FlyATM4E

Flying Air Traffic Management for the benefit of environment and climate

SESAR Exploratory Research Projekts

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EUROPEAN PARTNERSHIP

DLR

FlyATM4E

Co-funded by the European Union

FlyATM4E Research questions

SESAR 2020 Exploratory Research Project
Duration: Jun 2020 – Nov 2022

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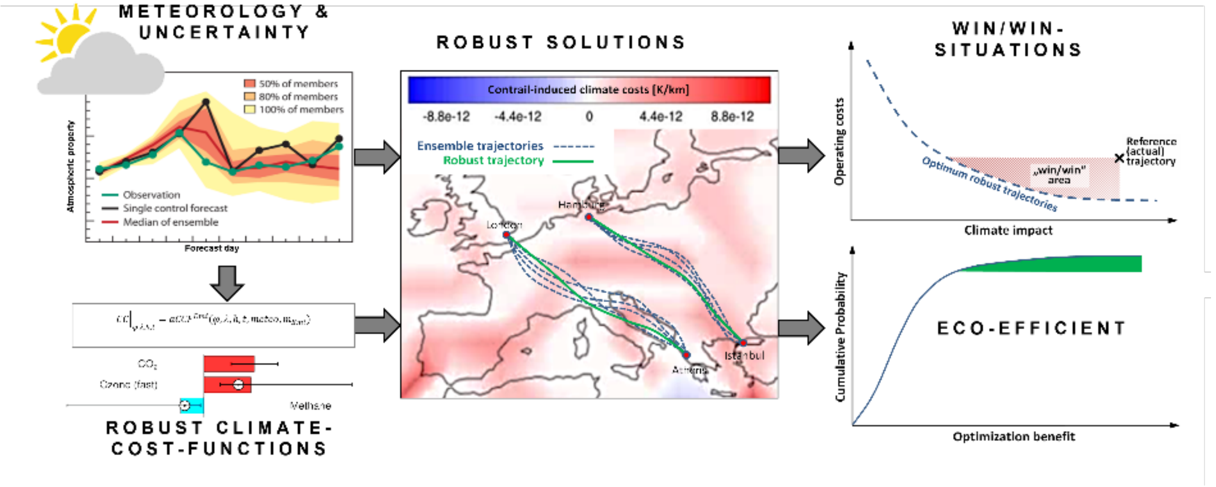
FlyATM4E

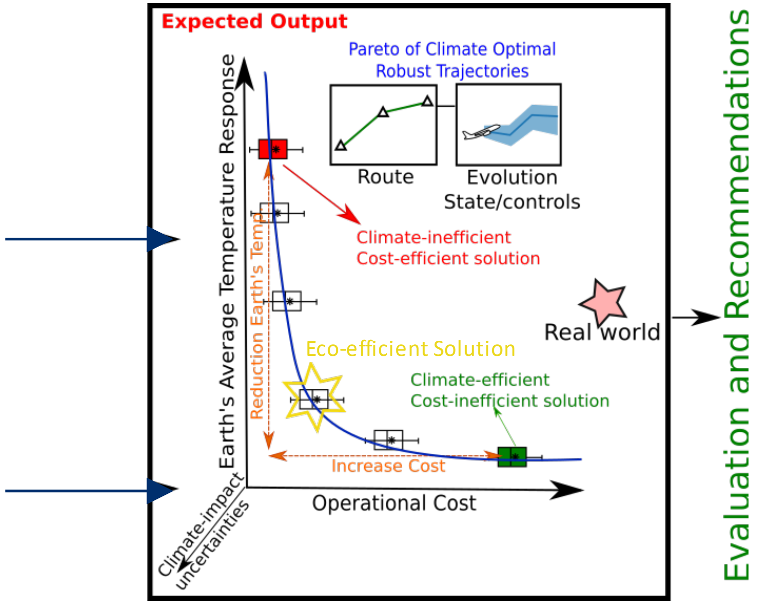
- How can **climate-optimized trajectories** reduce the overall climate effects and what is needed for ATM?
  - **FlyATM4E project objectives**
- How does aviation have an **influence on climate**?
  - **Physical and chemical basis of aviation climate effects**
- How can **information on climate effects** be handed over to air space users?
  - **Sol-FlyATM4E-01 Enhanced situational awareness on climate effects**
- How **can robust alternative climate-optimized** trajectories be identified under uncertainty conditions?
  - **Sol-FlyATM4E-02 Robust climate optimized trajectories for European Airspace**
- How can climate optimized trajectories be **implemented** in the overall air transport system?
  - **Thoughts on implementation of climate-optimized trajectories**

