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D-KULT: data and tools for routine eco-efficient flight operations

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Abstract. The climate effect of aviation is significant and expected to increase. Reducing the sector's environmental footprint to contribute to global temperature targets will require not only investments in airframe and engine technologies but also operational strategies such as eco-efficient flight routing, focusing on reducing non-CO_2 effects. The D-KULT project (Demonstrator Climate and Environmentally Friendly Air Transport), funded under the German Federal Aviation Research Programme (LuFo), aims to demonstrate the feasibility of optimising flight trajectories with respect to climate effect. The project addresses a multi-objective optimisation problem in which flight trajectories minimise climate effects while maintaining operational and economic efficiency. Operational constraints such as meteorological hazards, regulatory requirements, airspace and airport capacity need to be incorporated to ensure real-world applicability. This work provides a comprehensive overview of the project, describing new developments and major challenges on implementation pathways and summarizes the key findings.

D-KULT developed an end-to-end information chain integrating aviation weather forecasting, flight planning, air traffic control, and climate benefit assessment to enable eco-efficient flight routing for testing purposes. Achieving this complex operational and environmental objective required close collaboration across multiple disciplines and substantial upgrades to the majority of participating components. Novel aviation weather products were generated that estimate the climate sensitivity of emissions under prevailing meteorological conditions. Flight planning tools have been extended to take this information into account in addition to the standard data in the flight planning optimization algorithms. In this way, flight planning tools can calculate emissions and corresponding climate effects along flights, both as part of strategic (pre-departure) and tactical (pre-take-off and in-flight) eco-efficient flight optimisation. Developments within D-KULT were tested through a large-scale national contrail avoidance flight trial campaign, including enhanced satellite-based contrail detection methods and assessment

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of achievable climate benefits. Further evaluation focused on operational integration, examining air traffic control procedures, and workflow implications in a high-fidelity simulator environment.
Results demonstrate substantial progress toward operational climate-optimised aviation but also highlight remaining challenges, including uncertainties in weather forecast and non-CO_2 climate effects, automation needs along the workflow and increased controller workload in dense airspaces. A key requirement for operational implementation is transparent information of prediction uncertainties, enabling informed decision-making when rerouting for climate benefit. These remaining research and development needs form the basis for the planned successor programme to D-KULT.

1 Introduction

The climate effect of air transport is undisputed: Aviation contributes currently about 3.5% to the total anthropogenic effective radiative forcing of climate (Lee et al., 2021). This share will continue to grow due to the high demand and its rate of increase, both in absolute terms and in relation to other modes of transport and industrial sectors (Grewe et al., 2021; Klöwer et al., 2021). The governments have agreed to minimise the anthropogenic temperature increase in the atmosphere to 1.5°C, if possible. Air traffic must make its contribution, but it turns out that the 1.5° target for aviation is very ambitious and that technological improvements alone do not suffice to let aviation meet its environmental goals. Eco-efficient flight routing (i.e. avoiding climate-sensitive areas when planning flights) is considered an additional way for air traffic to approach this target.
Planning and flying eco-efficient routes are primarily tasks for the airlines and for air traffic control. However, this is not possible without enabling them with a meteorological service of climate response functions (Matthes et al., 2012), which predicts where aircraft emissions have relatively large or relatively small climate impacts. Such information can be cast into climate-cost functions which can be applied in flight-routing software to find, for any given origin-destination pair, an eco-efficient route, i.e., a route that minimizes climate effects without increasing costs too much. Such strategies have been investigated in theoretical settings in the past (Sausen et al., 1994, 1996; Williams et al., 2002, 2003; Fichter et al., 2005; Grewe et al., 2014, 2017; Frömming et al., 2012, 2021; Arrowsmith et al., 2020; Teoh et al., 2020; Yamashita et al., 2021; Matthes et al., 2020, 2021; Rao et al., 2022). Now it is time to enter practice.
The LuFo project D-KULT (Demonstrator Climate and Environmentally Friendly Air Transport - funded by the German Federal Aviation Research Programme - LuFo), for the first time, builds the necessary information and collaboration chain from the (aviation-) weather forecast to the eco-efficient flight planning and operation. The chain starts with aviation weather information, as it is provided routinely to aviation actors. These meteorological data are supplemented with some special forecast fields (related to the formation potential of persistent contrails and other non-CO2 effects, see below), which are needed to formulate climate cost functions (van Manen and Grewe 2019, Dietmüller et al. 2023, Yin et al. 2023). The latter are then employed in the strategic flight planning process for eco-efficient routing or in tactical in-flight profile optimization (to avoid flying in climate sensitive regions). Undoubtedly, the highest priority remains that flight operations and flight routes must be legal, flyable, and safe. Under this condition, eco-efficient route planning and tactical measures can be added to flight

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route management, and airlines and air navigation service providers must establish efficient and robust decision-making processes for this purpose. Therefore, air traffic management and control need to be involved in the development of procedures for eco-efficient flying to assess if developed procedures can be applied under realistic operational conditions. This is the goal, which has been defined for the information chain in D-KULT.

Safety aspects that are also considered within the framework of D-KULT relate to the handling of thunderstorms along the flight route and the radiation exposure of flying personnel. D-KULT additionally covers the aspect of noise of taking-off and landing aircraft. These additional aspects are described elsewhere in order not to overload the present paper.

This concept paper aims to advance climate-optimized flight planning by establishing an integrated collaboration workflow through modifying, advancing and connecting state-of-the-art methodologies, available data products and their interfaces. It is important that those responsible for these components work closely together and build a mutual understanding, especially at the interfaces. The collaboration chain and its components are tested and assessed extensively and challenges and recommendations for future development and operational integration are elaborated.

State-of-the-art data and methods enabling aircraft trajectory optimisation are introduced in Sect. 2, while Sect. 3 presents the integrated collaboration chain expanding current existing flight planning and in-flight optimization capabilities for climate-optimized flight trajectories, required modifications and specific advancements are described. The workflow including enhanced data and methods was tested experimentally with prototype versions of the optimization tools, which is described and evaluated in Sect. 4. The new achievements are discussed in Sect. 5 before a summary and conclusions (recommendations) are given in the final Sect. 6.

2 Basic methods

Although the climate effect of aviation is a matter of concern and a research topic since at least the 1990s (Schumann, 1994), identification of alternative eco-efficient aircraft trajectories with lower climate effects remained complex and a field for theoretical studies and scientific experiments for many years. For competition and cost reasons, the aviation industry is continuously introducing more fuel-efficient aircraft with ever lower specific fuel consumption (that is, fuel need per passenger-km), thereby focusing on a corresponding reduction in specific CO_2 emissions (ITF, 2012). The aviation industry approached greener flights merely for the goal of cost reduction by employing more efficient aircraft with ever lower specific fuel consumption (that is, fuel need per passenger-km). At the same time, the level of scientific understanding of non-CO_2 effects was still considered low (Lee et al. 2010).

The aim of flight routing was thus cost optimization (specific for each airline focussing on i.e. fuel, time or total costs) and the meteorological services provided mainly forecasts of wind, temperature and pressure, which suffices for that purpose. This section describes the status quo of flight planning tools and the necessary data before the D-KULT project added the aspect of eco-efficiency. The necessary enhancements of the data and tools are described in the next section.

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2.1 Meteorology and climate response fields

In Germany, DWD (Germany's national meteorological service) provides an aviation weather forecast with its World Aviation Weather Forecast (WAWFOR) dataset which is derived from numerical weather predictions based on the ICON (Icosahedral, non-hydrostatic) model (Zängl et al., 2015). WAWFOR is delivered globally with 0.25° × 0.25° (~25 km × 25 km) horizontal grid size and especially for Europe and the eastern Atlantic from the ICON-EU Nest on a 0.0625° × 0.0625° (~6.5 km × 6.5 km) grid. WAWFOR uses 57 vertical pressure levels, stemming from the 120 vertical model levels of ICON, interpolated to flight levels (FL in hft, about 30.5 m), from FL 50 to FL 600 in steps of 10 hft and additionally FL 675. WAWFOR consists of five data packages, from which package 1 contains for instance wind, temperature and humidity, that is, standard meteorological data. The other packages contain special data for significant weather like icing conditions, turbulence, etc. Such weather forecast data are used in the aviation flight routing software, for instance to avoid strong headwinds and to exploit strong tailwind (e.g. in the jet stream).

2.2 Formation and persistence of contrails

Long-lasting condensation trails (so-called persistent contrails) contribute, according to current knowledge (Lee et al., 2021), the largest effective radiative forcing (ERF) of all aviation climate effect components. Although a large ERF does not necessarily imply a large eventual climate effect (Bickel et al., 2025), avoidance of persistent contrails is expected to help to make aviation sustainable in view of the finding of Grewe et al. (2021) that aviation can achieve its share to the 1.5° goal only, if all possibilities to lessen radiative effects are taken.

In order to avoid the formation of persistent contrails, it is necessary to reliably predict 1) the formation of contrails (short and persistent ones) and 2) their longevity. While the first task involves merely a simple thermodynamic criterion, the Schmidt-Appleman criterion (Schumann, 1996), which weather forecast models achieve with good success (Gierens et al. 2020), the prediction of ice supersaturation (ISS), which is the necessary condition for contrail persistence after formation, is currently a problem (Hofer et al. 2024) for many reasons. A major reason is that weather forecast models traditionally either do not allow supersaturation or, otherwise, supersaturation, once it appears, is completely consumed too early (Sperber and Gierens, 2023). These problems are dealt with in other projects. In D-KULT, one simple and one more sophisticated approach is taken to predict ice supersaturated regions (ISSRs), see below (Sect. 4.1.1).

2.3 Climate response and calculation of climate effects

For eco-efficient flight trajectory optimization, which integrates climate effects as an additional term in mathematical formulation of the optimization function (Matthes et al., 2012), so called algorithmic climate change functions (aCCFs) are used. ACCFs provide spatially and temporally resolved estimates of climate response (in terms of a physical climate metric as, e.g., average temperature response ATR, see e.g. Megill et al., 2024) to aviation induced non-CO_2 emissions. These include the response for water vapour (H_2O), nitrogen oxide (NO_x)-induced species (ozone (O_3) and methane (CH_4)), and for persistent

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contrail cirrus. The concept of aCCFs emerged from Climate Change Functions (CCFs) (Grewe et al., 2014, Frömming et al., 2021) which were initially developed by means of Lagrangian tracking of aviation emissions within detailed and computationally demanding climate–chemistry simulations. CCFs map the accumulated climate effect of an emission (during its lifetime or residence time) to the location (longitude, latitude, altitude) and time (date, hour) of the emission. While CCFs are too computationally demanding for efficient use in operational flight planning, aCCFs offer a suitable alternative, though they involve significant simplifications. In effect, aCCFs were obtained via regression of CCFs onto local meteorological characteristics (e.g. temperature or geopotential) at the location and time of the emission (van Manen and Grewe, 2019). Thus, aCCFs are used to estimate CCFs (expectation values) as simple functions of local meteorological variables, while avoiding lengthy climate-chemistry simulations, and provide a rapid, operationally feasible method particularly suitable for real-time applications such as climate-optimized aircraft routing (Matthes et al., 2020; Lührs et al., 2018). The publication of Yin et al. (2023) presented the first consistent set of prototypic aCCFs for NO_x-O_3, NO_x-CH_4, H_2O, CO_2, and contrail cirrus effects (aCCF Version V1.0). The technical implementation of aCCF-V1.0 is provided in the open-source Python library CLIMaCCF V1.0 (Dietmüller et al., 2023). The aCCFs were developed based on Lagrangian simulations under summer and winter weather conditions (those for contrails only based on winter weather conditions) and have only been determined for the North-Atlantic flight corridor and small parts of Europe and North America (35 °N – 60 °N, 0 °W – 70 °W, for more details, see Yin et al., 2023). The application outside the original geographic scope and seasonal representation is subject of analysis but generally not recommended. Furthermore, the algorithms in their current version are only valid at pressure levels between 200 and 400 hPa and are not intended for usage beyond this domain.

An alternative method for estimating the climate effect of contrails is the Contrail Cirrus Prediction Tool (CoCiP). It is a fast parameterized Lagrangian plume model designed to simulate the formation, evolution and radiative effects of contrails and contrail cirrus (Schumann, 2012), and allows a large range of parameter settings on both technical aspects and atmospheric physics, e.g. time steps, humidity corrections, crystal shapes. CoCiP is a numerical tool and its output has been statistically analysed using satellite data from 230 individual flights (Schumann et al., 2017) and global traffic analyses (Schumann et al., 2013, 2021, Vazquez-Navarro et al., 2015). In addition, lidar and in-situ observations were also used (e.g., Voigt et al., 2010, 2017, 2022; Märkl et al., 2024; Teoh et al., 2024). The latest version of CoCiP is available as open-source software in the Python package *pycontrails* (Shapiro et al., 2023), and strong sensitivity of climate response to humidity data is reported.

