x (red curve).

It is the first time that algorithmic Climate Change Functions were used in such a wide-ranging optimization. The comprehensive trajectory data and the multitude of optimizations per route using different cost function weights (overall, 2 TB of data were generated during the optimization campaign) allow for various interesting assessments. In general, it is observable that in the majority of cases a vertical change of the flight profile is preferable to a lateral rerouting.

Then, for the environmental-optimized air traffic the implications to the European Air Traffic Management Network (EATMN) were analyzed. Planning and executing environmental-optimized flights systematically results in altered traffic flows and consequently leads to changes in the demand-capacity situation in the airspace. It is of particular interest, if and where imbalances occur.

For this purpose, the relative sector load difference between the respective scenario (B or C) and the reference scenario (A) in terms of entry counts normalized by the reference demand-capacity ratio was determined for all sectors in the EATMN using NFE both for the minimum fuel (B) and the minimum climate impact scenario (C). The results for scenario C can be seen in Figure 13.

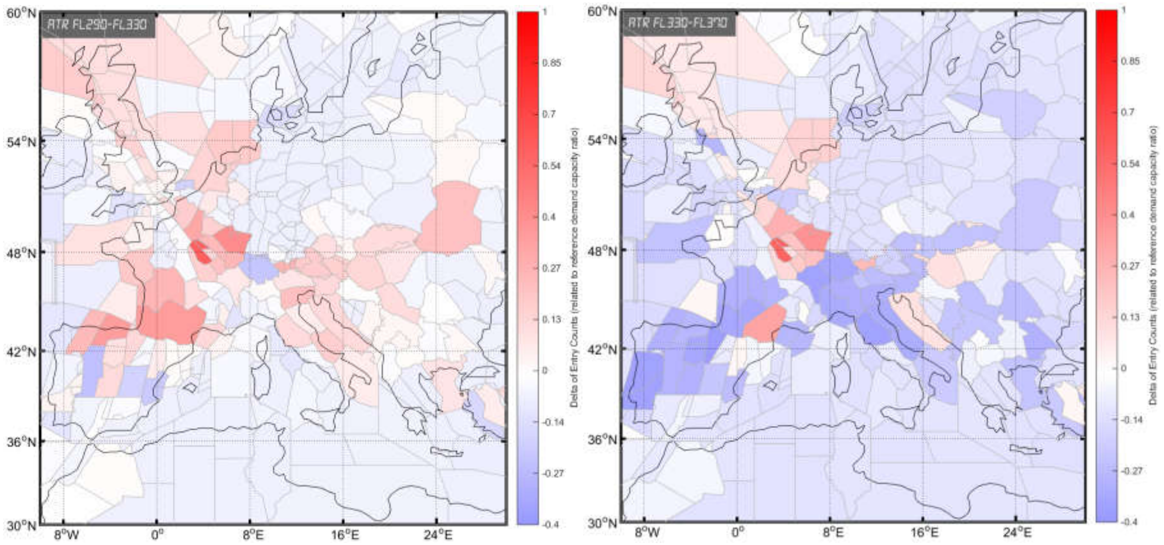
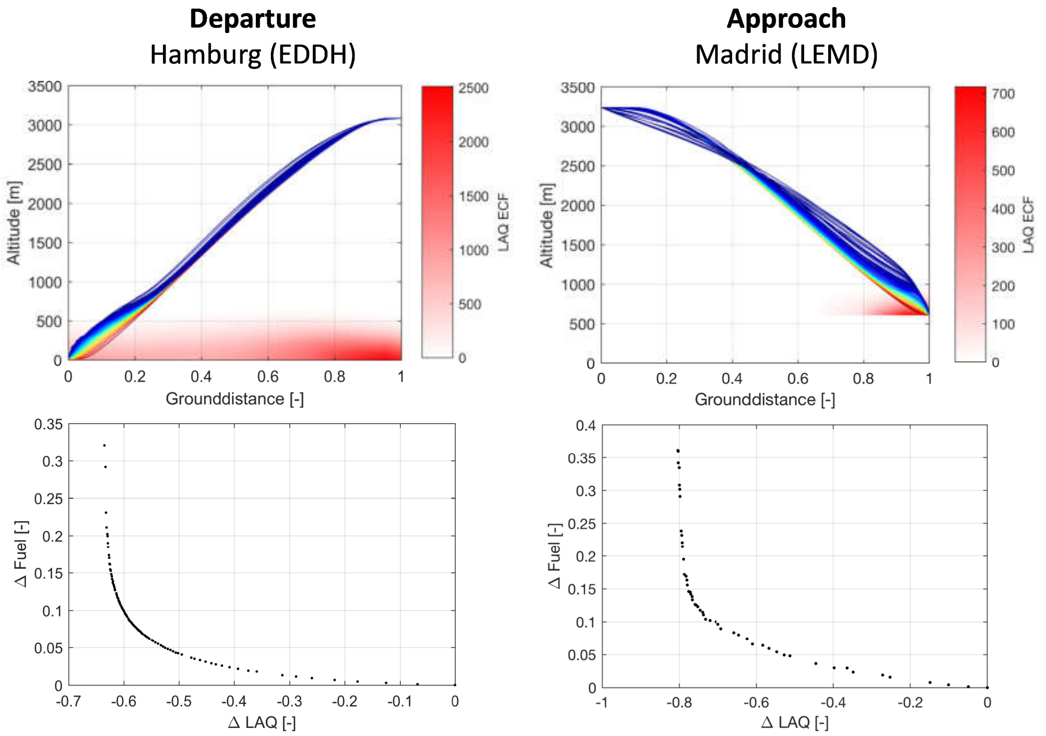


Figure 13: left: Sector load changes (daily mean value) of the minimum climate impact scenario (C) relative to the reference scenario (A) for sectors between FL290 and FL330; right: Sector load changes (daily mean value) of the minimum climate impact scenario (C) relative to the reference scenario (A) for sectors between FL330 and FL390

It can be clearly observed, that due to the shift of mean cruise altitudes to lower flight levels resulting from optimizing flights for minimum climate impact, certain sectors are facing a load increase by about 40% in an altitude band between FL290 and FL330, whereas those sectors above (FL330 to FL390) experience load reductions of the same order. At the same time, flights are planned such that areas where contrails could potentially form are avoided leading to "corridors" of sectors with increased load. The European ATM network would in this case have to deal with a change of traffic flows leading to significant shift of sector load from one set of sectors to another with a clear tendency of relocation to lower altitude sectors. The ATM system in this case, needs to be prepared and to provide the flexibility to increase sector capacities, e.g. by re-allocating air traffic controllers, whenever required on a day-to-day basis depending on the meteorological conditions.

Finally, the environmental optimization was extended towards the airports. While the en-route portions of the flights have been optimized with respect to climate impact using the aCCFs, during departure and approach local LAQ ECFs have been applied in order to minimize the flights' LAQ impact. For this purpose, the cost function within the TOM tool was adapted to include LAQ effects and the trajectory optimization was carried out for a number of selected flights between the airports Hamburg (EDDH) and Madrid (LEMD), which served as the representative airports for LAQ and noise modelling. For one of these flights Figure 14 shows the LAQ optimization results. While in the left column the optimization of the take-off phase at EDDH is shown, the right column contains the results of the landing phase. By setting certain boundary conditions in TOM, it is made sure that the flights adhere to the runway direction during take-off and landing. Different weightings between fuel and LAQ cost were applied resulting in a variety of altitude profiles as shown in the upper part of Figure 14. While the minimum fuel trajectory is characterized by red color, the minimum LAQ one is marked blue. Intermediate weightings are colored accordingly (e.g. yellow, green).