Partners: DLR, TU Delft, TU Hamburg, UC3M Madrid

Project Goals and Objectives
Project Objective (1/2)

FlyATM4E developed a concept to identify climate-optimised aircraft trajectories which enable a robust and eco-efficient reduction in aviation's climate effect.





Climate optimization took into account CO_2 and non-CO_2 effects, such as contrails and contrail-cirrus, water vapour, NO_x and particulate emissions.

Project Goals and Objectives
Project Objective (2/2)

- FlyATM4E **identified those weather situations** and aircraft trajectories, which lead to a robust climate effect reduction despite uncertainties in atmospheric science that can be characterised by ensemble probabilistic forecasts. This improves the assessment of aviation's climate effect (O1, O2).

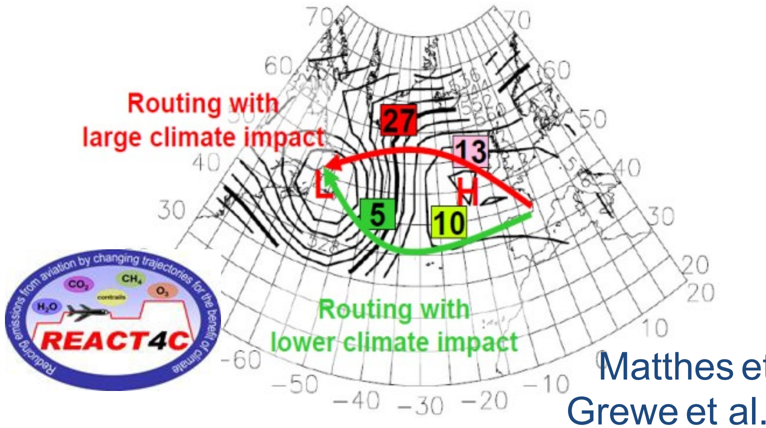
- FlyATM4E further **identified those situations** where there is a large potential to reduce the climate effects with only little or even no cost changes (Eco-efficient solutions) and those situations where both, climate effects and costs can be reduced ("Win-Win") (O3).

- As a summary, FlyATM4E **formulated recommendations how to implement** these strategies in meteorological (MET) products and enable not only the understanding of ATM possibilities to reduce aviation's climate effects, but moreover how to implement such eco-efficient routing (O4).

FlyATM4E Climate-optimization of aircraft trajectories

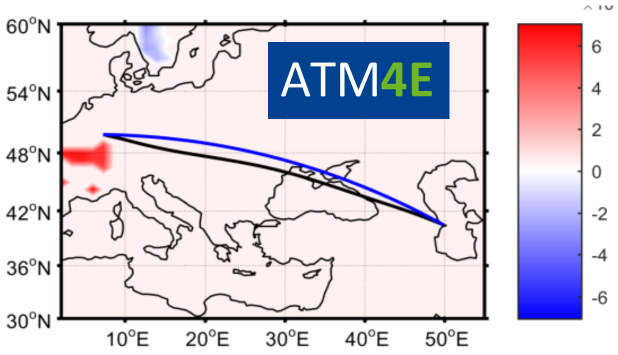
- Aviation is concerned by reducing climate effect of its operations. **Aviation climate effect** is caused by CO_2 and non-CO_2 emissions, comprising effects of **contrails**, **nitrogen oxides** impacting ozone and methane, **water vapour**, and **aerosol effects**.
- **Non-CO_2 climate effects** show a strong spatial and temporal variation, which can be exploited when identifying **alternative trajectories**, by **avoiding those regions** where emissions have a large effect.
- However, during flight planning currently emission information is available, but no **environmental effect information** linked to the emitted amount is available along the trajectory.