Climate change functions use physical climate metrics for description of the climate response of an emission in the unit of climate effect, e.g. temperature change per emission. By multiplying the climate change function at the respective location with the emitted quantity, the climate effect can be calculated. To estimate the climate effects of an aircraft trajectory, as has been introduced in Matthes et al. (2012), the path integral along the flight path is typically represented by summing up the products of climate change functions and emissions over the individual flight segments.

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2.4 Flight planning, trajectory optimization and air traffic control

The optimization of flights targeting climate-friendly flight operations is subject not only to a wide range of target criteria but also to the requirements and boundary conditions of the various flight planning phases. In particular, the operational constraints of any airline (aircraft and crew rotation, scheduling adherence, etc.), but also the availability and quality of meteorological and climate data are relevant. In D-KULT, tools for trajectory optimization for strategic (pre-flight) and tactical (in-flight) phases are being further developed to include climate data and impact mitigation criteria. These tools include Lido Flight 4D, FPO Cloud and pyTOM, the latter tool being DLR's trajectory optimizer for mapping a large number of flights with multi-criteria objective functions.

Lido Flight 4D is a software service to help airlines optimize flight trajectories. It is equipped with various cost factors that can play together based on the dispatcher's settings. This can be fuel and time costs as well as overflight charges implied by the ATC sectors. The Lido optimizer is using a graph-based optimization algorithm to solve the shortest-path problem between departure and destination. Additional rules published by EUROCONTROL and short notices like airspace closures must be respected. Eventually, flight safety relevant parts, such as extended twin engine operations (ETOPS), terrain clearance and emergency cases (engine out, depressurization) are all relevant during the optimization. Taking all those aspects into account, we can call such a flight plan "legal".

To conduct vertical pre- or in-flight trajectory optimizations, PACE Flight Profile Optimizer (FPO Cloud) is using a legal flight plan, latest weather forecasts and mission parameters like fuel on board as input. The resulting vertical flight profile is optimized in terms of time- and fuel costs, if no other constraints like turbulence avoidance have been enabled.

During execution of flights, DFS, the German air navigation service provider, ensures safety in German airspace. It controls all aircraft flying under instrument flight rules (IFR) in Germany. DFS is a company organised under private law (GmbH) and wholly owned by the Federal Republic of Germany. Its task is to control air traffic in Germany in a safe, orderly and expeditious manner. This is what the German Aviation Act (LuftVG) in Article 27c (1) demands. Route optimization in cooperation with airspace users is a common task for an ANSP (Air Navigation Service Provider).

2.5 Contrail detection with satellite data

In principle contrails can be detected with ground-based instruments – cameras exploiting visible and/or thermal radiation. However, only satellites offer a global coverage and an unhindered view, independently of low-level clouds and illumination conditions, on contrails, which are formed in the upper troposphere and lower stratosphere (UTLS). In particular, geostationary platforms have a very large field of view and high repetition rates such that entire flight paths flown at any time of the day and the night can be investigated to identify contrails in their vicinity and are expected to prove whether an avoidance or an observation flight (one without avoidance to control the contrail prediction) was successful. Until December 2024, Meteosat Second Generation (MSG) was the operational geostationary satellite for the European and African continent that could be used to perform this task. It carries the SEVIRI instrument (Spinning Enhanced Visible Infra-Red Imager): an imaging

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radiometer with four channels in the solar and eight channels in the thermal range. Apart from the high-resolution visible channel with a nadir sampling distance of 1 km, all other spectral bands have a spatial resolution of 3 km at nadir. For the operational service, MSG/SEVIRI acquires an image of the full Earth disk every 15 min, in rapid scan mode it scans Europe and North Africa every 5 min.

Automatic contrail detection has been originally developed for the AVHHR (Advanced Very High-Resolution Radiometer) sensor aboard the polar-orbiting NOAA (National Oceanic and Atmospheric Administration) satellites with a better spatial resolution (around 1 km at nadir) by means of image processing techniques by Mannstein et al. (1999) exploiting brightness temperatures and brightness temperature differences. This algorithm has been applied to other polar orbiting sensors like MODIS (Moderate Resolution Imaging Spectroradiometer, Duda et al. 2013), and also to MSG/SEVIRI (Mannstein et al. 2010, Dekoutsidis et al. 2023). In particular, for MSG/SEVIRI the channels centred at 8.7 and 12.0 µm were used in Mannstein et al. (2010), while Dekoutsidis et al. (2023) tested the usage of the water vapour channel centred at 7.3 µm. Unfortunately, due to its relatively coarse spatial resolution, MSG/SEVIRI is prone to relatively high false alarm rates and low detection efficiencies, and a contrail is expected to appear in a satellite image at least 30 but more probably 60 min after an individual flight has passed through the pixel (Duda et al. 2004, Vazquez-Navarro et al. 2015, Gierens and Vazquez-Navarro 2018).

3. Enhanced methods for eco-efficient flights

Several research and development projects have been undertaken for many years to investigate the feasibility of integrating available information on weather and climate effects into existing flight planning and ATM (Air traffic management) processes to avoid climate-sensitive regions. The timeline of these operational processes, as well as the timeline of regular weather forecasts from the meteorological service, determine the timeframe into which the use of additional data and tools must be integrated without exceeding the limits of existing procedures and processes, i.e., among other things, that calculation times must not change significantly. Thus, the objectives of the ongoing projects are to investigate the feasibility of eco-efficient trajectories and their impact on flight operations and on the airspace as a whole.

In doing so, the German project D-KULT developed the workflow in an integrated collaboration chain in which the National Meteorological Service Provider (DWD), climate research and aviation research institutes (DLR), flight planning software developers (Lufthansa Systems and PACE), airlines (Lufthansa) and air traffic control (DFS) are involved.

As a prerequisite for climate-optimization, the D-KULT partners first started the development and implementation of an experimental dataset of an expanded meteorological (MET) service which informs air space users and air traffic control on those regions where contrails can form and persist and where other non-CO_2 effects are large. In this section, we describe how this information is provided and then used in pre-tactical and tactical flight planning and optimisation and how it is used and presented to air traffic controllers who finally have to guide the flights securely and efficiently.

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3.1 Integrated collaboration chain for flight planning and climate optimization

An integrated collaboration chain to separate the tasks and challenges for future operational implementation illustrates the overall workflow of climate optimized trajectories (see Figure 1). This overall workflow represents various options of implementation of alternative trajectories, comprising strategical alternative flight planning, which incorporates all mitigation needs into an environmentally optimized flight plan, in-flight optimisation or tactical measures performed by air traffic control (ATC), were ANSPs would take a role in directing the mitigation. The overall chain consists of providing weather forecast, together with climate response functions as climate forecast data and follow on with the respective planning and execution phases. The last step in this workflow in D-KULT is an intensive analysis and evaluation for validation purposes.

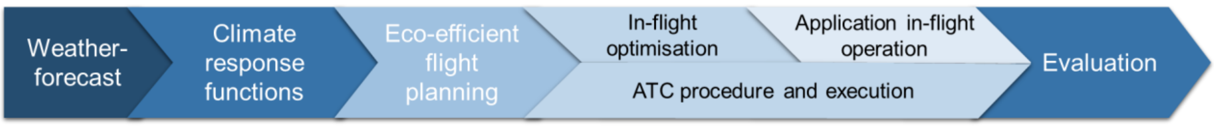

Figure 1: Schematic workflow of integrated collaboration chain as established in D-KULT.

In each step dedicated developments were performed which are described in detail in the following chapters. Based on these main tasks a good understanding for future operational use was obtained as well as some severe issues which have to be solved in order to achieve that goal.

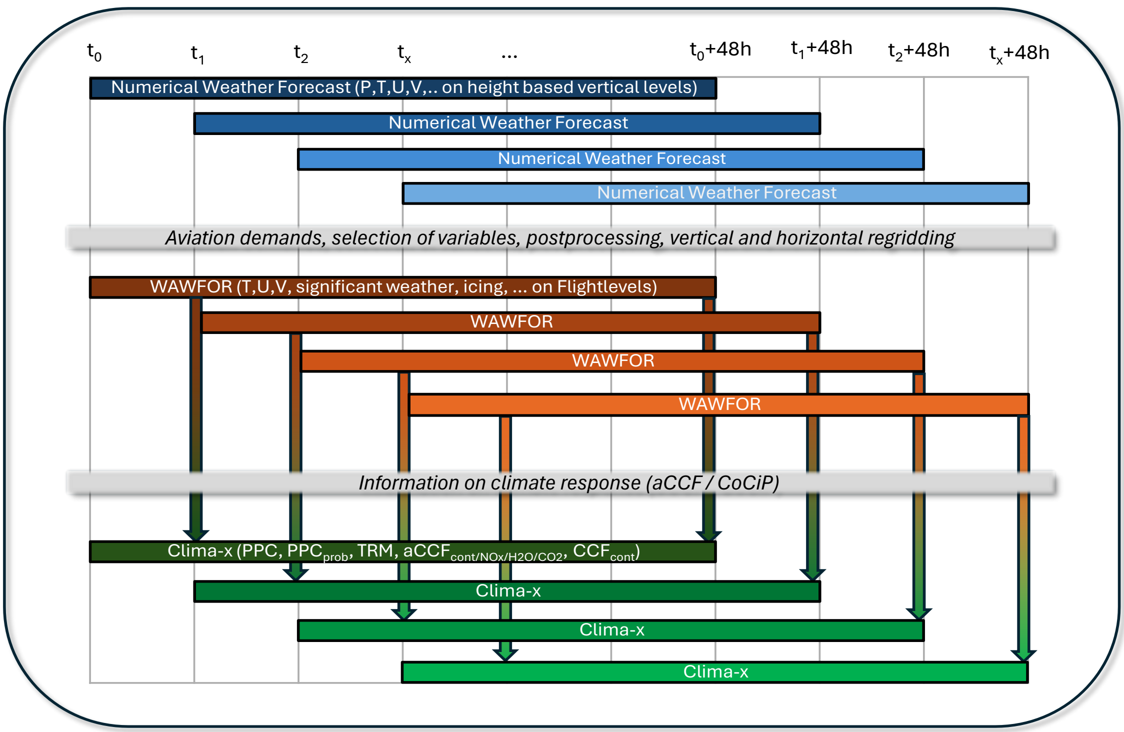

Figure 2: Schematic overview of connections between Numerical Weather Forecast, WAWFOR and the Clima-X datasets.

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240 **Table 1: Experimental data sets for eco-efficient flight planning containing climate response functions computed from standard or experimental numerical weather forecast.**

Clima-	Microphysics	Response functions and meteorological parameters	Comments
1	1-Moment	PPC, $aCCF_X$, TRM from the deterministic runPPC_{prob} from the 40-member ensemble (hourly output for the EU-nest, 6 hourly for the global ICON)	Based on operational Standard ICON model, EU-Nest and global Ice supersaturation > 93% RHi
1s	2-Moment	$aCCF_X$, TRM from a 10-member ensemble average, PPC from the 10-member average of RHi and T PPC_{prob} from the 10-member ensemble	Initialisation with the standard ICON, only global Ice supersaturation > 100% RHi
2		Radiation quantities only: Net longwave and shortwave radiation fluxes	Based on operational Standard ICON model, for research purpose only, can be extended
3s	2-Moment	Like Clima-1s, but aCCF for contrails is computed with CoCiP (Fortran version)	
4s	2-Moment	Air temperature, pressure and density, zonal and meridional winds, vertical wind, specific ice content and specific humidity, relative humidity over ice, and cloud cover, geopotential and potential vorticity, outgoing longwave radiation, solar direct radiation, total net solar radiation.	Based on 1st ensemble member. Intended for application in MRV system

Table 2: Variables contained in the experimental Clima-1, Clima-1s and Clima-3s data sets.