Departure
Hamburg (EDDH)

Approach
Madrid (LEMD)

Figure 14: Results of the LAQ-driven optimization during departure and approach for an exemplary flight from Hamburg to Madrid. Left: departure; right: approach. Top: Different optimal vertical trajectories with various weighting between fuel cost and LAQ cost (red=minimum fuel profile, blue=minimum LAQ profile). Bottom: Pareto-front for fuel/LAQ trade-off (minimum relative fuel penalty for a relative LAQ reduction).

During departure (see Figure 14, left) one can observe that with an increasing importance of the LAQ effect the initial climb gradient is significantly increasing. While in the minimum fuel case, the aircraft climbs with a small initial flight path angle, which then progressively increases, when optimizing for LAQ a larger initial climb angle is observed after lift-off with a declining tendency afterwards. Obviously, by steeper climbs the aircraft is able to leave areas with higher LAQ impacts faster leading to a reduced LAQ impact. The corresponding Pareto-front indicates that e.g. the LAQ impact can be reduced by 50%, if a fuel penalty of 4% is accepted.

During approach (see Figure 14, right) a similar behaviour can be observed. The higher the importance of LAQ in the cost function of the optimization is set (blue profiles), the steeper the final descent becomes. This is consistent with the expectations, as the amount of NO_x emissions released in lower altitudes (where the LAQ ECF is high) is reduced. As a consequence, the aircraft needs to remain longer at higher altitudes requiring an increased thrust level. This leads to a higher fuel consumption by up to 35% (see Pareto-front on the bottom right), compared to the minimum fuel trajectory (red). However, in terms of absolute changes, from the analysis of the results it is found that the optimization with respect to LAQ during landing is much less effective than during take-off, due to the naturally low thrust level close to idle and the corresponding small amount of absolute NO_x emissions during the approach phase. Moreover, it should be noted that the modelling of emissions during idle is connected to higher model uncertainties (both aircraft performance and emissions) compared to other flight phases.

2.4.3 WP3 Verification of environmental impact reduction from ECFs

The first key project result from WP3 is verification that the algorithmic climate change functions, developed in WP1, reduce the climate impact of aviation when used in flight trajectory optimisation case study. An example which focuses on the NO_x-O_3 aCCF is presented. Figure 15 gives a brief overview of the simulation set-up. Two simulations with daily air traffic for the European region are performed [28]. In the first simulation, air traffic trajectories are optimized with respect to costs and in the second, with respect to climate impact by NO_x-O_3, which is described by the O_3 algorithmic climate change functions (aCCFs). Hence in the second simulation climate sensitive regions are avoided. In the two simulations, the NO_x emissions affect ozone concentration, and hence radiative forcing (RF) in different ways.

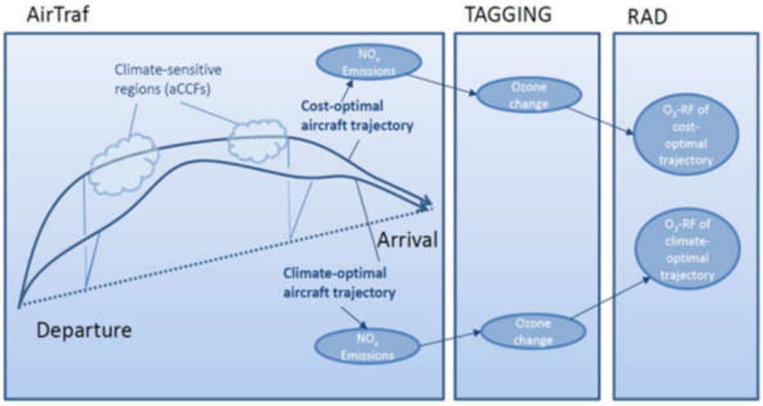


Figure 15*:* Sketch of the performed simulations and used EMAC sub models (boxes), which deal with the air traffic simulation (AirTraf), the contribution of air traffic to the atmospheric chemical composition (TAGGING) and the radiative forcing (RAD).

The composition change, which results from the change in the aircraft trajectories, is shown in

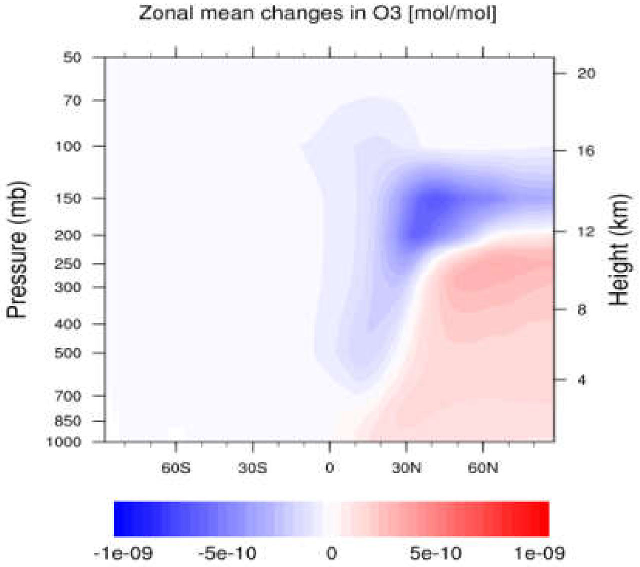


Figure 16. A clear shift in the ozone concentration changes to lower altitudes and higher latitudes is found. The radiative forcing is reduced by 2%, hence reducing the climate impact from aviation and proving the concept of aCCFs [29].

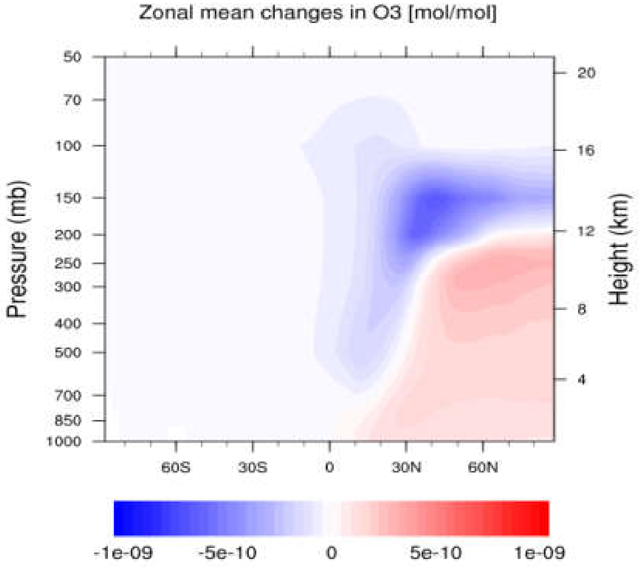


Figure 16: Ozone changes (mol/mol) arising from flying climate optimal routes compared to cost optimal flights.