Concept: Feasibility study



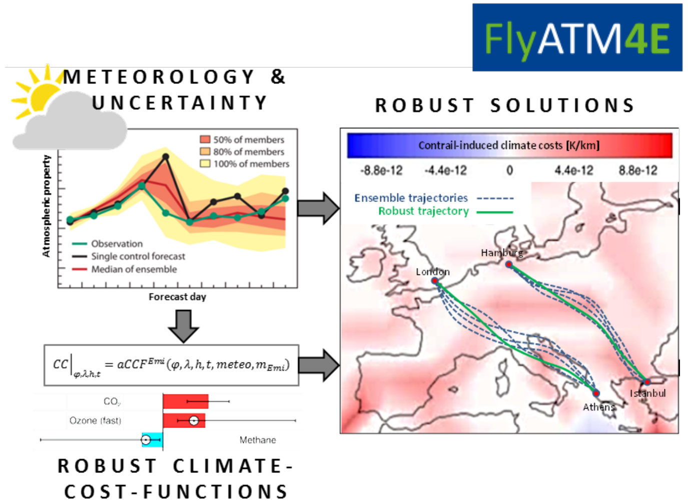
Matthes et al., 2012
Grewe et al., 2014a,b

European Application: Case study



Matthes et al., 2020

Uncertainties and robustness



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The FlyATM4E-Solution-01

The merged aCCF concept and the associated CLIMaCCF python library: paving the way towards aviation-induced climate effect as a MET service

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Algorithmic Climate Change Functions (aCCFs)

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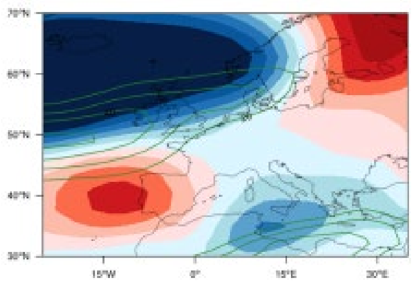
- Prototype algorithmic climate change functions (aCCFs) non-CO_2 effects give **climate effect of aviation emissions at a specific location and time** (in terms of average temperature response ATR) (Yin et al., 2023)
- aCCFs provided for contrail-cirrus, water vapour, NO_x-induced changes of ozone and methane. First consistent set: **aCCF-V1.0** (Dietmüller et al., 2023), **aCCF-V1.0A** (Matthes et al., 2023)
- aCCFs are calculated from local meteorological parameters (e.g. temperature, geopotential at emission location from numerical weather prediction data for trajectory optimisation.

METEO, ERA5

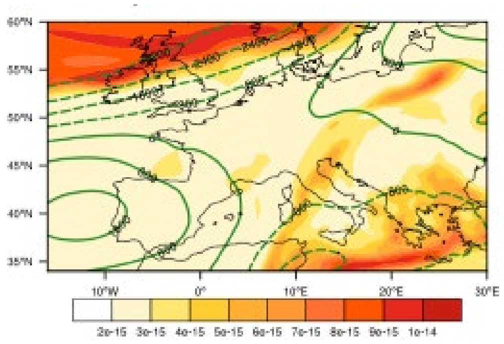
geopotential



aCCFs

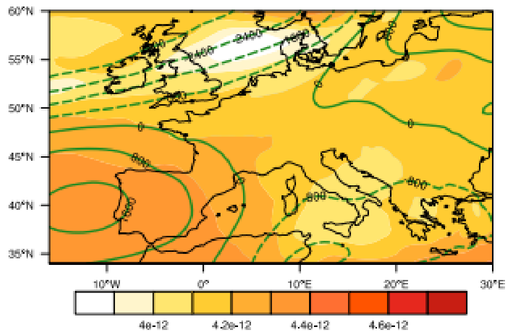
mathematical formulas -> computational efficient

Water vapour aCCF



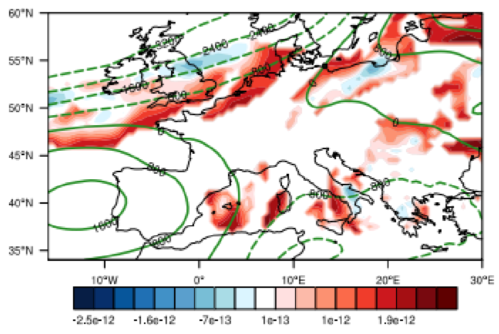
[K/kg(fuel)]