Name	Parameter	Type	Unit
PPC	Potential Persistent Contrail. PPC=0: contrails are either not possible or not persistent; PPC=1: persistent contrails are possible. Derived from the deterministic runs of ICON	Binary	
PPC_prob	Probability Potential Persistent Contrail: The fraction of the 40 or 10 members of an ensemble forecast that predict PPC=1.	0-1 [Real]	
TRM	Transmission Probability: an indication whether a contrail in a certain altitude can be detected by a satellite if the field of view is covered with additional cirrus clouds.	0-1 [Real]	

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ACCF_CONTRAIL	Algorithmic climate change function contrail cirrus[1]: climate effect that is expected to arise if a persistent contrail of a length that can be flown with on kg of fuel is formed at a certain location and time.	Real	K/kg fuel
ACCF_NOx	Algorithmic climate change function NO_x: climate effect that is expected to arise if one kg of NO_2 is emitted at a certain location and time.	Real	K/kg NO2
ACCF_H2O	Algorithmic climate change function water vapour: climate effect that is expected to arise if H_2O is emitted by burning one kg of fuel at a certain location and time.	Real	K/kg fuel
aCCF_CO2	Algorithmic climate change function CO_2: climate effect that is expected to arise if CO_2 is emitted by burning one kg of fuel at a certain location and time.	Real	K/kg fuel
ACCF_PLACEHOLDER	Placeholder for future enhancement		
CLD_INDIRECT	Placeholder for future enhancement		

3.2 MET-service: Aviation weather forecast enhanced with new fields

3.2.1 Novel data packages Clima-X with the WAWFOR structure

In order to enable eco-efficient flight route planning, the flight routing services must not only know the standard meteorological parameters (like wind and temperature) but additionally the current values of the weather-dependent climate response functions, which describe the individual climate effects of unit emissions (e.g. 1 kg) of an aircraft. These data are provided through a series of experimental climate data sets compatible with the structure and design of WAWFOR, schematically illustrated in Figure 2. We call these data sets Clima-X where X is a placeholder to distinguish between the different data sets (see Table 1). The 4-dimensional (latitude, longitude, altitude, time) response functions (aCCFs) and parameters for contrail prediction contained in the Clima-X data sets are listed in Table 2. All variables are interpolated vertically from the height levels of the original NWP model to flight levels and horizontally from a triangular grid to a regular lat-lon grid.

3.2.2 Contrail-formation related functions

A significant contribution of D-KULT has been the introduction of the concept of "PPC areas" (Potential Persistent Contrail areas) in addition to the term "ISSR" (Ice Supersaturated Regions). While ISSR refers to regions with ice supersaturation, which is a thermodynamic condition for contrail persistence, the term PPC involves additionally the thermodynamic condition for contrail formation, the so-called Schmidt-Appleman criterion (see below). Only if both conditions are met, PPC is set to one (or TRUE).

[1] Climate response in aCCF_contrail originates from aCCFs (Clima-1/1s) or CoCIP (Clima-3s) models.

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To allow the formation of contrails, the temperature must be low enough to fulfil the Schmidt-Appleman criterion (SAC, Schumann, 1996), which states that the evolving mixture of engine exhaust gases with ambient air must transiently become water-(super)saturated, such that the emitted water vapour can condense on the co-emitted soot particles. The SAC depends on the type of fuel used and the overall propulsion efficiency of the aircraft. For D-KULT, we assume the general use of kerosene with an emission index of water vapour of 1.25 kg/kg and a lower heating value of 43 MJ/kg. We assume an overall propulsion efficiency of 0.365.

Contrail persistence requires that the ambient relative humidity with respect to ice, RHi, exceeds 100%, that is, that the water vapour is ice-supersaturated. However, the operational version of ICON does hardly ever produce such high values of RHi, because of simplifications in the implemented one-moment cloud physics parameterisation. In order to account for this deficiency, D-KULT follows two strategies, a simple one and a more sophisticated one. The simple approach is to consider any situation where the relative humidity with respect to ice (RHi) exceeds a certain threshold as ISSR. In D-KULT, we chose a threshold of RHi=93% (as in Hofer et al., 2024). Such a low threshold (instead of the physical one at 100%) is intended to balance the low bias that the forecast model otherwise produces. The more sophisticated approach is to use an experimental version of ICON equipped with a two-moment cloud ice-microphysics scheme (Hanst et al., 2025) that does not consume ice supersaturation too quickly after cloud formation. Here the threshold is set to its physical value at 100%.

In the experimental dataset Clima-1, PPC_{prob} is the fraction of 40 ensemble forecast runs with the operational ICON model that show PPC=1. In Clima-1s, PPC_{prob} is defined analogously, based on 10 ensemble members using the two-moment cloud ice-physics scheme.

Note, that the experimental forecasts using the two-moment scheme have no own initialisation (i.e., data assimilation cycle); they use the operational ICON initialisation, that is obtained with the one-moment scheme. As the latter has practically no supersaturation, it needs about 12 hours of forecast lead time to build up such cases in the experimental forecasts, the so-called spin-up time. Furthermore, while the operational ICON has a deterministic run different from the 40 ensemble runs, the ensemble average of the 10 experimental forecast ensemble members is taken for the deterministic run that determines PPC and TRM.

The transmission probability TRM is a simple probabilistic estimate of whether a contrail can be seen from an earth-observation satellite (Gierens, 2023). This quantity can be used for two purposes: To plan an avoidance experiment and to plan a rerouting operationally. An avoidance experiment should only be planned if there is a sufficiently high chance that the result of the experiment can be controlled by satellite observations. In a similar spirit, contrail avoidance should only be performed if the contrail would have a measurable effect on the outgoing (in particular, infrared) radiation. Both situations imply a sufficiently large transmission probability (a practical threshold has not been determined yet).

3.2.3 Climate response/change functions – spatially and temporally resolved

ACCFs are computed in D-KULT directly from meteorological output quantities of the underlying ICON model by means of simple formulas as given in Dietmüller et al. (2023) and Yin et al. (2023). ACCFs for NO_x, water vapour and contrails are

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available in the experimental data set Clima-1 (deterministic run) and in Clima-1s (average of 10 experimental forecast ensemble members). In Clima-3s, the aCCF for contrails is replaced by a climate response calculated with grid-based CoCiP. The available package of aCCF uses the climate metric F-ATR100 and provides climate response at a certain location and time for individual species in K per unit emission of NO_2 (in case of aCCF-NO_x) or in K per unit fuel consumed (in case of all other species). ACCFs of NO_x are converted to climate response per fuel using aircraft specific emission indices and aircraft performance models in the flight planning process. The climate response can be converted to other climate metrics simply by conversion factors individually for each species (e.g. Dietmüller et al., 2023).

ACCF-contrail in Clima-3s and Clima-4s is calculated with the CoCiP model (Schumann, 2012). CoCiP provides detailed estimates of contrail microphysics, lifetime, geometry and radiative properties. It is applicable globally under both day and night conditions, with explicit criteria for determining contrail persistence based on lifetime. While the condition PPC=1 and the corresponding calculation of aCCF (contrail) in Clima-1s requires ice supersaturation, CoCiP defines persistent contrails via ice water content thresholds. Clima-3s utilizes the original Fortran version of CoCiP while Clima-4s is calculated with the *pycontrails* Python implementation, (see details of history in Engberg et al., 2025). Designed for trajectory-based inputs, CoCiP has been adapted for grid-based operations to forecast regions where contrails form, enabling large-scale predictions of contrail cirrus effects (Engberg et al., 2025). By integrating time-resolved radiative forcing over the contrail's lifetime and spatial extent, CoCiP determines the energy forcing, which is converted into a global mean radiative forcing and then, analogously to aCCF, translated into other climate impact metrics. Many more details on this tool can be found in the publications of Schumann (2012) and Engberg et al. (2025).

Figure 3 shows climate responses from experimental Clima-1 and Clima-1s for contrails, for NO_x and for H_2O exemplarily for 18.07.2024. In addition, the contrail climate response from Clima-3s is shown.

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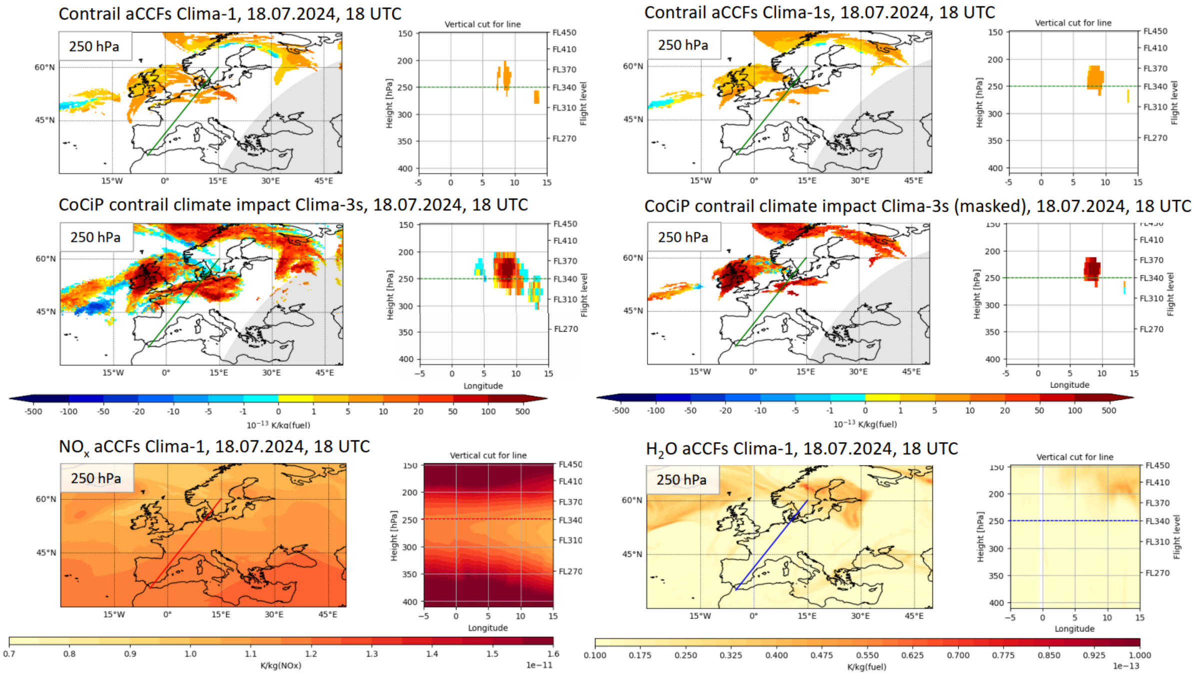

Figure 3: Dataset comprising Clima-1, Clima-1s, Clima-3s and Clima-3s (masked by ensemble mean PPC) climate response functions for contrails, NO_x and H_2O for 18 July 2024, as derived from ICON operational and experimental simulation runs. The vertical cut is along a theoretical flight from Malaga to Stockholm.

While aCCFs of NO_x and H_2O are nearly identical between the deterministic run and the ensemble mean (not shown), contrail aCCFs show discrepancies between the various data sets. Reasons for these include the different thresholds for ice supersaturation (93 and 100%), averaging in case of the two-moment scheme, and the completely different computation methods between the aCCF for contrails and CoCiP.

The Clima-4s data set (see Table 1) is intended to serve as a meteorological input data set for climate response models with an extended set of variables. It could be e.g. used as input data for the weather-based approach of the Monitoring, Reporting and Verification (MRV) System. The 15 meteorological parameters are determined on the basis of the first ensemble member. The data output is in an aviation-usual lat/lon grid structure with a horizontal resolution of 0.25° × 0.25° degree and vertically on pressure levels between Flight Level 160 and Flight Level 460 in 10 hft steps. The forecast time covers the usual +48 hours for flight planning and the +13 hours of the pycontrails life cycle, in 1 hour forecast increments.

3.3 Single flight trajectory optimization for eco-efficient operations

3.3.1 Strategical flight planning

Different approaches to trajectory optimisation are being pursued in the D-KULT project. On the one hand, legal eco-efficient trajectories are planned and calculated. On the other hand, approaches for continuous trajectory optimisation have been developed for the purpose of benchmark calculations.

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For the planning of legal eco-efficient trajectories, the Lido optimizer was extended to take climate sensitive areas into account during the optimization. These areas are determined using the aCCFs from the Clima-X data sets. To include those climate sensitive regions (non-CO_2 effects) in the optimization, their monetized climate effects are added as climate costs to the total cost function. In the mono-criterial optimization all those cost components need to be expressed in the same unit, a monetary value. As the non-CO_2 climate effects are represented as Kelvin values (i.e. as a temperature change) they needed to be converted first. This conversion factor is calculated based on the CO_2-price and the aCCF for CO_2.