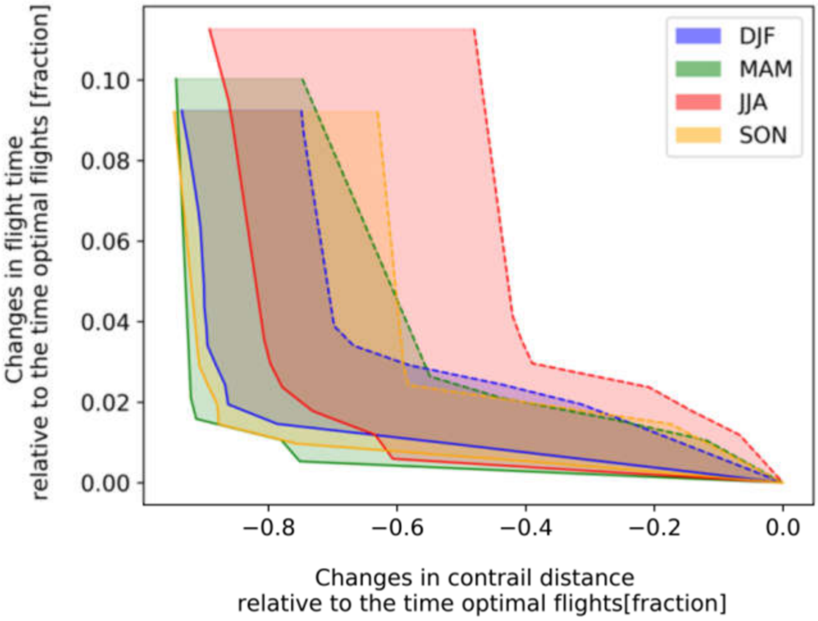


Figure 17: Trade-off between flight time and contrail avoidance through different seasons: winter (blue colour, DJF), spring (green colour, MAM), summer (red colour, JJA), and autumn (yellow colour, SON). The baseline is the flight time optimal situation.

The second key project result from WP3 is the verification of the contrail CCF leading to a much lower contrail occurrence for only small changes in traffic routing [30]. Two one-year simulations with EMAC are performed for a traffic sample, which are optimised for contrail avoidance and for flight time, respectively. The simulations include the daily and hourly varying meteorology of that year, which impacts both the location of contrail forming areas and the location of head and tail winds. The x-axis in Figure 17 shows the fractional change in contrail distance with respect to the flight time optimal flights. The y-axis shows the change in flight time with respect to the flight optimal flights. A large variability can seen in the achievable reduction of contrail distance between each season as well as within a specific season, e.g. by allowing 2% increase in flight time, the contrail distance reduces from 20% to 90% depending on the local meteorological conditions.

A partial mitigation strategy for up to 40% reduction in contrail coverage can be achieved for all the seasons with less than 2% increase in flight time, which represents a reasonable trade-off between flight time increase and contrail avoidance.

To reduce contrail formation, flights tend to go further south in winter, whereas in summer a relocation to either south or north is expected depending on the geographical location (not shown here). Moreover, increasing flight altitude is in many cases beneficial for contrail avoidance compared to the time optimal flights. However, there is a large day-to-day variability.

The third key project result of WP3 is the verification of the effectiveness of the aCCF-concept in reducing the environmental impact at a relatively low cost. The results from WP2 (see above) were used to compare the overall Pareto-Front (Figure 12) to literature and to verify that the cost-benefit approach used within ATM4E leads to comparable results.

The forth key project result of WP3 is the verification of the aircraft performance modelling in the modelling approaches utilised in ATM4E. The models AirTraf used in WP3 and TCM used in WP2 were compared to the FAST (**F**uture civil **A**viation **S**cenario software **T**ool) model, which is an established aviation emissions modelling tool, widely used in research and policy projects since the 1990s. The model has been used extensively in the ICAO-CAEP arena in the development of international policy and regulation of emissions from international aviation, most recently in the development of the ICAO aeroplane CO_2 certification standard and in the ICAO Trends Assessments. Analysis identified cruise altitude as the parameter that is most sensitive in an aircraft performance model, i.e. fuel flow estimation on a specified aircraft type. All three models compared well (within 5% of each other) and hence, verified the TCM and AirTraf trajectory setup.

2.4.4 WP4 Assessment and Exploitation

Within this WP stakeholder exchanges were organised, comprising regular meetings of the External Experts Advisory Board, during the project duration. In February 2018, a stakeholder webinar took place with broad participation from different stakeholder groups including regulatory bodies and ANSPs (Eurocontrol, FOCA, NATS etc.), airlines (i.e. IATA) and aircraft/engine manufacturers (Airbus, Rolls-Royce, Snecma, etc.). In April 2018, a dissemination event was organised in Berlin during ILA (Internationale Luft- und Raumfahrtausstellung).

These events were an opportunity for the Consortium to present their results, identify specific areas where input from stakeholders was required and receive suggestions for clarification and improvement. Information is available on the project web-site [32]. The outcome of those dissemination activities as well as of other events (e.g. regular teleconferences with the EEAB) that took place during the entire course of the project, shaped the roadmap which was developed and presented in detail in deliverable D4.2 [13].

The ATM4E concept was very well received and there was a clear interest to further explore the possibilities for implementation in close collaboration with stakeholders. Since the concept is rather novel, commitment requirements were also discussed with stakeholders. In particular, the discussion was centred on the following topics: generation of ECFs and uncertainties, implementation methods and requirements, connection to existing initiatives and last but not least economic cost.

Overall, it became evident that gaining effective buy-in from stakeholders depends an collective ability to harmonize information management systems as well as solutions to avoid phase differences in knowledge and expertise within different stakeholders and system users. These discrepancies tend to lead to inefficiencies in the overall aviation system and should be avoided as much as possible.

2.4.5 WP5 Management

Among the achievements of this workpackage was successful implementation of overall project management and workplan, comprising schedule of dissemination activities. Publications, articles, and conference abstracts are available in the activities areas of the project web-site [32]. Dissemination activities started in autumn 2016, with conference contributions at the Greener Aviation Conference in Brussels, Oct 2016 [17] and at ECATS Conference, Athens, Nov 2016 [18], and SESAR Innovation Days, Delft, Nov 2017 [19]. The overall concept for a multi-criteria impact assessment was published in a peer-reviewed publication [20] and calculation of algorithmic climate cost functions were presented in a master thesis [21], and thematic research papers were submitted on algorithmic climate change functions [25]. The concept of climate-optimized trajectories was presented at ICAO/CAEP Independent Expert Workshop in Berlin (Oct 2018) [22], SESAR Innovation

Days 2018 in Delft (Nov 2018) [23], and at AeroMetSci 2017 in Toulouse organised by WMO (Nov 2017) [24], and at Transport and Environment Workshop in Brussels (Jan 2018) [26]. A concept paper on usage of climate change functions for trajectory optimisation in an integrative approach was presented and published at the 36th IEEE/AIAA Digital Avionics Systems Conference, in St. Petersburg (FL, USA, Sep 2018) [27]. Currently a series of scientific publications is currently under preparation on algorithmic climate change functions [28], verification of mitigation effort for aviation NO_x impacts [29], trajectory optimisation for contrail avoidance [30], and mitigation potential from case study for Europe [31].