NO_x-induced aCCF



[K/kg(NO2)]

Contrail (daytime) aCCF



[K/km(contrail)]

- Water vapour and NO_x induced aCCF is positive (warming)
- Contrail (daytime) aCCF warming/cooling effect in areas where contrails can form

aCCFs characterize sensitivity of atmosphere to aviation emissions at specific location & time

⇒ **MET product for climate-optimized trajectory planning**

Characterization of prevailing uncertainties when providing climate change functions (CCFs)

Source of uncertainty	Origin of uncertainty
Meteorological Forecast	
Quality of meteorological forecast	Weather forecast data contains deviation from real world situations measured by quality of the forecast and its skill.
Calculation of climate effects and impact	
Representation of atmospheric processes	Chemistry scheme (e.g. O_3 production), cloud parametrization, horizontal and vertical resolution.
Change in GHG concentration/contrails	Background (e.g. temperature bias in EMAC).
Radiative forcing (RF)	Estimate of RF depends on assumption of linearity for radiative transfer calculations.
Temperature calculation	Temperature change calculation depends on assumptions on efficacy and temporal evolution of emissions/RF.
Physical climate metric	Climate metric has to be appropriate for the targeted climate objective but should still allow some variation with respect to assumptions on background emission scenario/model, emissions evolution (pulse/sustained/future scenario), climate indicator (e.g. averaged temperature response), and time horizon (e.g. ATR20).
Development of Algorithms to represent CCFs (=aCCFs)	
Development of algorithms in aCCFs	Due to the fitting of CCF data to meteorology at the location of emission, imperfections in the relationships are identified.
Emission calculation in emission model	
Emission index/conversion merged aCCFs	Assumptions in emission model.

Table from FlyATM4E: List of sources of uncertainties for individual aCCFs and for their associated calculations on climate effect.

FlyATM4E has developed a concept to **characterize prevailing uncertainties** and introduced **mathematical concepts** on how to integrate identified uncertainties in the overall climate effects assessment.

This is a prerequisite in order to **characterize robustness** of alternative **climate-optimized aircraft** trajectories.

This methodology has been applied in **case studies** (summer & winter, 2018) for aircraft movements in the European Airspace where **mitigation potentials due to climate-optimized routing** have been identified (Matthes et al., 2023) and their associated **uncertainty ranges** have been quantified.

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ACACIA
Aeronautics Horizon2020

To **improve scientific understanding** of those impacts that have the largest uncertainty, in particular, the indirect effect of aviation soot and aerosol on clouds.

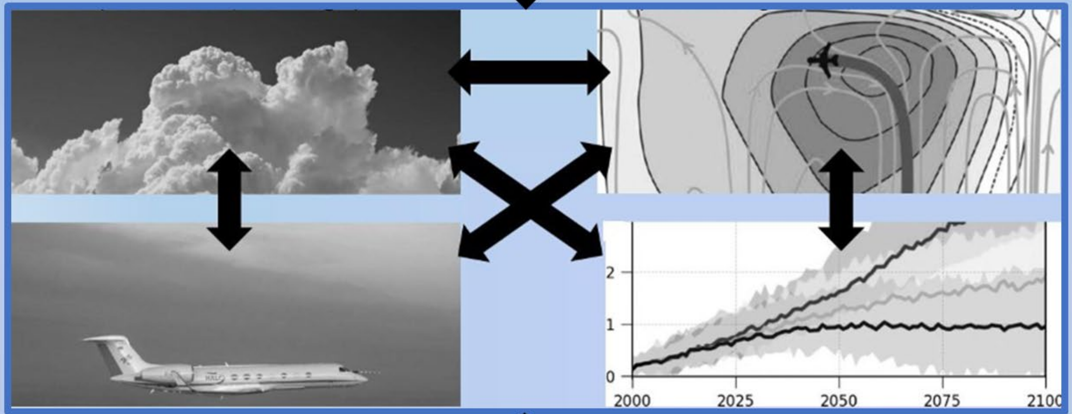
To put all **aviation effects on a common scale** that allows providing an updated climate impact assessment. Uncertainties are treated in a transparent way, trade-offs between different mitigation strategies are evaluated.