Adding non-CO_2 -costs into the cost-function will not only have an effect locally to avoid certain regions but can result in completely different trajectories. As seen in Figure 4, optimizing the flight Frankfurt to Miami based only on fuel and time costs, the trajectory (orange) crosses the North Atlantic. With non-CO_2 costs added the optimizer chooses a route over the United Kingdom, Greenland and Canada to reach Miami (green).

DLR's Python-based Trajectory Optimization Module (pyTOM) is utilized to develop environmentally and climate-efficient flight trajectories with a continuous trajectory optimisation (Lührs et al., 2016, the actual version is described in Lau et al., 2022). Initially, a feasible solution is generated, which is then refined through an optimal control algorithm to produce a dynamically consistent and optimal trajectory, incorporating a detailed aircraft performance model (using EUROCONTROL's Base of Aircraft Data (BADA) Revision 4.2, Nuic and Mouillet, 2012). Actual emissions are computed with the Boeing fuel flow method BFFM2 (DuBois and Paynter, 2006), which are then multiplied with the aCCFs (climate response per unit emission). When optimizing for climate impact, the resulting trajectory is obtained as a weighted sum of direct operating costs and climate effects. The climate impact is represented as the time integral of aCCFs multiplied by the corresponding emission flow. Even if the resulting continuous trajectories may be unrealistic in terms of flyability with regard to flight safety, elementary quantifications of the maximum climate impact reduction can be turned into legal eco-efficient trajectories.

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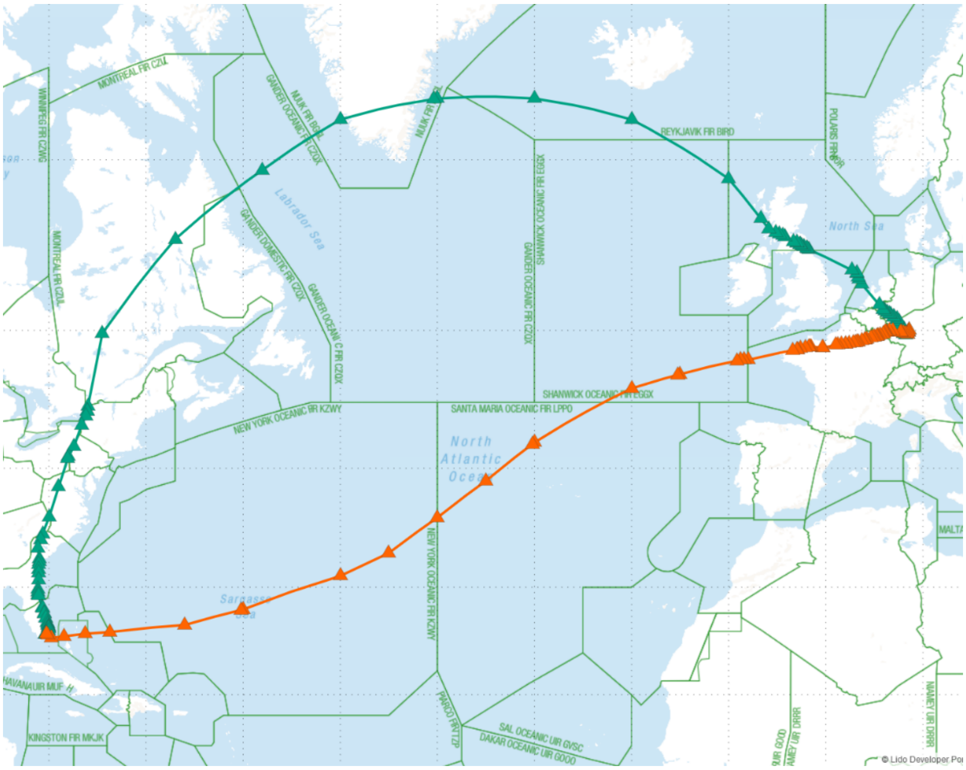

Figure 4: Optimized routes with non-CO_2 effects (green) and without non-CO_2 effects (orange) within the airspace structure (triangles) Copyright 2025 Lido Developer Portal.

3.3.2 Tactical vertical flight routing

The Flight Profile Optimizer FPO Cloud by PACE is a tool that allows flight crews to upload the most recent weather information immediately before and during the flight and to compute an optimal vertical flight profile. In D-KULT, FPO Cloud has been enhanced by two new features for the calculation of climate efficient trajectories: one for PPC (PPC-mode), where the flight length through PPC=1 areas will be minimized and one for aCCF (ECO-mode), calculating the expected total climate responses for CO_2, NO_x, H_2O and contrails, to minimize the warming of the atmosphere. Figure 5 shows examples of a pre-flight calculation for these features. The maps view in PPC-mode (upper part) shows the lateral route and surrounding map and, as grey dots, areas where PPC=1 at the first cruise flight level (here FL 380) of the initial flight plan. In addition, weather data at the actual time can be displayed. The profile view of PACE FPO Cloud (lower part) consists of flight plan information (times, way points, and Flight Levels) and weather data (PPC=1) at respective local times of the flight plan. Both the initial active trajectory (time and fuel optimal, green) and the resulting trajectory of the contrail avoidance optimization (time and fuel and climate optimal, blue) are shown. Selection of the ECO-mode enables the pilot to select one of three aCCF parameters for visualisation. In Figure 5, the visualisation of aCCF Contrail is selected and the grey dots can be seen in the maps- and in the profile view. The values in the blocks show the climate response functions of these areas. Depending on species, the

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potential climate response can be positive or negative (i.e. warming or cooling), which is indicated in the profile view as grey (positive response) or light blue (negative response) blocks.

Adding a climate relevant aspect to the optimization process will lead to an increase of time and/or fuel in many cases. An information pop-up is shown in the middle of the profile view, that informs the pilot about the consequences of following the new, climate optimised trajectory.

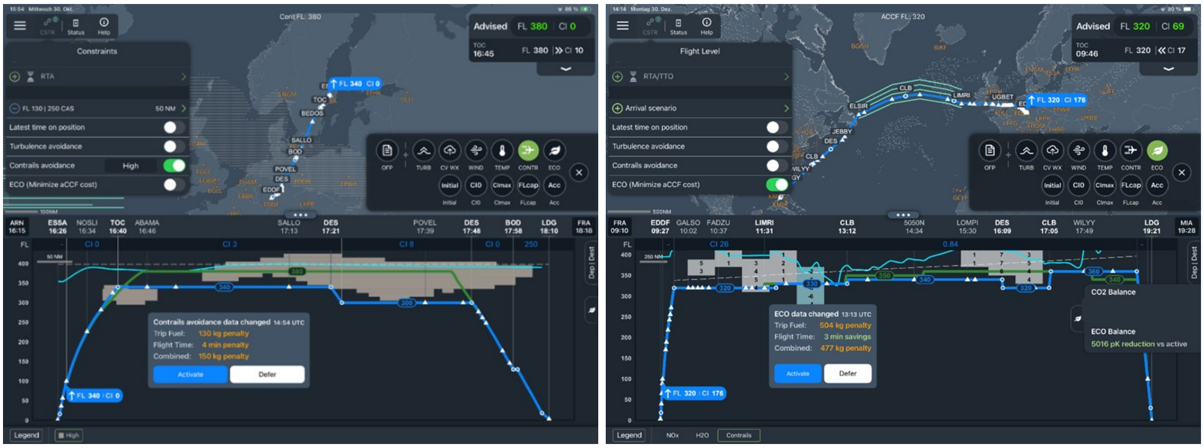

Figure 5: FPO Cloud screenshots. Left: PPC-mode, right: ECO-mode. In PPC-mode, the optimizer minimizes the path length through PPC=1 regions, in ECO mode it calculates a trajectory with minimum intersection with climate sensitive regions (as defined via aCCFs). The upper part of the screen shows a map with the flight path, the lower part displays the vertical view of the trajectory. The original trajectory is shown in green, the eco-efficient one in blue. Insets show, how much extra fuel and time needs to be invested for the eco-efficient trajectory. Source: PACE - FPO Cloud.

3.3.3 Representation of potential persistent contrail formation regions at DFS for air traffic controllers

For inhouse evaluation of PPC-areas, DFS has developed an own display-software to represent the PPC-areas and to calculate data for statistical analysis. This visualization tool (PPC tool) can graphically process the forecast data of the DWD for different times and altitudes, as well as the Clima-X data of DWD, see Figure 6, left panel. This initial representation has been converted for use on the controller's radar screen (Figure 6, right panel) to indicate the tactical avoidance areas. The hexagon (honeycomb) shape was chosen because it does not conflict with other area representations on the radar screen and is also relatively easy to adapt. For each forecast hour, the PPC areas are calculated per flight level based on weather data. An algorithm is used that marks a hexagon as active if at least 50% of its area is covered with PPC=1 at the respective flight level. All active hexagons are then combined into a three-dimensional structure. The lateral dimensions are defined by the hexagon identifiers, and the vertical thickness is represented by the lower and upper flight levels. The honeycomb structure was deliberately not extended to the external air space boundaries in order to allow a buffer of approximately 10 NM (nautical miles) for aircraft to return to their sector exit level. However, the simulation showed that this buffer was not necessary. A new base structure is currently under development.

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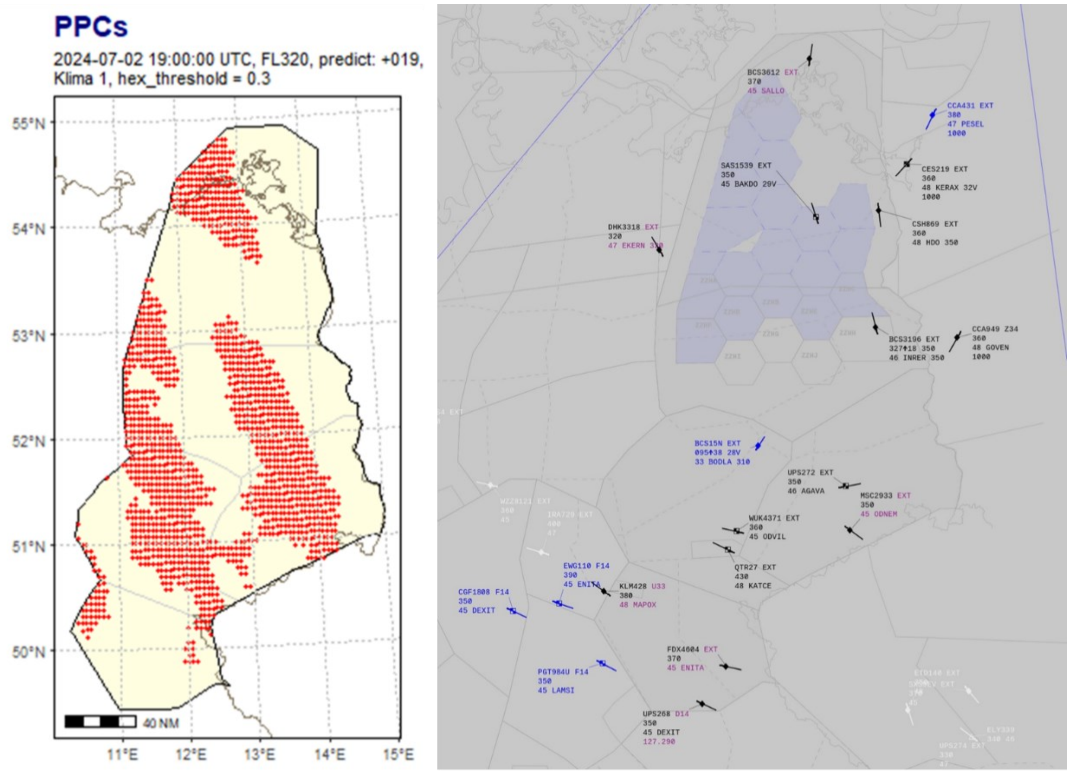

Figure 6: Left DFS PPC tool representation of climate sensitive areas for a specific airspace (KUAC) at one instant of time. Right PPC=1 areas on the Controller's Radar screen (illustrative example). Source: DFS.

With this approach, DFS became one of the first organizations worldwide to integrate PPC areas into the main traffic window of its Air Traffic Control System for validation purposes. However, there is still no satisfactory representation version that meets all requirements. The development and definition of an optimal display remain important next steps for the practical implementation of the procedure to avoid persistent contrails.