2.5 Technical Deliverables

<table>
<tr><th>Reference</th><th>Title</th><th>Delivery Date[1]</th><th>Dissemination Level[2]</th></tr>
<tr><th colspan="4">Description</th></tr>
<tr><td>D1.1</td><td>CCF data for algorithm based ECF analysis</td><td>04/11/2016</td><td>CO</td></tr>
<tr><td colspan="4">This was a data deliverable which identified and transferred the climate change function (CCF) data that had been generated within the EU Framework project REACT4C that were required by ATM4E work package 1 for the algorithm-based Environmental Change Function (ECF) analysis.</td></tr>
<tr><td>D1.2</td><td>Air quality and perceived noise data for algorithm based ECF analysis</td><td>16/06/2017</td><td>CO</td></tr>
<tr><td colspan="4">This deliverable described the methodology developed within WP1 to produce local scale data for the non-climate components of the algorithm-based Environmental Change Function (ECF) analysis. The data produced can be separated in two categories: data for local air quality and noise. This document presented these data as well as the various tools used to produce them.</td></tr>
<tr><td>D1.3</td><td>Report on algorithm based ECF analysis</td><td>31/07/2017</td><td>CO</td></tr>
<tr><td colspan="4">This described the development of Environmental Change Functions (ECFs), which are a core part of ATM4E. ECFs indicate the environmental impact of aviation as a function of aircraft location to allow the impact of alternative aircraft trajectories to be assessed. Three components make up the ECFs - global climate change, and local air quality and noise in the vicinity of airports. The major methodological step is the use of detailed REACT4C data to develop “algorithmic” CCFs (aCCFs) which use a small number of predictors to allow rapid calculation in a flight-planning environment. ECFs for noise and local air quality had previously not been derived, making this work entirely novel. It required significant adaption of existing tools and detailed calculations to derive data from which aECFs could be derived.</td></tr>
<tr><td>D1.4</td><td>Report on development of multidimensional environmental impact metrics</td><td>31/07/2017</td><td>CO</td></tr>
<tr><td colspan="4">This deliverable presented multi-dimensional impact metrics which can be implemented in a flight planning tool in order to enable environmental assessment or environmental optimisation of aircraft trajectories. This integration relies on advanced MET information, which is represented by environmental change functions. An introduction to the multi-dimensional impact metrics is provided and it is described how this concept establishes a link to ATM for a simultaneous consideration of distinct environmental impacts.</td></tr>
<tr><td>D2.1</td><td>Air traffic datasets for sample region</td><td>25/11/2016</td><td>CO</td></tr>
<tr><td colspan="4">This data deliverable contains the reference air traffic data used in the course of ATM4E’s WP2 as basis for the planning of environmental-optimized flights. In the accompanying document EUROCONTROL’s Demand Data Repository, which the flight data is obtained from as well as the structure of the data are described. Also, the selection process, which was done in order to identify a meaningful and representative dataset out of the available amount of flights, is explained. Moreover, a brief statistical analysis of the selected traffic data concludes the document.</td></tr>
</table>

Table 2: Project Deliverables (1/3 continued)

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[1] Delivery data of latest edition

[2] Public or Confidential

D2.2	Report on the environmental impacts over sample region for selected air traffic conditions	25/11/2016	CO
This deliverable summarizes the results of an environmental impact assessment of the selected traffic sample as conducted in work package 2. After describing the input filtering approach the applied methodology which makes use of a database of reduced emission profiles is explained. The database is created using a trajectory calculation module and an engine emission model. The application of reduced emission profiles is described including a mechanism to take the wind influence into account. Finally, results for CO_2, NO_x emissions as well as contrail formation regions are presented.			
D2.3	4D Environmental optimised trajectories for different ATM strategies	01/12/2017	CO
This data deliverable contains the results of the optimization campaign performed within work package 2 to determine environmental-optimized trajectories. It is accompanied by a document with the purpose to support the understanding of the data structure and how the data was generated. Moreover, it contains a description of the required preparatory work and the theoretical background of the optimization as well as an overview of the resulting trajectories including a discussion of the most interesting and significant routes.			
D2.4	Report on network implications for environmental optimised air traffic	22/03/2018	CO
The deliverable describes the analysis of the network implications caused by environmental-optimized air traffic in Europe. The applied analysis process is explained, including a description of the involved software tool Network Flow Environment (NFE). This tool provides an experimental platform for research to evaluate new techniques to solve Air Traffic Flow Management (ATFM) problems and includes the required analysis capabilities connected to Demand-Capacity-Balancing aspects. Necessary tool adaptations are explained before key results of the analysis are presented.			
D3.1	Technical note on the definition of verification procedure	04/11/2016	CO
The deliverable describes the procedure to verify the various aspects of the ATM4E concept of algorithmic environmental change functions. Procedures of three verification aspects are aspects are presented in detail. These aspects are (1) the verification of the algorithmic climate change functions, (2) the verification of the effectiveness of the aCCF based ATM4E concept with respect to its potential in reducing climate impact from aviation (3) Verification of the applied trajectory calculations.			
D3.2	Report on changes in atmospheric parameters (ozone, contrails, RF) for the Earth-System-Model simulation with optimised air traffic	09/02/2018	CO
The deliverable describes the changes in atmospheric parameters (NO_x and ozone) and in climate parameters (Radiative Forcing) when using the algorithmic climate change functions for optimising air traffic. The results are obtained by comparing two simulations with the Earth-System Model EMAC, one with cost optimal daily routes and one with aCCFs optimal routes. It includes a description of the models used, the experimental set-up and the results.			

Table 2: Project Deliverables (2/3 continued)

D3.3	Verification report	16/03/2018	CO
The deliverable describes the results of the three verification procedures which are defined in D3.1. First, the algorithmic climate-change functions are verified by a closure experiment, showing that both the climatological values of aCCFs agree with literature and the climate optimized routing actually reduces the climate impact from aviation (more details on this aspect are given in D3.2). Second, an overall assessment of the climate impact reduction is performed and verified based on available literature. Third, calculated aircraft trajectories are verified by comparing results of different calculation methods.			
D4.1	Technical note on environmental impact assessment of case studies	15/12/2016	CO
This technical note provides a more detailed description of the case studies that are used for the assessment of environmentally optimised ATM operations. Assessment aims at evaluating the multi-dimensional impact of aircraft flight routes on the environment (climate, air-quality, noise) through an extensive modelling approach that incorporates a large number of processes.			
D4.2	Intermediate solutions and implementation strategy	21/02/2018	PU
This report delivers a conceptual roadmap with recommendations and an implementation strategy for environmental-assessment of aircraft trajectories (environmental-optimization). It summarizes necessary steps and the envisaged changes towards the Environmental Optimization of the future ATM System, together with requirements and future implementation steps. Moreover, it outlines the roadmap towards the implementation of the ATM4E concept which is currently under development.			
D4.3	Conceptual roadmap	29/03/2018	PU
Based on the implementation strategy a conceptual roadmap was developed considering recommendations from stakeholders. Overall objectives is to introduce environmentally-optimized flight operations. This roadmap was equally shaped in collaboration with major aviation stakeholders who kindly reviewed the project results and offered insight on current and future environmental, operational and technical requirements of the aviation sector.			
D5.1	Project Management Plan (PMP) (including schedule)	25/11/2016	CO
The Project Management Plan (PMP) provides a comprehensive description of project management in the Management Plan, including a brief description of project bodies, e.g. Steering Committee. In the Risks and Issues Management Plan relevant risk and proposed risk-mitigation measures are provided. The Communication Plan details planned communication activities, as well as a Dissemination Plan, for dissemination of project results, both enabling the project to promote its results by providing targeted information to relevant audiences in a strategic and effective manner. Dissemination of this interdisciplinary project is performed as combination of scientific level and conceptual infrastructure and information management level dissemination.			
D5.2	Project Results final report	13/04/2018	PU
The Final Project Results Report covers all the research activities performed by the project in sufficient detail so that the reader can identify which deliverables might be of interest in case he wants to read more detail. The reports forms a basis to discuss the transition to subsequent development stages including a self-assessment of the TRL (Technology Readiness Level) achieved at the end of the project. A R&I proposal is integrated and provides the outline of the concept and the identification of potential benefits and risks, together with a preliminary proposed Plan for next R&D phase.			