Management

Science

Advancing our knowledge on indirect aviation effects

Estimation aviation non-CO_2 effects and uncertainties



Concept of measurement campaigns

Impact of future aviation scenarios / developments

Exploitation and dissemination

To identify **needs for international measurement campaigns** to constrain numerical models and theories with data and to formulate design options for such campaigns.

Recap of goals

To provide the knowledge basis and **strategic guidance** for future implementation of mitigation options, giving robust recommendations for no-regret strategies for achieving reduced climate impact of aviation.

DLR

This work received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 875036 within the Aeronautics project ACACIA.

FlyATM4E-Solution-02

Aircraft trajectory optimization, climate change, and its associated uncertainties: quantifying the cost of climate mitigation flight operations

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Climate effect mitigation potentials of alternative routings

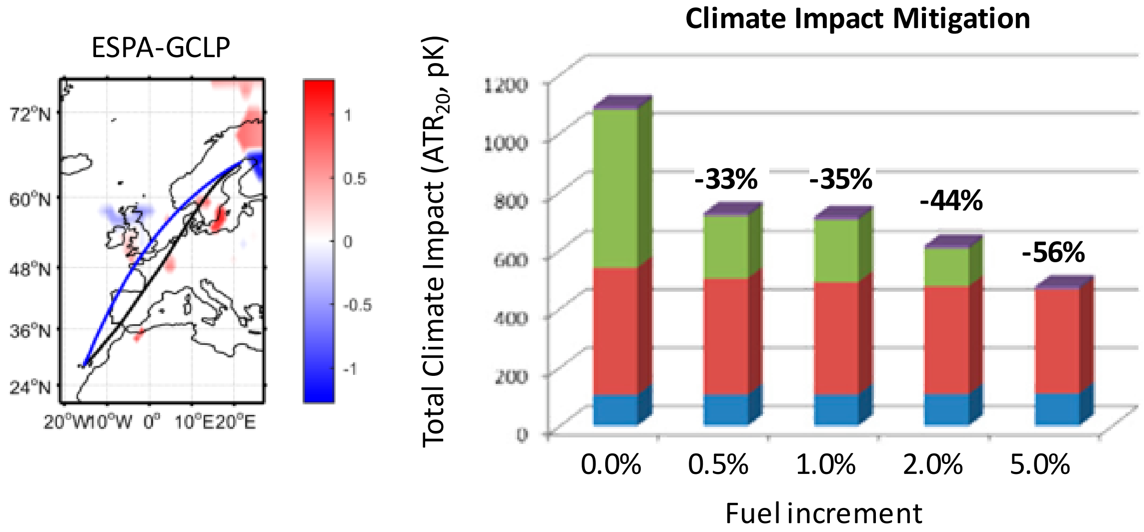
One Day Case Study of European Air Traffic on 18 December 2015