3.4 Numerical workflow for trajectory performance evaluation including uncertainties

For the evaluation of trajectory performance, it has to be noted that these estimates inherently contain uncertainties. More specifically evaluating the climate effects and potential mitigation gains, currently various concepts and tools exist on how to estimate climate response with the required spatial and temporal high resolution. While aCCF rely on a statistical concept of representing meteorological processes, CoCIP/pycontrails in applied version uses single Lagrangian trajectory calculations with detailed assumptions on contrail characteristics. We recognize that these various methodologies and numerical tools provide different estimates of the potential climate effects, representing a considerable source of uncertainty when evaluating trajectory performance. To implement such prevailing uncertainties in the overall performance analysis a statistical workflow was suggested (Matthes et al., 2020). The proposed mathematical integration relies on combining distinct estimates in a risk analysis, error propagation and Monte-Carlo analysis, where the respective parameters are varied within dedicated uncertainty

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ranges, in order to construct a probability distribution of . As a result, robustness of mitigation gains as well as corresponding confidence intervals can be achieved, allowing to estimate the probability of a desired outcome. Furthermore, methods are currently under development how to integrate these uncertainties mathematically and statistically as part of the overall decision-making framework, comprising estimates of confidence intervals for climate effects and mitigation gains on individual trajectories. In this study, we tested various meteorological model versions and climate response tools during evaluation of trajectory performance as illustrated in section 4.1.3, however integration of all known sources of uncertainties as proposed for a comprehensive decision-making framework is beyond the scope of this paper.

3.5 Methods for the validation of contrail avoidance

The contrail detection algorithm (CDA) by Mannstein et al. (1999), developed for the AVHRR sensor aboard the NOAA polar orbiting satellites, exploits the fact that contrails appear as cold/dark lines in brightness temperatures BT(12.0) in the channel centred at 12.0 µm due to their location in the upper troposphere and show high brightness temperature differences BTD(10.8-12.0) between 10.8 and 12.0 µm because of their low optical thickness and small ice crystal effective radii. The steps that eventually lead to the desired contrail mask are described in the paper by Mannstein et al. (1999). For the validation of contrail avoidance, it is not ideal to rely on polar orbiting satellites; instead, geostationary satellites like MSG are needed since only they provide a continuous view on the airspace. However, contrail detection for MSG/SEVIRI is challenging mainly due to the moderate spatial resolution of the instrument. SEVIRI has seven spectral channels in the thermal infrared instead of two of the NOAA/AVHRR sensor. Thus, to enhance the capabilities to identify contrails with MSG/SEVIRI data the procedure described by Mannstein et al. (1999) is applied twice to BT(12.0) and BTD(10.8-12.0) on one hand and BT(12.0) and BTD(8.7-12.0) on the other hand.

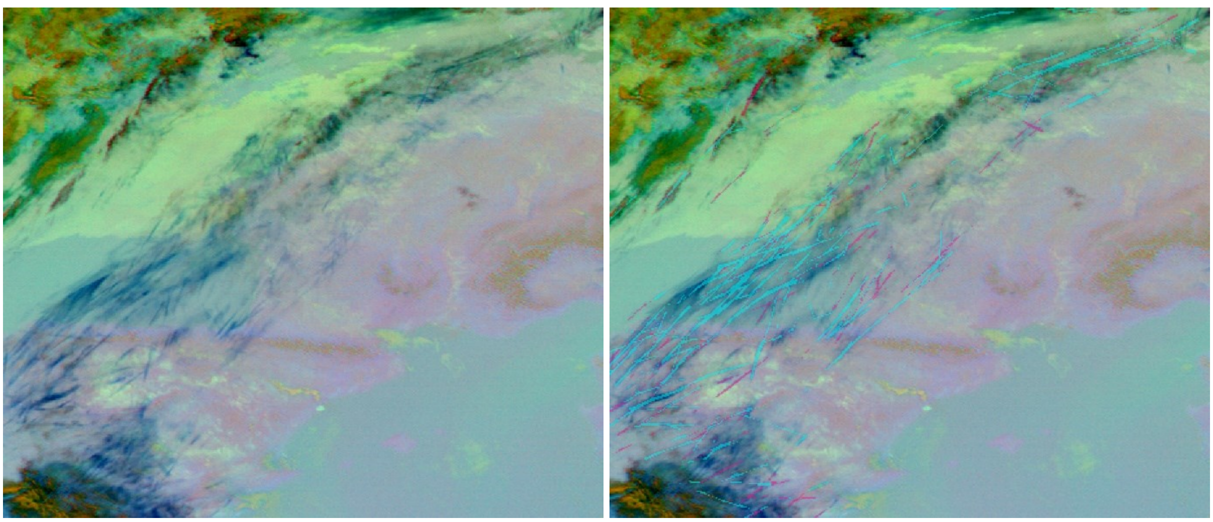

Figure 7: MSG/SEVIRI observation over Spain and France on 16.02.2019 at 10 UTC. Left: Ash RGB highlighting contrails as dark blue lines. Right: Contrails detected by contrail detection algorithms (CDA). Cyan pixels indicate those contrails detected by the CDA using BTD(10.8-12.0) and BTD(8.7-12.0) separately, while the pink pixels indicate the contrails additionally detected by the new CDA version presented here.

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In addition, for every channel combination the use of the 19 x 19 pixels large line filter is complemented by an additional 17 x 17 pixels large line filter that aims at detecting thinner and/or fainter contrails. Finally, these filters are applied to 32 different directions in order to allow for a better coverage of all possible orientations. The final contrail mask consists of the union of the contrails resulting from all the channel and filter combinations. An example is shown in Figure 7 for a situation with many contrails over Spain and France at 10 UTC on 16.02.2019. In the right panel, pixels are marked in cyan that are detected by the former versions of the CDA for MSG, while the pink pixels represent the additional contrails detected by the current version.

The new CDA is used to identify contrails in quicklooks after contrail-avoidance experiments and for an initial visual evaluation of the contrails in regions where D-KULT flights of the TF-100 have taken place. For a quantitative evaluation of the success of the avoidance and observation flights a technique (described elsewhere) has been developed that is based on contrail detection but additionally exploits properties of the single contrails and their temporal evolution to associate observed contrails to the flight under consideration.

4. Implementation of novel parts for climate-optimized aircraft trajectories (eco-efficient)

4.1 Tests of predictions of contrails and non-CO_2 effects

4.1.1 Forecast of ice supersaturation and verification with radiosonde data

In the context of D-KULT, improving the numerical weather prediction of relative humidity with respect to ice is essential, as it represents the key meteorological parameter for deriving the potential of persistent contrails. The current status of RHi forecasts is unsatisfactory (Gierens et al. 2020, Hofer et al., 2024). In the operational global ICON model used at DWD, a one-moment cloud ice microphysics scheme is employed in which only specific ice mass is treated as a prognostic variable, while the number concentration of ice particles is parameterized in terms of temperature. This approach tends to overestimate ice particle concentrations at low temperatures, resulting in unrealistically short phase relaxation times and, consequently, reduced levels of ice supersaturation.

For the D-KULT project, DWD has configured a dedicated ICON ensemble system comprising ten members, in which a two-moment cloud ice microphysics scheme - adapted from Köhler and Seifert (2015) - has been implemented. Unlike the one-moment scheme, the two-moment approach treats both ice mass and ice particle number concentration prognostically, allowing for more realistic phase relaxation times and RHi values. This approach allows in particular to use the physically correct threshold for ice (supersaturation), namely at RHi=100%, for forecast of ISSRs. More details on the two-moment scheme and the setup of the simulations can be found in Hanst et al. (2025).

The two-moment scheme was evaluated using 14 months of radiosonde data. Compared to the one-moment scheme an increased probability of detection (POD) for ice supersaturation was achieved (0.6 instead of 0.4), while maintaining a relatively low false positive rate (FPR) below 0.1.

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A Receiver Operating Characteristic (ROC) analysis conducted (see Figure 8a) on the ten-member ensemble revealed that requiring at least three members to indicate ice supersaturation yields a strong predictor, with a substantially improved POD of 0.8 compared to the deterministic forecast, while maintaining a relatively low FPR of 0.13. Additionally using ensemble spread (standard deviation of RHi across the ensemble, Figure 8b) for dynamic adjustment of the decision threshold allows to keep the FPR generally below 0.1. For more details and results on the ensemble analysis of the two-moment scheme see Hanst et al. (2025).

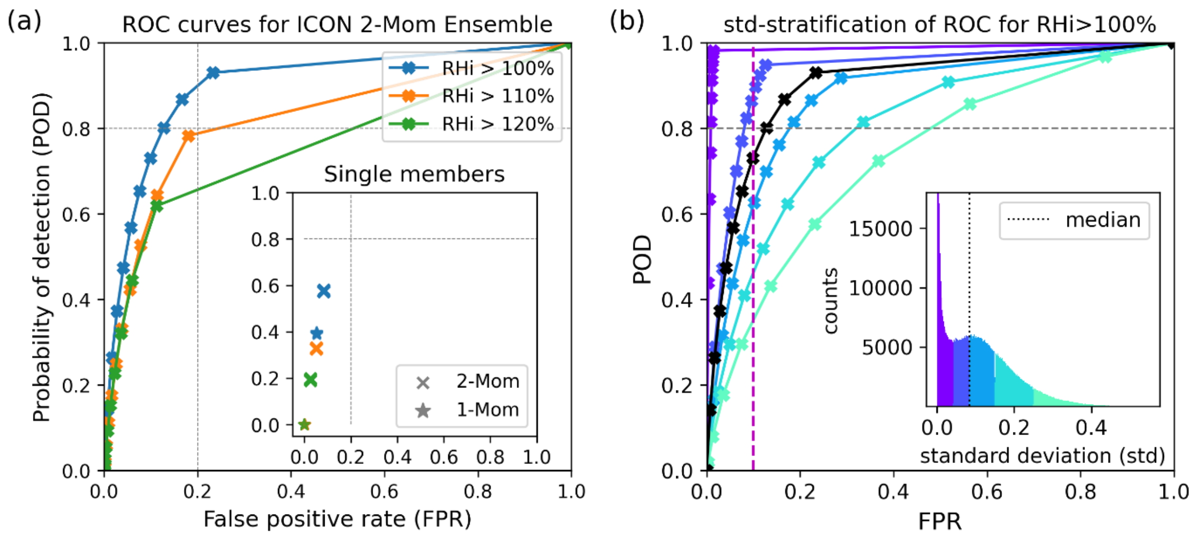

Figure 8: Receiver Operating Characteristic (ROC) Analysis. (a) ROC curves for predicting ice supersaturation (blue) and higher supersaturation. The first non-trivial marker (top right) indicates the decision rule requiring at least one ensemble member to predict the condition; subsequent markers represent stricter criteria (e.g., ≥2 members, etc.). Each point shows the false positive rate (FPR) versus the probability of detection (POD). Verification is based on Vaisala RS41 radiosonde observations over 11.5 months (15 June 2024–31 May 2025) in the 8500–12500 gpm (geopotential metres) altitude range. Inset: FPR versus POD for each of the ten ensemble members (serving as approximations of the deterministic model), using the ICON model with both the operational one-moment and the experimental two-moment cloud ice microphysics schemes. (b) ROC curves for ice supersaturation, stratified by ensemble standard deviation (std) of RHi. The black curve shows the unconditioned ROC curve as in (a) for comparison. The inset histogram illustrates the distribution of std values and serves as a legend for the conditioned ROC curves. Verification period 14 month: 1 April 2024–31 May 2025; all other conditions as in (a).

4.1.2 Forecast stability of PPC fields

For the assessment of forecast stability instantaneous and temporal aspects were considered. For the instantaneous component of PPC forecasts, the agreement of ensemble members with the deterministic run is examined. On average an agreement of about 75% between ensemble members and the deterministic run is found. Details are elaborated in von Bonhorst (2024). The temporal aspect evaluates the consistency of PPC forecasts for forecasts with different lead times towards a certain forecast time (targeted time). The results are categorized and expressed using the equitable threat score (ETS). The analysis shows a decline in forecast skill with increasing lead time, with ETS values decreasing from 0.7 for a 6-hour lead time to 0.4 for lead times of 24-30 hours (v. Bonhorst et al., 2025). Notably, the forecast skill is insensitive to the choice of microphysics scheme

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(one-moment versus two-moment ice microphysics scheme), indicating that the primary source of uncertainty is the inherent nonlinear behaviour of the atmosphere rather than the choice of model configuration. Consequently, forecast uncertainty can only be minimized by incorporating the most recent weather information.