Table2: Project Deliverables (3/3 continued)

3 Links to SESAR Programme

3.1 Contribution to the ATM Master Plan

ATM4E addressed the most-relevant research questions in order to realize environmentally responsible Air Vehicle & ATM operations, hence contributing directly to the European ATM Master Plan which aims at enabling "the delivery of safe, cost-efficient and environmentally responsible Air Vehicle & ATM operations, systems and services". Furthermore, ATM4E addresses high-level environmental SES targets, being primarily to enable a 10% reduction in the effects that flights have on the environment (compared to 2005) and extends the original focus (flight efficiency only) to the consideration of the overall environmental perspective.

ATM4E performed work relevant for various operational improvement steps defined in the ATM Masterplan (see e.g. D4.2 [13] for a list of SESAR2020 solutions that might incorporate knowledge from ATM4E). However, due to the fundamental nature of the project, it does not directly contribute to a maturity increase of existing OI steps or Enablers. Hence, the project team proposes to add one new Enabler and one new OI step described in Table 3.

Code	Name	Project contribution	Maturity at project start	Maturity at project end
EN: METEO-XX	Algorithmic Environmental Change Functions for Environmental-optimized flight planning	Basic principles have been further investigated with initial knowledge from REACT4C project.	TRL1 Intermediate	TRL1 full
The concept of aECFs as enabler for the planning of environmental-optimized flights considering the impact on climate as well as LAQ and noise around airports has been described for the first time. The basic principles have been investigated during case studies and reported.				
OI: AUO-XXXX	RBT/SBT optimized for minimum environmental impact	Research towards enabling of environmental optimized trajectories considering current weather	TRL0	TRL1
It was shown that airspace users can plan effectively environmental-optimized trajectories (RBT/SBT) with high climate impact reductions for comparably low additional (fuel) cost based on the current weather situation using algorithmic ECFs. The corresponding phenomena have been observed and documented.				

Table 3: Project Maturity

3.2 Maturity Assessment

Table 4: ER Fund / AO Research Maturity Assessment for EN: METEO-XX

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?	Achieved	Enabling environmental optimisation of aircraft trajectories requires measures to include multiple environmental effects (climate impact, local air quality, noise) in multi-criteria trajectory optimisation. Environmental change Functions were identified as an innovation to overcome that problem (see section 2.4.1).
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Partial - Non Blocking	The Environmental Change Functions for climate impact, local air quality and noise were developed and partially verified (see section 2.4.3). The effectiveness of the ATM4E concept in reducing the environmental impact was quantified for a case study. The results are promising not blocking further developments.
TRL-1.3	Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? - The problem/challenge/need under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others.	Achieved	Weaknesses and constraints were identified in D4.2 [13], D4.3 [14]: Currently the geographic coverage of the Environmental Change Functions is limited; the analysis is based on a case study, only, robustness measures are not defined, costs of measures are not covered by e.g. the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) or EU's Emission Trading Scheme (ETS). Environmental Change Functions for local air quality/noise require further improvements.
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	The ATM4E concept is defined, described, a case study analysed, and reported in detail in the open access publication (Matthes et al., 2017) [20]. Further publications are currently in preparation.

TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM MP Level?	Achieved	Direct contribution to the key performance area "Environment": There is fundamental research in the atmospheric science area supporting the importance of non-CO_2 effects, such as contrail formation and NO_x effects on ozone. Especially the spatial variations of these effects are supported by basic research. Details are partially given in section 2.4.3 as well as in Matthes et al. (2017) [20].
TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? - What are these new capabilities? - Can they be technically implemented?	Achieved	There is a wide range of fundamental research in the atmospheric science and aviation science supporting the solutions of reducing effects, such as contrail formation and NO_x effects on ozone, by re-routing. ATM4E suggests using Environmental Change Functions within flight planning as innovative solution to consider climate, noise and local air quality effects at the same time. A technical implementation using the System Wide Information Management infrastructure is proposed and technically feasible.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Achieved	The concept of Environmental Change Functions is largely based on physical laws: The calculation of environmental impacts is purely based on physical and chemical laws modelling radiation physics and the chemical processes in the atmosphere caused by aviation emissions. Aircraft emit gaseous emissions like carbon dioxide, nitrogen oxides, water vapour, unburned hydrocarbons, soot, and carbon monoxide. Under certain conditions, if the air is cold and humid enough, the released water vapour can also lead to the production of condensation trails (water condenses on particles, e.g. soot, in the air), which may freeze and become persistent. Some of those

			products have a direct impact on the climate by directly reflecting radiation (e.g. soot, contrails), others (like CO_2 and H_2O) act as greenhouse gases or (like NO_x) run through photochemical reactions changing the concentration of other greenhouse gases (ozone, methane) and consequently influencing the earth's surface temperature. Those phenomena are captured by the atmospheric models used in ATM4E.
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and disbenefits identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information already exists, in which case it should be used if possible.	Partial - Non Blocking	The potential strengths have been clearly identified in this report as well as in Matthes et al. (2017) [20]; the Environmental Change Functions enable the planning of environmental-optimized flights based on multiple criteria. Limitations, such as the accuracy of the Environmental Change Functions are identified in D4.2 [13] and outlined in this report. A qualitative assessment of the benefits is performed on the basis of a case study. Limitations are qualitatively assessed.
TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	Initial scientific observations were reported in various technical project reports, scientific publications and conference papers (e.g. Matthes et al., 2017; Yin et al., 2018; [17-27]).
TRL-1.10	Have the research hypothesis been formulated and documented?	Achieved	The research hypothesis with respect to the Environmental Change Functions is defined in section 2.3.3 as well as in the publication Matthes et al. (2017) [17].
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	The implementation of the ATM4E concept in an operational framework requires more research, which is identified in the roadmap including next steps in D4.2 [13] and described in detail in section 4.3.

TRL-1.12	Are stakeholder's interested about the technology (customer, funding source, etc.)?	Achieved	There was a large interest from stakeholders in the ATM4E project, e.g. documented in the large audience during the webinar and dissemination activities (D4.3) [14]. Industry stakeholders have indicated large interests in implementing the concept in their flight planning tools.