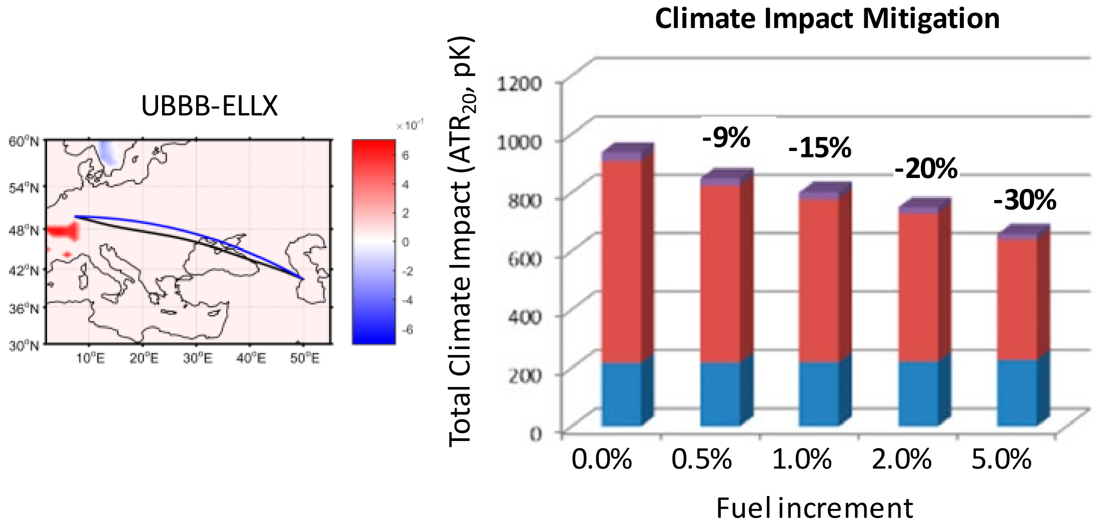
ATM4E

Matthes et al., 2020

Example 1: Lulea – Gran Canaria (ESPA-GCLP)
Contrails-dominated climate effect

Example 2: Baku – Luxembourg (UBBB-ELLX)
NO_x-dominated climate effect (no contrails)





- **Climate-optimized routings can mitigate the total climate effect significantly**
- **The total climate effect of a flight can decrease despite increasing emissions** (e.g. -35% ATR_{20} for +1% fuel increase)
- **Climate-optimized routings might not be cost-optimal** (need for market-based / policy measures)

H_2O
AIC
NO_x
CO_2

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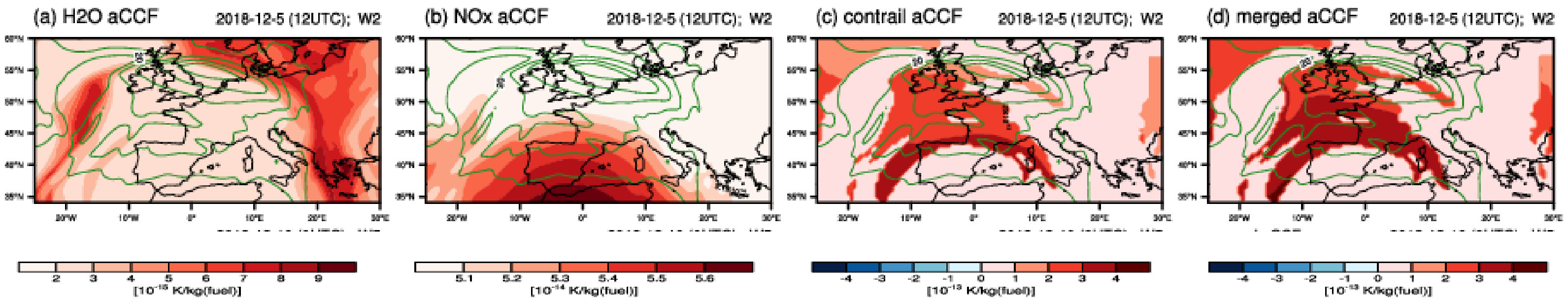
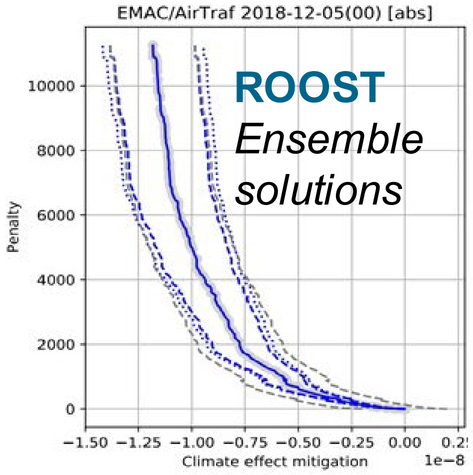
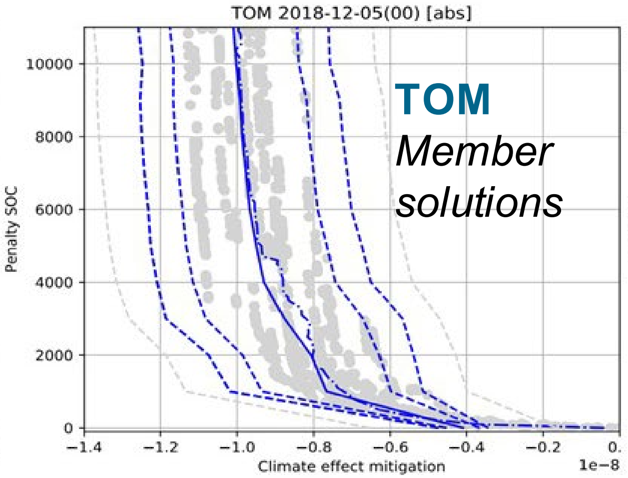
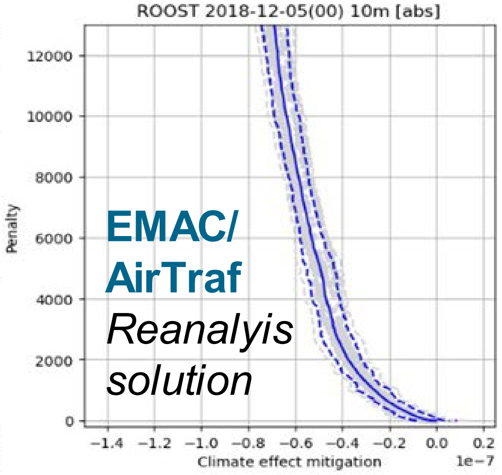
Ensemble forecast: Trajectory optimisation

