Eco-efficient aircraft trajectories

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DLR
ECATS

FlyATM4E

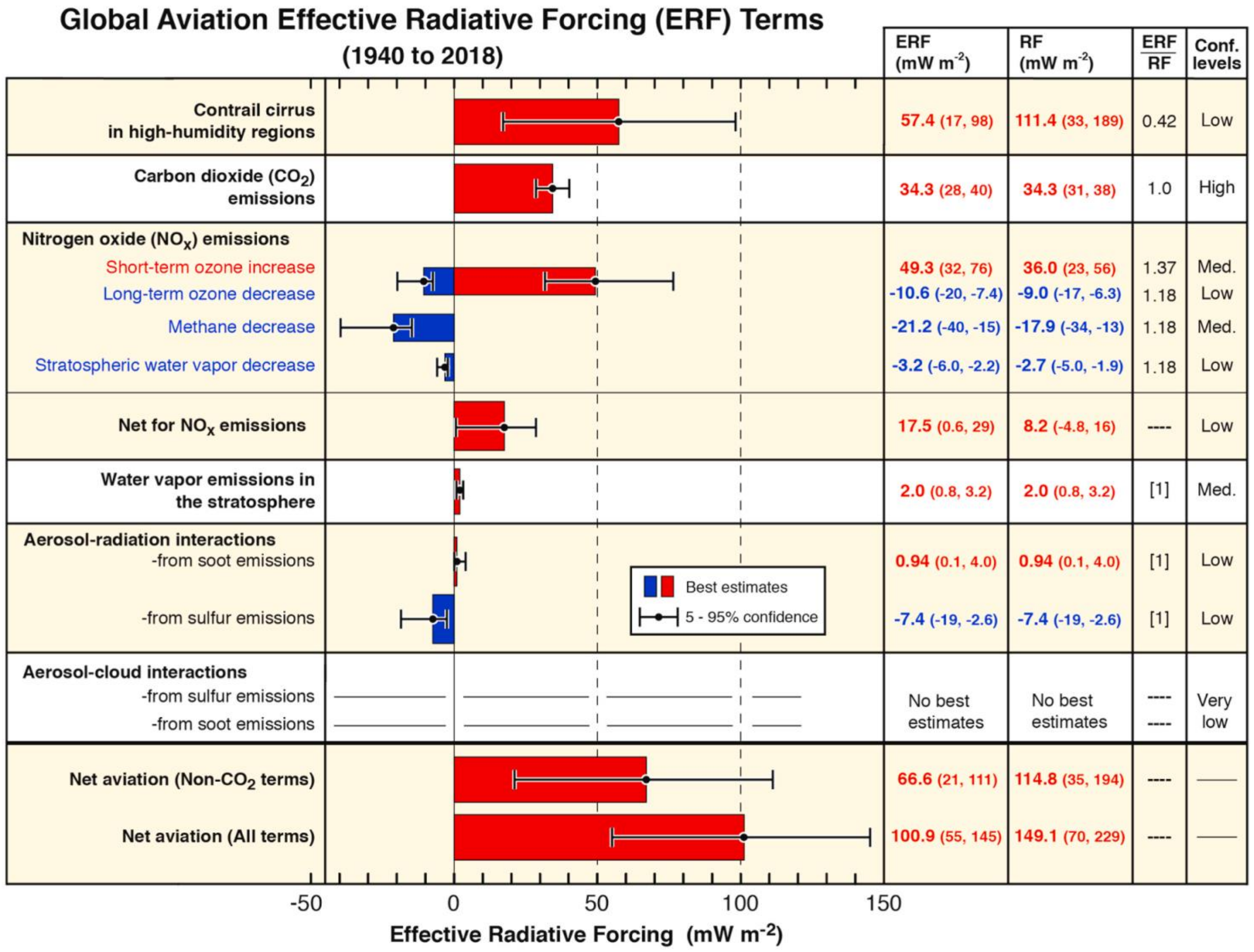
SESAR
JOINT UNDERTAKING

FlyATM4E (SESAR ER)
Mitigating aviation climate impact by climate-optimized aircraft trajectories

SESAR Exploratory Research Project, *Grant No 891317*

Sigrun Matthes
Florian Linke, Feijia Yin, Manuel Soler, Benjamin Lührs, Simone Dietmüller, Patrick Peter et al.
DLR Institute of Atmospheric Physics, Oberpfaffenhofen, Germany
TU Delft, The Netherlands,
TU Hamburg, Germany,
U3CM, Universidad Carlos III Madrid, Spain

Effective radiative forcing (ERF)