Table 5: ER Fund / AO Research Maturity Assessment for OI: AUO-XXXX

ID	Criteria	Satisfaction	Rationale - Link to deliverables - Comments
TRL-1.1	Has the ATM problem/challenge/need(s) that innovation would contribute to solve been identified? Where does the problem lie?	Achieved	Environmental optimisation of aircraft trajectories in day-to-day operations requires fast and robust enhanced meteorological information. Algorithmic Environmental Change Functions were identified as an innovation to overcome that problem (see section 2.4.1). However, this constitutes an additional capacity constraint, as results from the ATM4E hot spot analysis (see section 2.4.2) show. Innovations and recommendations to overcome this problem are formulated in section 4.3 including the proposition of more flexible airspace capacity management and staffing.
TRL-1.2	Has the ATM problem/challenge/need(s) been quantified?	Achieved	The aECFs as advanced meteorological information were developed and partially verified (see section 2.4.3). The effectiveness of the ATM4E concept in reducing the environmental impact was quantified for a case study. The impact of environmental-optimized flight planning on the ATM network in terms of the demand-capacity situation was quantified (see section

			2.4.2).
TRL-1.3	Are potential weaknesses and constraints identified related to the exploratory topic/solution under research? - The problem/challenge/need under research may be bound by certain constraints, such as time, geographical location, environment, cost of solutions or others.	Achieved	Weaknesses and constraints were identified in D4.2 [13], D4.3 [14]: The planning of environmental-optimized flights can potentially lead to imbalances in the demand-capacity situation in the European ATM network. This capacity constraint has been identified (see section 2.4.2) and should be evaluated further.
TRL-1.4	Has the concept/technology under research defined, described, analysed and reported?	Achieved	The ATM4E concept is defined, described, a case study analysed, and reported in detail in the open access publication (Matthes et al., 2017) [20]. Further publications are currently in preparation.
TRL-1.5	Do fundamental research results show contribution to the Programme strategic objectives e.g. performance ambitions identified at the ATM MP Level?	Achieved	Direct contribution to the key performance area "Environment": Case studies demonstrate that the environmental impact of flights (specifically the non-CO_2 effects) can be reduced significantly by accepting minimum cost increases (see section 2.4.2).
TRL-1.6	Do the obtained results from the fundamental research activities suggest innovative solutions/concepts/ capabilities? - What are these new capabilities? - Can they be technically implemented?	Partial – Non Blocking	There is a wide range of fundamental research in the atmospheric science and aviation science supporting the solutions of reducing effects, such as contrail formation and NO_x effects on ozone, by re-routing. The project results indicate that the analysed environmental-optimized flight planning approach is posing challenges for the ATM network, which are worthwhile to be solved. Due to various dependencies its technical feasibility is subject to further research.
TRL-1.7	Are physical laws and assumptions used in the innovative concept/technology defined?	Achieved	The flight mechanics and assumptions used for environmental-optimized flight planning are defined

			and documented. Some can be found in section 2.4.2. The algorithmic ECFs are derived from ECFs using mathematical (statistical) methods.
TRL-1.8	Have the potential strengths and benefits identified? Have the potential limitations and disbenefits identified? - Qualitative assessment on potential benefits/limitations. This will help orientate future validation activities. It may be that quantitative information already exists, in which case it should be used if possible.	Partial - Non Blocking	The potential strengths have been clearly identified in this report; a large potential exists to reduce the environmental impact with only minor changes to the aircraft trajectories. Limitations, such as capacity constraints or robustness of the environmental trajectories are identified and outlined in this report as well as in D4.2 [13]. A qualitative assessment of the benefits is performed on the basis of a case study. Limitations are qualitatively assessed. Algorithmic Environmental Change Functions enable a real-time usage of meteorological information to plan environmental-optimized flights. Limitations, such as the accuracy of the algorithmic Environmental Change Functions are identified and outlined in this report as well as in D4.2 [13].
TRL-1.9	Have Initial scientific observations been reported in technical reports (or journals/conference papers)?	Achieved	Initial scientific observations were reported in various technical project reports. Several scientific publications and conference papers (e.g. Luehrs et al., 2018; Linke et al., 2018; Lau et al., 2018) are currently in preparation.
TRL-1.10	Have the research hypothesis been formulated and documented?	Achieved	The hypothesis with regard to the ATM network impact has been formulated in the project plan as well as in section 2.3.2 and will be published with the corresponding results in Lau et al., 2018.
TRL-1.11	Is there further scientific research possible and necessary in the future?	Achieved	The implementation of the ATM4E concept in an operational framework requires more research, which is identified in the roadmap described in D4.2 [13] and next steps are described in detail in section 4.3.

TRL-1.12	Are stakeholder's interested about the technology (customer, funding source, etc.)?	Achieved	There was a large interest from stakeholders in the ATM4E project, e.g. documented in the large audience during the webinar and dissemination activities (D4.3) [14]. Industry stakeholders have indicated large interests in implementing the concept in their flight planning tools.

4 Conclusion and Lessons Learned

4.1 Conclusions

It has been established that information on the climate impact of aviation emission can be provided to flight planning systems by the use of environmental change functions (ECFs). Importantly, algorithmic ECFs, which use MET data readily available at the flight planning stage, have been shown to give reasonable representations of detailed ECFs, and this enables operational implementation. The potential for more work to improve on these algorithmic ECFs, and to characterize the impact of uncertainties has been identified. In summary, the project has demonstrated that this advanced MET service has the strong potential to enable environmental assessment of aircraft trajectories, identification of climate-optimized routes and provision of environmental performance data.

The results show many cases where reductions in the climate impact of order 10's of % can be achieved for an increased fuel burn of order of a few percent. Importantly, the reduction in climate impact has been shown to be large for some flights (for example, where relatively small deviations in flight route lead to avoidance of contrail formation) but are much less for others; this is likely a characteristic of the relatively short flights within Europe, as this was less apparent for the longer trans-Atlantic flights studied in REACT4C. Hence, as the case studies showed, a large fraction of the overall mitigation potential lying in the climate-optimization of European air traffic can already be gained by focussing on a limited number of "critical" flights only.

It was beyond the scope of ATM4E to examine how airlines could be incentivized to bear extra costs, especially where they might be borne by a small number of operators on a given day. Nevertheless, it is the view of the project team that such cost increases seem easily within the scope of appropriate financial and political instruments. The implementation of such routing would need quantitative performance indicators to be able to demonstrate benefits for environment (Key performance area KP05) in order to gain the confidence of the stakeholder community.

It has also been found that environmental-optimized flight planning on a large scale in Europe could lead to imbalances in the demand-capacity situation in specific parts of the airspace assuming that capacity is managed and provided as it is today. This is, because this specific case study a part of the flights would be flying lower to avoid areas of high climate impact under this meteorological situation. Also, the cruise altitude band could be narrowed leading to a higher aircraft density at lower altitudes. The European ATM Network has to cope with accommodating these traffic flow changes, if environmental optimization plays an increasing role in flight planning in the future.