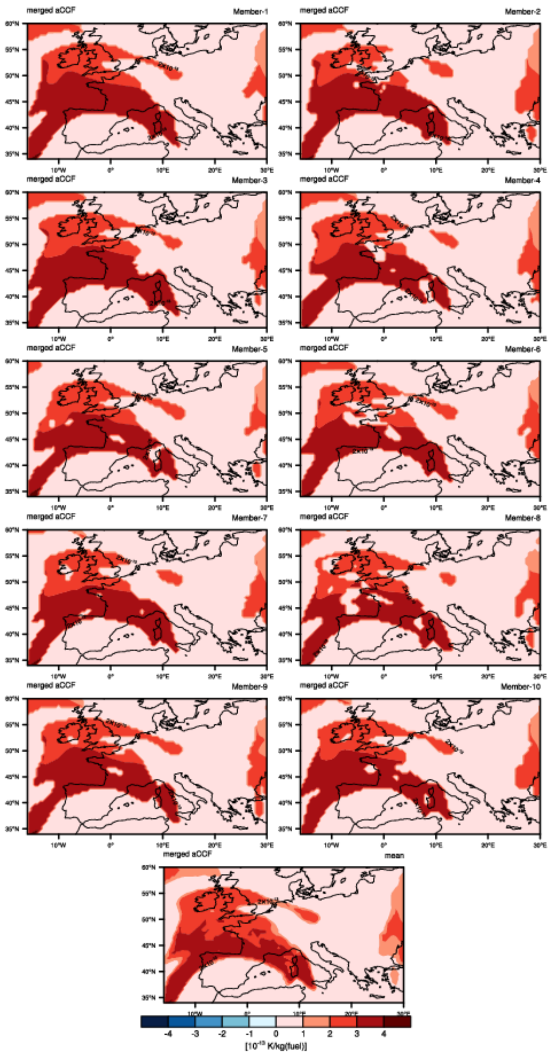


- **Climate effects** estimated with aCCFs
- **Weather** 5 Dec 2018 ECMWF, 10 member ensemble (EPS)









Matthes et al., 2023

- Reduction in climate effect from climate-optimized aircraft trajectory planning
- Top 100 city pairs in **Europe** on 5 December 2018 departing at **midnight**
- **Tools: EMAC/AirTraf, ROOST, TOM**

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Implementation and next steps

Challenge #1

Provision of aCCFs & representation of uncertainties

Challenge #2

Implementation of climate-optimized routing

Challenge #3

Policy measures and incentives

D-KULT PROJECT
LUFO VI-2 (2022-2025)

D-KULT

Gefördert durch:

Bundesministerium für Wirtschaft und Klimaschutz

aufgrund eines Beschlusses des Deutschen Bundestages

Sigrun Matthes (project coordinator) & D-KULT Team

DLR Institute of Atmospheric Physics, Oberpfaffenhofen, Germany

DLR

DLR DFS Deutsche Flugsicherung Deutscher Wetterdienst Wetter und Klima aus einer Hand DWD BOEING TXT PACE Lufthansa Lufthansa Systems AIRBUS BDL DHL EUROCONTROL

Exploring climate-optimized trajectories

State of the art

- **Basic concept of climate-optimized trajectories**
- **aCCF concept as a candidate SESAR enabling solution FlyATM4E**
- **Mitigation potentials in the European Airspace**
- **Evaluation of a MET Service on climate-optimized trajectories (aCCF V1.0A)**

Gefördert durch:

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aufgrund eines Beschlusses des Deutschen Bundestages

D-KULT project

- **NWP data for aviation (WAWFOR from DWD)**
- **New data set in WAWFOR Klima1: Structure and examples on synoptic situations**
- **Novel 2-moment-scheme at DWD**
- **Demonstration of contrail avoidance in German Airspace**
- **Evaluation of mitigation gains from contrail-avoidance and climate optimized trajectories**

- Challenge 1: Which requirements exist for a dedicated MET Service?
- Challenge 2: Can we expand operational procedures in order to demonstrate optimized trajectories?

D-KULT: Technological objectives

- ✈ **Establish a flight planning and flight control system with** expansion of flight guidance in order to **avoid formation of persistent contrails and contrail cirrus;**
- ✈ Establish a **flight planning system for climate-friendly flight trajectories** on the basis of climate change functions (aCCF).
- ✈ **Modification of procedure** for **low-noise approach and departure**.
- ✈ **Demonstration of feasibility of eco-efficient flight trajectories** by comprehensive **simulations** and **application in operations** (**Vavoding persistent contrails and contrail cirrus**)

DLR DFS Deutsche Flugsicherung Deutscher Wetterdienst Wetter und Klima aus einer Hand DWD BOEING TXT PACE Lufthansa Lufthansa Systems AIRBUS BDL DHL EUROCONTROL D-KULT
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Lines of action: Life-trials for contrail avoidance, eco-efficient trajectories und Low-noise-eco-efficient trajectories

Trial Contrail Avoidance ATC	Weather Forecast	ISSR- Forecast	Trial Operations Exercise/ Operations	Analysis / Satellite Evaluation	
Trial Contrail Avoidance Dispatch	Weather Forecast	ISSR- Forecast	Live Trial Dispatch Exercise/ Planning	Analysis / Satellite Evaluation	
Eco-efficient trajectories	Weather Forecast	Multi-crit. Evaluation function → aCCF	Scenarios, Metric, Boundary conditions	Trajectory Optimisation	Ecoefficient trajectories Dispatch (shaddow)
Low-noise eco-efficient trajectories	LNAS Forecasts	Retrofit	Implementation Ecoefficient Trajectories	Design of procedures	

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Climate-optimized trajectories in flight planning – Tasks

Lufthansa

01

- Evaluate weather data formats
- Identify relevant weather parameter & improve RH
- Integrate requirements in operations
- Represent aCCF- and ISSR data and formats

03

- Implement optimisation algorithm
- Define operational boundary conditions and constraints
- Define scenarios on feasibility and economic efficiency
- Define basis for performance analysis

05

- Concept of operations, e.g. communication controler / pilots
- Implementation in Anbindung Standard Operating Procedures (SOP) comprising responsibilities and provision of decision criteria
- Estimate training requirements

02

- Collect airline requirements
- Analyse target values for optimization
- Define evaluation functions and setting of individual weights
- Define new targetfunction

04

- Testing & Evaluating of novel optimizers
- Scenario analysis in terms of feasibilty and economic efficiency by variation of relevant parameters
- Analyse multi-criteria optimized trajectories

DLR, DFS Deutsche Flugsicherung, Deutscher Wetterdienst, Boeing, PACE, Lufthansa, Lufthansa Systems, Airbus, BDL, DHL, Eurocontrol, D-KULT

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THANK YOU!

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