PPC=1 regions on a weather map can be characterised by, e.g., their size, their average PPC_{prob}, their location and orientation. These properties have been used to characterise the kinematics of ISSRs (Hofer and Gierens, 2025a). It turns out that ISSRs move mostly in similar directions as the local wind, but on average with slightly slower speed (21 m/s for the wind and 15 m/s for the ISSRs). This decouples over time contrails from the ISSR wherein they have been formed, an effect that contributes to constrain their lifetime (Hofer and Gierens, 2025b).

4.1.3 Climate response functions

With the regular daily operational deployment of the novel experimental Clima-X dataset, the full implementation chain for climate-optimized trajectory planning has been enabled. Within D-KULT, the successful setup, implementation, continuous generation, and provision of NO_x-, H_2O- and contrail climate response functions across various tools have been achieved, enabling complete execution of the eco-efficient trajectory planning workflow.

The comparison of various experimental contrail climate response tools revealed significant differences in the extent of regions with a potential contrail climate effect (Clima-1s vs Clima-3s), despite identical underlying meteorology. These discrepancies were primarily caused by differences in the sequence of calculation steps (see Sect. 2.2.3). While the overall magnitude of contrail climate response fields from Clima-1(s) and Clima-3s is comparable, peak values in some areas are up to a factor of 10–20 higher in Clima-3s (see Figure 3). Differences between the aCCF approach and pycontrails/CoCiP are being further investigated in the EU project CICONIA (Dietmüller et al., 2026, in prep.).

As illustrated in Figure 9, the effectiveness of eco-efficient routing depends strongly on the underlying meteorological dataset. Whereas CO_2, H_2O, and NO_x climate responses remain relatively stable, contrail-induced climate effects vary substantially and dominate the total F-ATR100 values in Clima-3s (F-ATR100 is the average temperature response over a time horizon of 100 years). Notably, the trajectory was optimized with respect to minimize the contrail climate response using Clima-1s meteorological fields. In this example this leads to a higher contrail climate estimate when evaluated with Clima-1, highlighting the sensitivity of the results to the chosen climate response model and the underlying meteorological input data. A detailed analysis of this sensitivity is presented in Peter et al. (2026, in prep.).

During deployment and application of the climate response functions within the D-KULT workflow, certain questions and issues emerged. These experiences were channelled into "best practice" recommendations such as: If underlying meteorological data need to be re-gridded in space or time it is important to perform the interpolation before the calculation of aCCFs. Although it is generally not recommended to employ aCCF formulas beyond the scope of validity, it is necessary to give recommendations for marginal areas. In case of NO_x aCCFs, due to the specific formulation, values below 400 hPa reach unrealistically high values at low altitudes and should be replaced with the specific value of 400 hPa, otherwise unrealistic

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values would be accumulated on flight trajectories during climb and descent. Best practice recommendations on how to use aCCFs can be found with the ClimACCF library (Dietmüller et al., 2023).

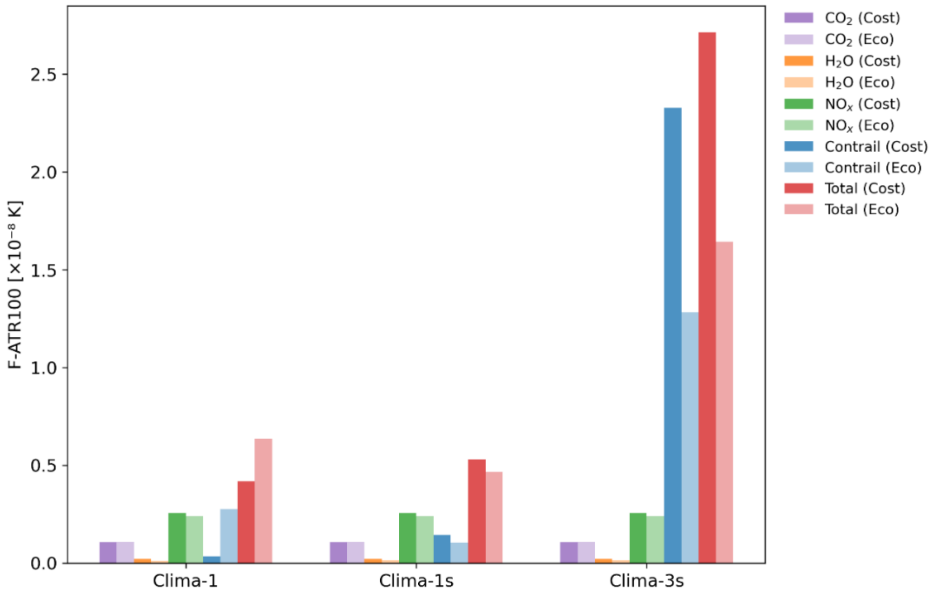

Figure 9: Comparison of climate response for one exemplary flight in Europe for cost-efficient and eco-efficient flight trajectories using three meteorological datasets (Clima-1, Clima-1s, Clima-3s): CO_2, H_2O, NO_x, contrail-induced radiative forcing, and total climate effect. Climate response is expressed as temperature change (F-ATR100) in units of 10^{-8} K.

4.2 Tests of the new features of the Lido and FPO tools (FPO cloud)

4.2.1 Tests of Lido: sensitivity of the solution to the weighting of climate vs. operational costs

Eco-efficient optimization includes the weighting of climate costs against operational costs. The resulting trajectory depends on the choice of these weights, and these are fixed in the enhanced Lido optimizer. The sensitivity of the solution to the choice of weights can be made visible using an additional bi-criterial extension of the Lido optimizer, which optimizes for operational and climate costs simultaneously. This implies that one cost component can only be lowered at the expense of increasing the other. In an operational-cost vs. climate cost diagram, the optimal solutions form the well-known Pareto-front where each point belongs to a different pair of weights. On a world map, each solution is represented as an individual flight trajectory (see Figure 10). In the shown example green trajectories have relatively low climate cost, but higher operational cost and vice versa for the red ones.

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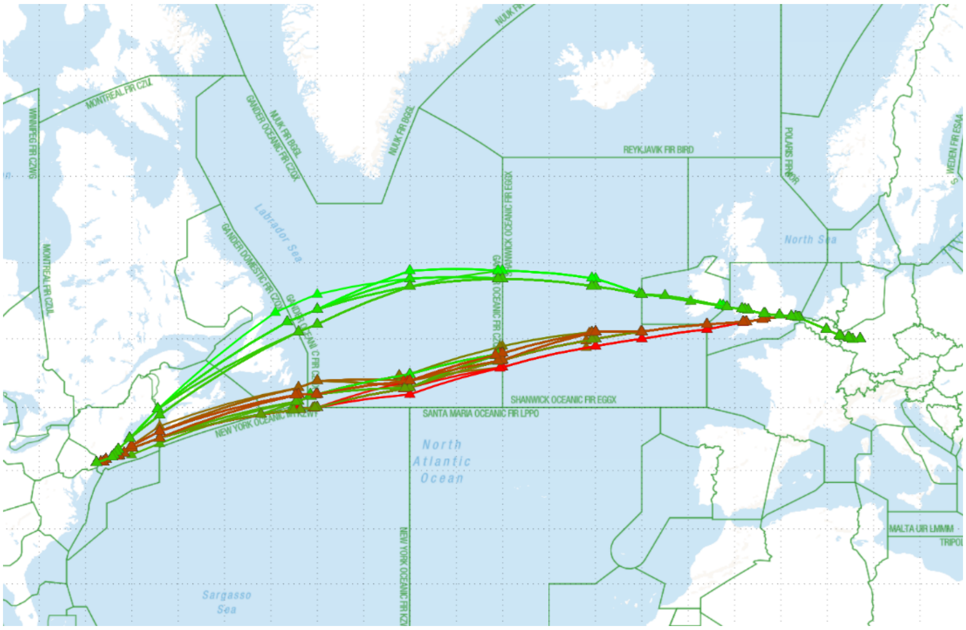

Figure 10: Trajectories behind pareto-optimal solutions from Frankfurt to New York. Copyright 2025 Lido Developer Portal.

4.2.1 Tests of Lido: strategic flight planning

Tests of new prototype modules for flight planning software (Lido 4D) were executed during test flights (called TF100) conducted in the framework of a German initiative AkkL (Arbeitskreis klimafreundliche Luftfahrt, see AKKL 2024). Key elements of the expanded D-KULT collaboration chain were added to the existing flight planning process thus creating a new modified manual flight planning process that was applied during the experimental test flights of TF100. Once a flight was selected for rerouting, its original operational flight plan was taken out of the Lido automatic flight planning tool and the flights' trajectory was optimized by the Lido 4D extended prototype to calculate an eco-efficient routing, avoiding potential contrail areas where possible and feasible. This eco-efficient routing was precisely replicated using the standard Lido 4D planning system and the resulting flight plan was then submitted to the Network Manager for approval. The flight crew had been informed to strictly follow the given routing.

The eco-efficient routing was calculated based on Clima-1s datasets provided by DWD displaying warming contrails aeras only masked by aeras with natural cloud cover (TRM). To select the candidate flights, a graphical representation of the same datasets was used (with 7 flight levels from FL290 to FL410 in 1-hour time steps), which dispatch experts could use to identify flights whose standard flight plan would have passed exactly through climate-sensitive areas (see Figure 11).

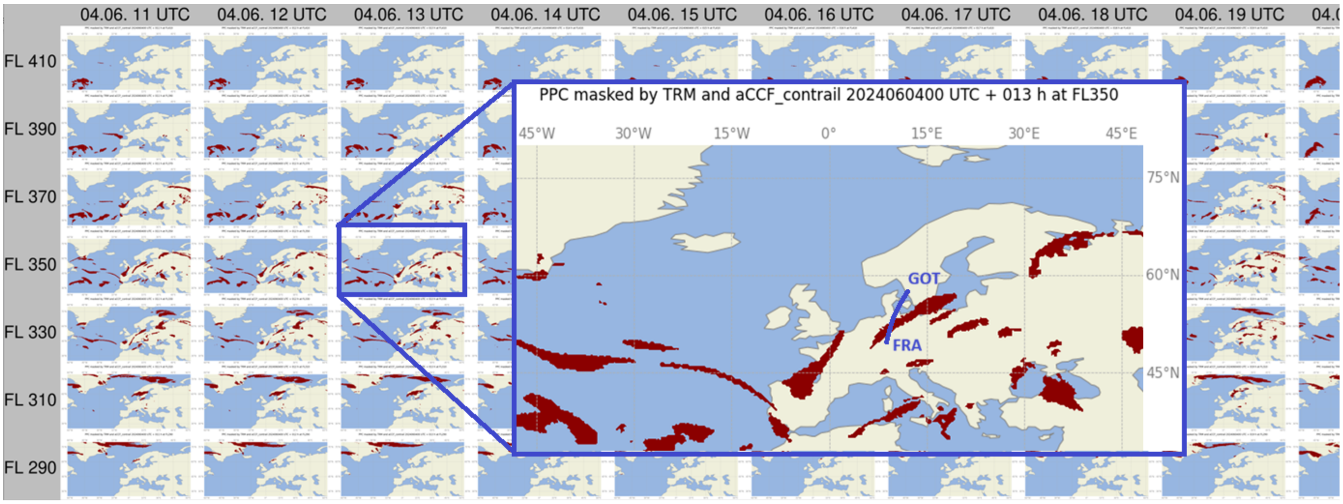

Figure 11 Graphical representation of a Clima-1s dataset that was used to identify candidate flights; here a flight from Gothenburg (GOT) to Frankfurt (FRA) was chosen for contrail avoidance.

The evaluation of the changing climate effect of the test flights is ongoing and the results will be published elsewhere. The test flights showed, that an implementation of climate-optimized trajectories could only be achieved by a workflow which relied on extensive manual interventions plus additional communication, e.g. with the pilots. For a possible future application in routine operations, automation of data flows and flight plan calculations is necessary, provided that weather and climate data are available in sufficient quality for the flight plan calculations. Further exploration needs to take place before active contrail avoidance could be implemented into the flight planning and filing process.

4.2.3 Tests of FPO Cloud on intercontinental flights

The new features of the FPO Cloud Tool have been tested on several flights starting 01.05.2024 on the Lufthansa B747 fleet: by mid-2025, 9 flights were selected for active contrail avoidance with tactical optimization and on 16 flights, the tool was used in shadow mode without active avoidance during flight execution for contrail monitoring.