4.2 Technical Lessons Learned

During project implementation, a clear vision on state-of-the-art knowledge and understanding was developed, leading to the identification of areas where challenges still exist and further research is required. The lessons learnt are presented in parallel with the establishment of the ATM4E roadmap, which investigates the operational and technical aspects associated with the validation and deployment requirements when the concepts are raised to higher TRL levels.

The aECFs developed in the context of this project were designed to meet the specific needs of European air space. Although a fuller implementation would require aECFs to be developed and tested for more world regions, and possibly examine their sensitivity to climate change, the key message of ATM4E is that the concept was proved to be scientifically and technically feasible.

ATM4E has necessarily focused on the better understood components of the environmental impact of aviation such as contrails, water vapour, and NO_x-induced changes in ozone and methane; it will be necessary to monitor whether ongoing and future research in these areas will impact significantly on calculated aECFs. There are additional environmental impacts that are at the frontiers of current research which need to be monitored to consider whether they should also be included within aECFs. These include the climate effect of aviation soot and sulphate emissions, via modification of cloud properties and the role of cruise level emissions on surface air quality. In addition, other aircraft safety/comfort issues would need serious consideration – for example, whether relationships between aECFs and predicted regions of significant turbulence can impact on route choices.

Moreover, current scientific uncertainties have to be addressed and a way to incorporate them into the aECF concept should be sought to provide a basis for robust decisions, or for "no-regret" measures.

A further related issue is the weighting of different environmental issues (climate/noise/local air quality). These may be particularly important in trade-off situations where environmental benefits in one domain are balanced by degradations in others. Possible scenarios include when longer climate-beneficial flights lead to requirement for more fuel and heavier aircraft with impacts on emissions impacting local air quality, or where longer-duration flights threaten possible breaches of noise curfews at airports.

Another major issue is dependency of aECFs on aircraft/engine characteristics. For example, the project team is aware that detailed prediction of contrail formation requires details of engine characteristics and aircraft size, so that ultimately route choices could depend on the aircraft type that is deployed on a route. However, the exact dependency on aircraft type needs to be quantified and before benefits can be assessed. Furthermore, the project team cannot be sure of the exact impact of future aircraft/engine/fuel developments on these results. Similarly, the project team cannot know how the future fleet composition will impact contrails formation (and consequently contrail-cirrus) and their potential formation in a future climate. This challenge would have to be met to encourage stakeholders such as airlines to burn more fuel to avoid contrails due to CO_2 whose climate effects are better understood and emissions for a given route much more easily quantified.

Fuel consumption and composition (i.e. biofuels) are another aspect that requires further research. From the evaluation of point profiles, within ATM4E, aircraft trajectories have been reconstructed, which provide an overall fuel consumption for individual missions. However, a risk of over- or underestimation of mission fuel is present due to lack of information on engine state. To overcome this, one option would be to make available detailed information on flight state for real-world trajectories. Another option is that airlines share their information on total fuel consumption, which they calculate within the framework of CORSIA activities. Currently airlines have started the initiative to monitor, report and verify overall mission fuel. An example of such a dedicated tool will be available within CORSIA[3]. It is calculating detailed information on CO_2 emissions. The project team notes that they do not expect, from the current planning, that CORSIA would be expanded to cover

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[3] CORSIA https://www.youtube.com/watch?v=iuwPjyCRlRo

non-CO_2 emissions. Furthermore the project team expects that in case additional information on other climate impacts, in particular non-CO_2 effects, would be included, another system would be required to be constructed. For this reason, the project team has suggested among stakeholder contributions to promote implementation that airlines share this data.

Regarding local effects, noise is certainly the most crucial issue. Although exposure to airport noise in Europe is not higher than for other transport sources, the annoyance experienced by people exposed to aircraft noise is greater than for any other. Thus, the metric for noise should be centred on annoyance instead of noise levels (in dB). However, an adequate metric for quantifying annoyance is not yet available and the ATM4E concept relies on physical metric(s) that can be modelled. As a result, the project team is currently limited to noise levels (in dB) combined with the number of population exposed to those levels. Also, detailed information on different groups of population exposed to the noise at different times was not available. Overall, noise and LAQ is an airport problem and is largely managed by the airports. Airports work in partnership with ANSP to decide the preferred routes for dep/arr. The order of priority is safety, noise, LAQ and lastly CO_2 emissions. So, essentially, the local impact ECFs may end up having different end-users to the global impact ECFs.

Further investigation is also required on how to quantify the exact benefit of re-routing. Currently, the expectations are unclear and key performance indicators (e.g. flight-by-flight basis, or fleet-wide and time-averaged basis) need to be defined.

We note that the algorithmic environmental change functions (aECFs) used in ATM4E were based on a balance between the needs of computational efficiency and accuracy. As experience with the computational demands of likely operational systems is gained, the formulation of the aECFs would need to be revisited; for example, that system may allow a more sophisticated approach to be used, than the ones adopted to demonstrate feasibility of the system in ATM4E. From an implementation point of view, the integration of the aECFs in to the existing aviation software system should be examined. This is where partnerships with other SESAR projects, Eurocontrol, IATA and aviation system specialists would be essential.

Finally, regarding ensemble forecasting and probability, recent advancements in meteorology have been enabled during the last decade also by ensemble forecasting methods. Such an ensemble provides a probabilistic forecast, but the way such probabilistic information can be used in the flight planning process would have to be considered in detail in future research. With regards to sustainable aviation and e.g. contrail avoidance or ozone mitigation strategies, the topic of predictability is of major importance. Only if operational weather forecast systems are able to predict occurrence of climate sensitive regions with a low risk of false alarm, efficient implementation can be enabled. However, from experience and knowledge gained by now, it is known that relevant atmospheric parameters (such as those that determine contrail formation) have a strong dependence on the occurring weather pattern. One efficient strategy for step-wise implementation could be to target such patterns with high probability first, in order to limit the risk of a false alarm. Based on comprehensive meteorological information being available, including satellite information, an evaluation of real-world conditions in comparison to forecast information can be performed, in order to assess effectiveness of identified climate-optimized trajectory options.

4.3 Recommendations for future R&D activities (Next steps)

ATM4E successfully achieved the development of a prototype for algorithmic Environmental Change Functions (aECFs), which meet the specific needs of the European air space addressing climate impact, local air quality and noise, starting from a TRL 1 at the beginning of the project. They comprise a unique method to enable both an environmental assessment of flights and environmental flight planning. The results of ATM4E are a proof-of-concept, showing the scientific and technical feasibility. However, it requires more steps before it can become operational. Therefore the major recommendation is to enhance the technological readiness level (Research Activity 1), which includes aspects of the completeness of the environmental information. Included in the aECFs (Research Activity 2) robustness in the flight trajectory decision making (Research Activity 3), and testing the decision chain in a trial that simulates those that would occur in a real-world situation (Research Activity 4).

Research & Development Activity 1: Enhancing the technological readiness level of the algorithmic Environmental Change Functions:

> The successful proof-of-concept, achieved within ATM4E, forms a convincing basis for pursuing the aCCF approach. ATM4E focussed on aspects of noise and local air quality, in a more exploratory way, e.g. for selected individual airports, and calculated climate impact aspects for en-route emissions, only. ATM4E further analysed routing impacts when adopting the ATM4E concept of aECFs, however, without any further consideration of the available quality of the weather and climate impact data. Therefore, a complete and robust environmental assessment requires
>
> - the enhancement of the current concept to fully cover all aircraft trajectories, starting and landing in the European Airspace (2nd recommendation) and
> - the incorporation of a concept which represents the information on the robustness of the environmental aircraft trajectories, considering the uncertainties from weather and climate impact data (3rd recommendation).

Research & Development Activity 2: Enlarge the aECF concept from a more case study oriented approach in ATM4E to a whole trajectory and full European scale application including performance indicators; expand ECF concept to represent aircraft/engine dependence.

> The exploratory concepts of LAQ and noise should be further refined taking into account further parameters that are critical to LAQ and noise assessments. For example, other pollutants important for LAQ such as non-volatile particulate matter and for noise the impacts of airframe.
>
> The aECF concept should be enlarged to cover a more complete assessment of the climate impact of individual routings, which include enlarging the aECFs
>
> - to cover the capability of assessing the climate impact during the phases from the take off to cruise and cruise to landing,
> - to cover international flights leaving and entering the European Airspace,
> - by refining the calculation of non-CO_2 climate effects including the incorporation of additional processes, such as soot and sulphur aerosol effects, which are currently regarded to be either of minor importance or too uncertain to be included in an assessment, and

- by adopting key performance indicators, which enable a meaningful quantitative, and easy to understand, environmental assessment.

Research & Development Activity 3: Enlarge the aECF concept by a robustness measure, which enables the minimization of the risk of wrong decisions.

The aECF concept, as it is now, does not take into account any information on the certainty or uncertainty of the environmental information. An environmental assessment of a flight in the current status does not include a risk assessment of failing in correctly assessing the environmental impact, nor does it include robust routing changes, or no-regret routing changes. This would need to account for uncertainties in, weather forecasts, uncertainties in the climate impact analysis, lack of exact routing knowledge, and others. The enlargement of the aECF concept by a robustness measure should include several steps:

- Step 1: Overview of concepts for representing risks in air traffic optimisation (robustness representation),
- Step 2: Overview and assessment of uncertainties associated with the aECFs,
- Step 3: Assessment of the robustness representation by combining step 1 and 2 and employing an air traffic optimisation including specific uncertainties. The assessment should be based on accuracy, feasibility and practicability.
- Step 4: Recommendation for an aECF concept, which includes information allowing for robust decision making.

Research & Development Activity 4: Perform a large-scale test of the proposed ATM4E methodology via the simulation of a live-trial which would not re-route real aircraft but would assess whether the decision and verification chain in a situation close to that needed in an operational environment. Such trials would likely require involvement of EUROCONTROL, a meteorological service and possibly at least some airlines. Such trials are likely to need to be repeated for several days, different weather situations and seasons to examine time-averaged performance. The project team envisages several steps:

- Step 1: Decision on whether to perform a live trial, or use retrospective data but with live time constraints.
- Step 2: Using ensemble weather forecast data, and relevant ATM and airline constraints, derive routes for both minimal costs and reduced environmental impact (possibly with different thresholds of allowable additional cost) using the available aECFs. Routes could also be derived which applied the robustness measures developed in the 3rd Recommendation
- Step 3: Using analysed meteorological data (which provide the best estimate of the weather conditions that actually occurred) and appropriate aircraft performance data, assess whether the planned reduced environmental impact routes would have achieved actual environmental benefit, and at what additional cost, both on a flight-by-flight basis and on a fleet-wide basis, and how the application of robustness measures alters the outcome.

Research & Development Activity 5: The implementation of environmental flight planning raises many issues in the political, economic and social domains which are beyond the remit of ATM4E and which would need to be considered in parallel to improvements in the technical and operational aspects of implementation. These include choices on, for example, the importance of CO_2 and non-CO_2 climate impacts, expressed by the metric used to compare CO_2 and non-CO_2 climate impacts, the relative priority given to measures to reduce climate change, improve local air quality and reduce noise, particularly in cases where there is a trade-off between these impacts. Decisions on these matters will ultimately be political ones, guided by the science, which will have to balance the needs of different stakeholders. The design of equitable and acceptable economic incentives would have to be investigated, especially given the key result from ATM4E that the largest environmental gain, on any given day, is likely to result from re-routing a relatively small number of flights.

Research & Development Activity 6: Prior to operational implementation of environmental-optimized flight planning a more distinguished analysis of the effects on EATMN capacity management should be conducted. Due to changes of traffic flows leading to significant shift of sector load from one set of sectors to another with a clear tendency of relocation to lower altitude sectors, the ATM system has to provide the flexibility to increase sector capacities, e.g. by re-allocating air traffic controllers, whenever required on a day-to-day basis depending on the meteorological conditions. It is therefore recommended, to conduct further research to study different options how to accommodate an increased traffic density in narrower altitude bands. This research should take into account (see 5th Recommendation) that environmental flight planning might affect only a relatively small number of flights as they are expected to gain the largest part of the optimization potential.

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Appendix A

A.1 Glossary of terms

Term	Definition	Source of the definition
AIR-REPORT	A report from an aircraft in flight prepared in conformity with requirements for position, and operational and/or meteorological reporting.	*ICAO Annex 3*
CLIMATE CHANGE FUNCTION or ENVIRONMENTAL CHANGE FUNCTION	A measure which quantifies environmental impact associated with aviation emission as a function of location and time of emission, in particular applied von non-CO_2 emissions, e.g., climate impact measured as surface temperature change per kilogramm emission	Matthes et al., 2017 [20]
CLIMATE COST FUNCTION	A concept which has been developed in earlier studies, now being expanded from climate to environment and being replaced by the term change functions, to emphasize that units used are in general not costs, but impact.	Grewe et al., 2014 [35]
CLIMATE OPTIMIZED TRAJECTORIES	A trajectory where environmental impacts have been considered during optimisation, and which has been modified in order to possess a lower climate impact.	Matthes et al., 2012 [35]

Table 6: Glossary

A.2 Acronyms and Terminology

Term	Definition
ATM	Air Traffic Management
ATM4E	Air Traffic Management for Environment
aCCFs	algorithmic Climate Change Functions
ATR	Average Temperature Response
CAEP	Committee on Aviation and Environmental Protection
CCF	Climate Change Function
DJF	December, January, and February
EATMN	European ATM Network
ECAC	European Civil Aviation Conference
ECF	Environmental Change Function
ECMWF	European Centre for Medium-Range Weather Forecasts
EMAC	ECHAM5/MESSy Atmospheric Chemistry model
ICAO	International Civil Aviation Organization

JJA	June, July, and August
LAQ	Local Air Quality
MAM	March, April, and May
NO_x	Nitrogen Oxides
REACT4C	Reducing Aviation Emission by Changing Trajectories (FP7 project)
RF	Radiative Forcing
SESAR	Single European Sky ATM Research Programme
SON	September, October, and November
SJU	SESAR Joint Undertaking (Agency of the European Commission)
TCM	Trajectory Calculation Module
TOM	Trajectory Optimization Module

Table 7: Acronyms and terminology

DLR envisa TUHH Technische Universität Hamburg-Harburg

Manchester Metropolitan University TU Delft University of Reading