The workflow remained a very manual process as the prototype tool was only available on a prototype device that could not be taken onboard the actual aircraft. The flight crew thus had to request an optimization during their flight preparation (approximately 2 hours prior take off). PACE could then calculate the optimized trajectory on the prototype device and send screenshots of the resulting optimizations to the flight crew via email. Such screenshots are presented in Figure 5. In FPO Cloud, the crew uses the information presented in the lower part of the screen to "Activate" or "Defer" the eco-efficient trajectory. Once on board, the flight crew used the PACE FPO classic tool to execute a routine flight optimization and compare that data with the screenshots of the FPO cloud prototype. Then, the decision whether it was feasible and / or possible to circumnavigate the PPC / aCCF contrail areas or not could be made and the flights vertical trajectory could be altered accordingly. Occasional circumstances can inhibit the tactical contrail avoidance, e.g. unavailable cruise levels due to surrounding air traffic, turbulence and convective weather, and prolonged flight times with significant additional fuel burn and emissions for the avoidance trajectories. Further exploration and testing need to be done in order to confirm the correct optimization and to further automatize the process.

4.3 Real-time simulation for tactical contrail avoidance

One of the main focuses of the project for DFS was the development of an operational concept and the execution of an operational trial to demonstrate the feasibility of avoiding persistent contrails. To define and refine the implementation and its parameters, it was determined that initial operational insights should be gained through a real-time simulation (RTS) in the fourth quarter of 2023. The goal of the simulation campaign was to examine the avoidance of PPC areas in terms of operational procedures and to assess their impact on, among other things, airspace capacity. A key advantage of a simulator campaign is the assessment of practicality of operational procedures and of the representation of climate sensitive areas on the controller's radar screen in a safe environment.

The simulation campaign involved preparation of simulation traffic scenarios, selection of PPC areas based on real weather situations, altitude information and dynamic progression as well as the transfer of this data into the ATC-System environment. Furthermore, briefing materials for controllers have been prepared, as well as questionnaires and debriefing questionnaires before and after each simulation run.

The developed operational procedure determined that PPC areas should be avoided laterally and vertically. The assumed reference value for level change of 2000 ft could hereby not be maintained as the areas had an average thickness of 4000 ft. The coordination with adjacent areas had to be considered to reduce the workload in the affected sector. It was planned that the LoAs (Letters of Agreement) with adjacent areas should be adhered to. Any aircraft had to remain within their designated airspace. Deviating into the underlying facility was not intended.

4.3.1 Execution of the Real-Time Simulation

The real implementation of tactical measures to avoid PPC areas in operational routine was demonstrated in the simulation in November/December 2023. The real-time simulation was conducted at KASIM (the simulator of the Karlsruhe Centre branch with the operational ATC system) and focused on a section of the EBG Ost (Operational Authorization Group East, including the sectors Baltic Sea, Havel, Saale, and Spree).

The avoidance of PPC areas using the developed operational procedure was examined with several variations during the simulation runs: Different scenarios with day or night configurations, various traffic loads based on real recorded traffic, different sector configurations, changes in working positions, as well as various PPC areas to be simulated both statically and dynamically. "Static" means that the selected PPC areas remain constant throughout the simulation run. In the dynamic case, the PPC area changes during the simulation. The information and PPC cells are displayed at the sector workstation.

Two time periods with different groups were planned for the simulation. Each group ran scenarios with both day and night configurations. The night configuration included two different traffic loads, while the day configuration included one. Each simulation day included 3–6 simulation runs with 10 participants (controllers), some of which were conducted in parallel. The

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day configuration included the combined sectors Baltic See and Havel, as well as the Saale and Spree columns. In the night configuration, all sectors were merged into one. Both configurations included all sectors of EBG Ost.

4.3.2 Insights from Real-Time Simulation

The newly developed operational procedure was evaluated, showing that the developed operational concept is basically usable. Extensive evaluations of the collected data were carried out following the simulation. Thus, the operational procedure described above is well approved. It represents a necessary step before such a procedure can be used operationally. During the five simulation days, well-founded statements on the feasibility of PPC avoidance could be made, and the planned simulation goals were achieved.

Significant additional workload for the air traffic controllers arose in the simulation, which resulted in capacity restrictions for operational use. These arose due to the reduction of available airspace, as flight levels and areas were kept clear of aircraft. The simulation scenarios were based on real traffic in one of the world's most densely flown airspaces. Although the number of aircraft in the scenarios was already reduced, additional workload due to the new procedure was still recorded. Further studies or simulations, including ergonomic aspects, are necessary to further develop the procedure to prevent a loss of situational awareness or an inappropriate increase in the workload of the air traffic controllers at their workplace. The additional workload also implied that not all flights could be rerouted around the PPC areas.

Figure 12 shows an example of the rerouted traffic in the simulation. Here, only 54% of the planned aircraft were kept out of the PPC area. According to a recent study, such a medium fraction of contrail avoidance in a region implies that only a smaller fraction (smaller than 54%, depending on meteorological circumstances) of the maximum possible climate benefit (achievable by keeping all aircraft out of the PPC area) would be achieved (Gierens, 2025).

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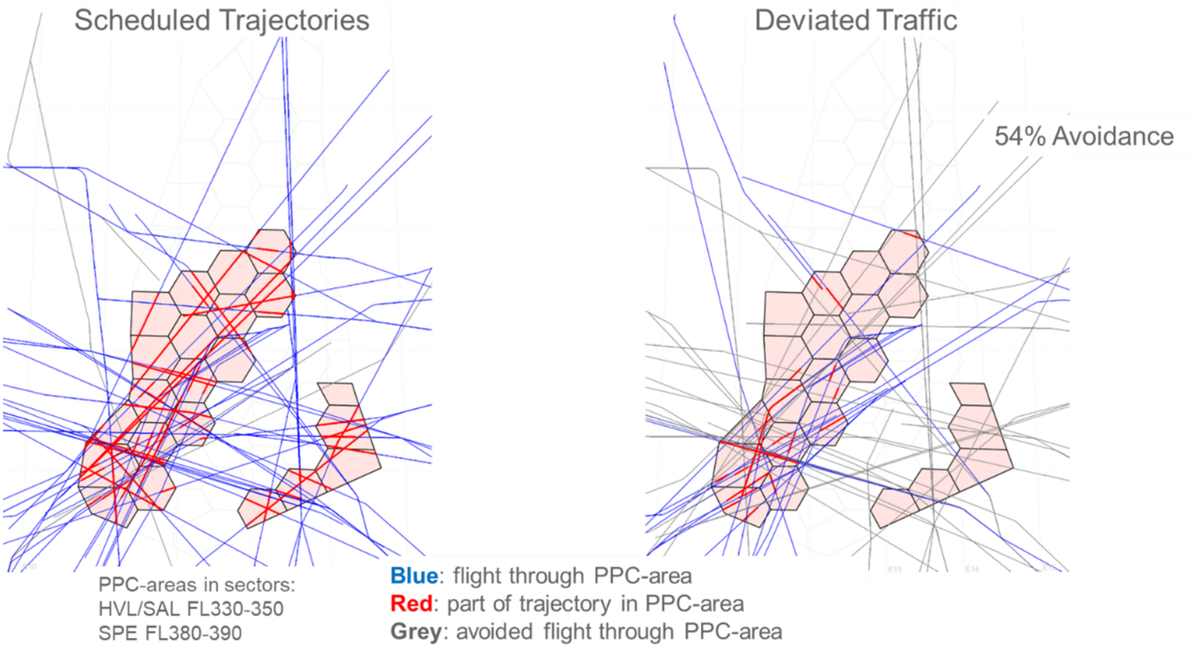

Figure 12: Comparison of planned traffic with controlled traffic to avoid the PPC-areas. Blue traces represent planned flight trajectories; the portion passing through a PPC area is marked in red. Grey trajectories were successfully rerouted above or below the PPC area. On the left, the intended planned flight paths are shown, and on the right, the result of the avoidance manoeuvre is displayed. However, several challenges and safety-related issues were identified that still need to be resolved. Three of them were due to display-related issues, and one was due to a system issue. As an example of a display-related issue, an overlap of the aircraft identification with the PPC honeycombs was observed, which rendered the identification unreadable. Such a label overlap is essentially uncritical in a simulation environment; however, it must never occur during actual operations. These issues will be re-evaluated in a safety assessment of the operational procedure.

We conclude that the validation of the operational procedures for the trial operation was only partially achieved and that the workload of the air traffic controller increased not only slightly. Therefore, essential prerequisites for a future operational trial operation are not yet in place. Further efforts are needed to make the procedure for avoiding persistent contrails feasible.

4.3.3 Estimating climate effects in Real-Time Simulation

The experiments of the real-time simulation have not only been used to assess the effect of eco-efficient flying on procedures at ATC and the resulting workload of the controllers. Additionally, the CO_2 and non-CO_2 climate effects of the involved flight deviations have been estimated in an effort to get an indication on the climate-success of the reroutings. Climate effects of the trajectories from the simulation were estimated post-flight, and the mitigation potential of contrail avoidance in the real-time simulation was quantified. While the real-time simulation needed only to consider the flight parts that crossed the EGB Ost, the assessment of trajectory performance and climate effects required consideration of complete trajectories from departure airport to destination airport, in order to accurately estimate changes in aircraft mass and fuel consumption. Based on the flight track data, the Trajectory Calculation Module (TCM, Linke, 2016) has been used. This module calculates 4D trajectories based on predefined aircraft performance parameters. The corresponding emission quantities are estimated using correlation methods

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(BFFM2 (Boeing Fuel Flow Method), DuBois and Paynter, 2006; see also Zengerling et al., 2022). The PPC areas used in the real-time simulation are based on actual weather conditions. For these days, forecast weather data from DWD (Clima-1) and historical ECMWF-ERA5 (European Centre for Medium-Range Weather Forecasts – ReAnalysis 5) are used to estimate the respective climate effect using the aCCF (algorithmic Climate Change Functions, Dietmüller et al., 2023). The tested situation is in principle similar to the one shown in Figure 12; of the many trajectories that cross the PPC=1 areas, not all could be diverted into a PPC=0 area.

Figure 13 shows bar charts for climate effect reductions in the F-ATR100 metric, comparing the climate effects from emissions of the reference and the PPC avoidance scenario. The x-axis of the charts is scaled in Kelvin (K) and quantifies the temperature change, while the y-axis lists the emissions components considered.

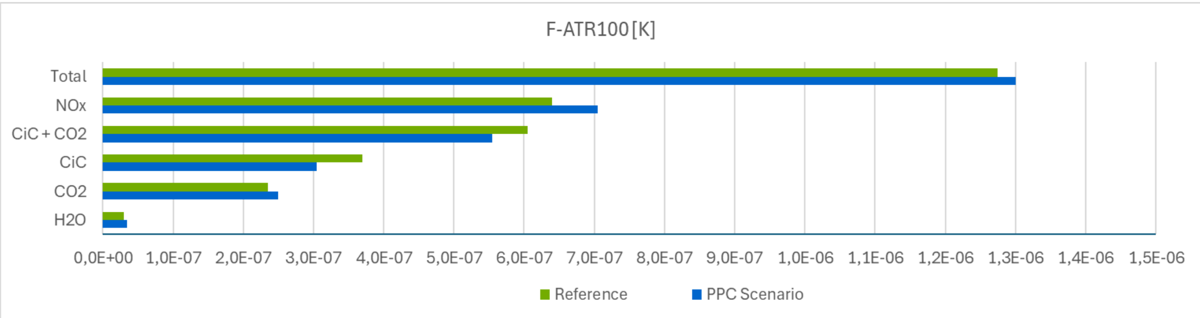

Figure 13: Comparison of the estimates of the reference and PPC scenario in terms of the climate metric F-ATR100.

Beyond the experimental nature of climate response tools, aCCFs of NO_x in their current version are not valid at altitudes below the pressure level of 400 hPa. In effect, NO_x aCCFs at these low altitudes deliver too large values. In the present experiment these values were set to zero for to avoid strong overestimation, note however, that the total quantities are slightly underestimated thereby. Estimates in Figure 13 show that the PPC avoidance scenario yields a reduction of CiC climate response in terms of F-ATR100 (by almost 18% compared with the component response in the reference scenario), which is, however, overcompensated in the total climate response due to increases of the NO_x and CO_2 contributions compared with the reference scenario. Overall, the PPC avoidance scenario yields an increase of total climate response of about 2%. If only looking at the combined CiC and CO_2 component effects, a reduction of nearly 4% is found for the PPC scenario compared to the total response of the reference scenario.

These estimates give indication that a reduction of CiC climate response due to the avoidance of contrail formation areas could partially be compensated or even overcompensated by an increase of CO_2 and other non-CO_2 climate responses. This indicative result clearly demonstrates that the inclusion of all component effects of air traffic is essential for rerouting planning and decisions. Compensating component effects (trade-offs) as well as the influence of short- and long-term climate metrics determine the overall result.

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4.5 Tests of the new contrail detection algorithm

Table 3: Probability of detection (POD, also called Recall) and Precision (1- FPR; FPR = false positive rate) for the three contrail detection algorithm versions mentioned in the text.

BTD used	POD	1-FPR
BTD(10.8-12.0)	0.2547	0.222
BTD(8.7-12.0)	0.3694	0.1183
BTD(10.8-12.0) & BTD(8.7-12.0)	0.4763	0.1071

The contrail detection algorithm (CDA) with various channel combinations has been evaluated against a set of 89 images of 256 x 256 pixel size with different numbers of contrails. All images have been manually labelled and serve as a reference for the determination of Probability of Detection (POD, Recall) and Precision (see Table 3). In general, for MSG/SEVIRI, Recall and Precision are relatively low. The original BTD(10.8-12.0) version shows the lowest Recall but the highest Precision, i.e. the lowest false alarm rate (FAR). The CDA with the second BTD combination – BTD(8.7-12.0) – has a large Recall but an even lower Precision. The CDA version that uses a pair of BTDs has the largest Recall but also a low Precision similar to BTD(8.7-12.0). A higher POD is essential for contrail detection in contrail avoidance experiments, but higher FARs are of course detrimental and must be considered in the detailed success evaluation of avoidance experiments.

5. Discussion

5.1 Overall progress toward eco-efficient flying

This concept paper presents an integrated collaboration workflow for climate-optimized flight planning which combines numerical weather prediction with climate response modelling, in order to inform the trajectory optimization process. The subsequent steps in the workflow comprise planning of eco-efficient trajectories which are made available to dispatch, completed by pre-flight and in-flight optimization, which can then be applied in operations while also exploring alternative ATC procedures. Modifications of the individual components as investigated by D-KULT are described systematically, subsequently demonstrating advancement and connection to state-of-the-art methodologies, available data products and existing interfaces that have been established.

More specifically, D-KULT achieved significant steps toward operational eco-efficient flying:

- The German Weather Service (DWD) is able to provide data including climate sensitive regions, using the output of regular weather forecasts to additionally compute algorithmic climate change functions and predict the formation of persistent contrails.
- LH Systems and PACE extended their flight planning/optimization software to use this climate information and compute eco-efficient trajectories.

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- DFS developed first methods and ideas to display climate sensitive regions on controller radar screens for simulation purposes.
- The legacy contrail detection algorithm has been extended for application to data from geostationary satellites for the evaluation of contrail avoidance experiments.
- D-KULT has accomplished the practical implementation of eco-efficient flights in real flight operations in an interdisciplinary collaboration involving all key stakeholders across the decision-making chain. The complete information chain has been established and successfully tested for the first time.

Despite this progress, the technical realisation and scientific background are not mature and robust yet, making adjustments necessary. Several key lessons emerged during the execution of the project. In the following we describe remaining challenges (along the information chain) that still need to be solved before flying eco-efficient flight trajectories can be regarded as a mature approach for real operation of flight planning and execution.

5.2 Meteorological data and predictability

Cirrus, contrails, upper-tropospheric humidity, and ice supersaturation were never in the focus of numerical weather prediction models. Improvement brings the foreseen operational introduction of the 2-moment cloud microphysics ICON scheme at DWD, which was initiated and tested as an experimental feature in D-KULT. Additional aircraft humidity sensors measuring at flight levels and used for assimilation are also expected to improve humidity forecasts (outside the scope of D-KULT). The usage of ensemble prediction systems can increase the forecast skill of PPC regions. And the predicted spread of the ensemble provides a predictability estimate and allows a quantification of uncertainty of the PPC prediction (see Figure 8b, and Hanst et al. 2025).

5.3 Uncertainties in climate response modelling (aCCFs, CoCiP, pycontrails)

As aCCFs are expectation values, residual uncertainties are inevitable, which is the price for an efficient, practical tool. So far, aCCFs exist only as prototypes and are limited to certain weather conditions, geographic scope and altitude range. An extension of their coverage across regions and seasons would require new calculations of CCFs with climate-chemistry models. The uncertainties of aCCFs arise from atmospheric model biases (Peter et al., 2025), statistical methods, assumptions in training datasets (e.g. contrail lifetimes), aircraft type and the algorithms themselves. Despite the uncertainties, the viability of O_3-aCCFs in reducing ozone climate response was demonstrated in comparison to detailed atmospheric chemistry-climate model simulations (Yin et al. (2023). Furthermore, a general agreement of absolute quantities and gradients of climate responses, but reduced variance of aCCFs compared to detailed chemistry-climate model simulations was found (Frömming et al., 2026, in prep.).

CoCiP and pycontrails are based on simplifying assumptions as well (Schumann 2012, Engberg et al. 2025; Akhtar Martínez et al. 2025) and their radiation calculation is based on regression (Schumann et al., 2012), thus yielding expectation values.

Differences in modelling tools and their application further complicates the comparison between the various Clima-X datasets. The modelling tools were compared in detail within another European project and results will be described there (Dietmüller et al., 2026, in prep.).

5.4 Sensitivity of climate benefits and trade-offs

The consideration of opposing climate effects was partially addressed in simulations in the study by Teoh et al. (2020), but these must be verified through actual flight trials. In our analysis we decided not to compare radiative forcing values, but rather the temperature reduction (over various time horizons) as has been evaluated in a sensitivity study applying a set of various physical climate metrics (Matthes et al., 2020). Furthermore, we consider necessary to evaluate climate effects from various non-CO_2 effects, comprising climate effects from contrails and NO_x emissions. Sensitivity studies evaluating individual climate effect components considering both long-term and short-term climate metrics and alternative contrail efficacies (Bickel et al., 2025) were carried out for the PPC avoidance flights. Avoiding PPC areas reduces the contrail climate response which is partially compensated by an increase of the CO_2 climate response due to enhanced fuel use during the rerouting. The combined effects (CiC and CO_2) yield a reduction of climate response in terms of F-ATR100, which may be even more beneficial on shorter time scales (20 years), but the compensation by counteracting effects from e.g. CO_2 and NO_x increases and potentially overcompensates the reduction on the long-term (as shown for ATR-100), which may result in an overall climate warming. Since uncertainties in the input data were not assessed, a realistic error margin could cross the zero line, making a beneficial overall outcome uncertain. A methodology integrating prevailing uncertainties has been suggested in Matthes et al. (2020) in order to explore robustness of mitigation gains. For future evaluations the analysis framework must be improved and uncertainties should be fully assessed.

5.5 Satellite-based contrail detection

For the evaluation of the contrail avoidance flights dedicated tools are necessary to bridge the time between contrail formation and contrail appearance in the satellite image. High detection efficiencies and low false alarms are needed for this task which remains challenging, due to the moderate resolution of the Meteosat Second Generation satellite instruments. An evident improvement is provided by the newly launched Meteosat Third Generation.

5.6 Air traffic controller workload, safety and air space capacity

Real-time simulations on tactical contrail avoidance revealed that controller workload increases significantly, which is related to grave flight capacity reduction. In combination with the identified safety-relevant issues, key prerequisites for launching a future operational trial have not yet been met. Further developments to adequately visualize PPC areas on radar displays of ATC-controllers are necessary. Reduction of flight capacity is a major constraint for the whole ATM network in Europe.

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5.7 Automation and data processing for operational use

It was demonstrated in an experimental environment, that the components of the D-KULT collaboration chain work together in principle. For operational use, the generation of large amounts of weather and climate data, processing and providing them in time and their integration into flight planning tools must be automated to meet existing flight planning and ATM process timelines.

5.8 Need for standardized approach and aviation-wide strategy

For air traffic management, a standardized calculation approach is of central importance to clearly identify climate-sensitive regions in the heavily frequented German airspace and evaluate avoidance strategies - taking into consideration their overall impact on airspace capacity. It should be noted that reduction of flight capacity is currently a blocking issue for the whole ATM network in Europe. Another crucial factor for successful implementation of eco-efficient flying is the development of a clear, aviation-wide strategy for dealing with *contrail prevention*. This requires close and coordinated collaboration among all relevant stakeholders in the aviation industry. In addition, continued fundamental research remains essential. For air traffic control, a standardized and consolidated calculation of PPC areas is of central importance in this context to clearly identify where climate-relevant areas are forming in the highly frequented German/Middle-Europe airspace.

5.9 Need for robust uncertainty indicators and decision support

Regarding an efficient decision support, it is recommended to make available methods that represent and integrate prevailing uncertainties mathematically and statistically as part of the overall decision-making framework. Despite the uncertainties, eventually given values of PPC and climate sensitivity in the Clima-X data sets have to be accepted and processed in flight route optimisation software. To support robust decisions in operational processes, data should be accompanied by an uncertainty indicator. Concepts, determining which data support robust operational decisions are required. Comprehensive studies with large sample sizes (flights) are necessary to identify statistically significant decision thresholds. The recommendations mentioned are to be specifically pursued in a potential follow-up project initiative, with the involvement of several of the D-KULT partners.

6. Concluding remarks

D-KULT has made the first steps from purely theoretical (numerical) trials of eco-efficient flights to eco-efficient flight planning in practice, that is, in daily operations, involving actors along the whole chain of decision-making. Such a wide collaboration over different disciplines is challenging but necessary to make such a complex objective like eco-efficient flight feasible. The highly-interdisciplinary integrated collaboration workflow has been established, by expanding state-of-the-art procedure, data and interface, and individual components have been tested for the first time. Open research questions, remaining challenges, and operational problems have been identified and will need to be addressed in future collaboration.

These open research topics and challenges to be solved are inter alia:

- The predictions of the 2-moment cloud microphysics scheme have been tested using radiosonde data which are lacking over many regions (e.g. the ocean). More data sources of relative humidity in flight levels are necessary not only for testing but in particular for assimilation into NWP models. The 2-moment scheme should become operational; however, the overall calculation times should not be higher than today since the weather and climate response data need to be delivered in time.
- New climate model simulations are necessary to widen the applicability-range of the aCCFs.
- All response tools (not only the two used in D-KULT) need further testing and tool comparison campaigns should be performed.
- The climate effect estimates change if different input weather data are used, also being influenced by the model capabilities to represent ice supersaturation. Inconsistencies are currently in the system, for instance if the route optimization used wind forecast data and the data on climate response functions are based on different NWP models.
- Uncertainty quantification and characterisation should regularly be performed and an uncertainty metric should be included in the distributed Clima-X data. The ensemble forecast system can be exploited to quantify the meteorological uncertainty, and subsequently define and formulate an uncertainty metric.
- Such a meteorological uncertainty metric can be used in a later rerouting decision. Overall, a comprehensive decision framework should be formulated which comprises a risk analysis and explores robustness of mitigation gains.
- The expanded flight routing software tools, e.g. Lido and FPO, exist solely in prototype version.
- The trial flights were only possible with a high level of manual work, both in flight planning and execution. An operational implementation of eco-efficient flight needs a complete automation of the process at all steps along the information chain.
- The trial flight involved only five German airlines, which implies that if contrails were avoided only partly, since other airlines did not avoid contrails. However, to avoid contrails completely in an extended PPC=1 area can cause congestion in a heavily flown airspace with other knock-on effects, e.g. increased work-load for air traffic controllers which may be a safety problem.

As the D-KULT project is now at its end, these (and other) research needs and technical developments are topics for the near future. These steps need to be taken successfully in order to make eco-efficient flights the routine.

Code, data, or code and data availability

This project is partly based on software codes that are owned by commercial companies (e.g. Lido, FPO). These codes are not publicly available. To work with the NWP code ICON, please contact Deutscher Wetterdienst. The pycontrail realisation of CoCiP is publicly available at Zenodo (see reference Shapiro et al.). Data produced by the German weather service are stored at the German Climate Data Centre. These data are available for research on written request to the coordinator, Dr. Sigrun Matthes.

Supplement link

There is no supplement.

Team list

The author list is complete.

Author contributions

All authors contributed text and figures that refer to their respective fields. SM, CF and KG produced the final draft from the individual contributions, SH checked the references. The research concept was developed during regular project meetings, involving all authors.

Competing interests

At least one of the (co-)authors is a member of the editorial board of Journal of Environmentally Compatible Air Transport System.

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