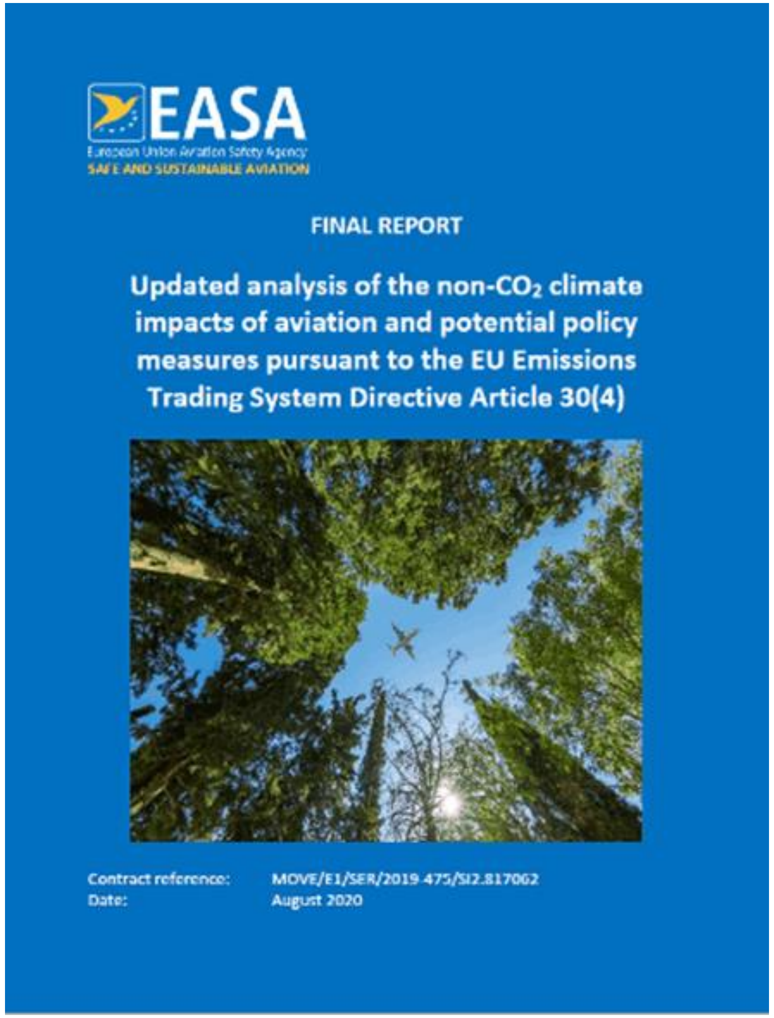
	ERF (mW m^{-2})	RF (mW m^{-2})	ERF / RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions				
-from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
-from sulfur emissions	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	——
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	——

Lee et al., 2021

$$\Delta T = \lambda \text{ ERF}$$

- According to Lee et al. (2021) non-CO_2 effects contribute at least 2/3 to the total aviation ERF.
- Non-CO_2 effects also occur if alternative fuels are used, in particular H_2; changes are expected.
- The magnitude of the non-CO_2 effects depends on location and time of the emissions.

Non-CO_2 effects of aviation: Concepts in Europe



EASA
European Union Aviation Safety Agency
SAFE AND SUSTAINABLE AVIATION

FINAL REPORT

Updated analysis of the non-CO_2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4)

Contract reference: MOVE/E1/SER/2019 475/SI2.817062
Date: August 2020

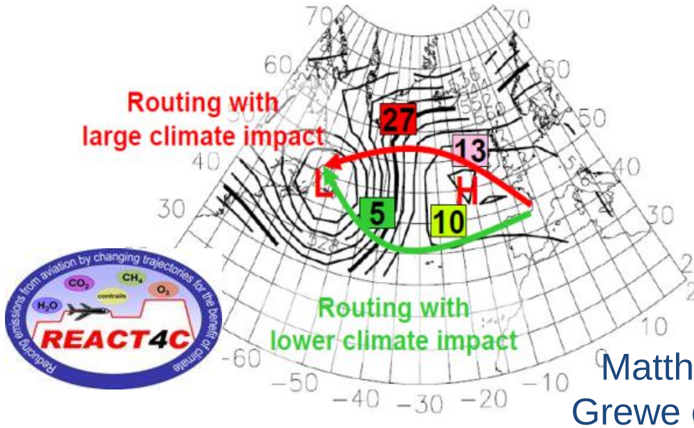
Arrowsmith et al., 2020

Type of Measure		Main non-CO_2 effect(s) addressed by the measure
Financial	1. NO_X charge	NO_X
	2. Inclusion of aircraft NO_X emissions in EU ETS	NO_X
Fuel	3. Reduction in maximum limit of aromatics within fuel specifications	Soot particulates and contrail-cirrus
	4. Mandatory use of Sustainable Aviation Fuels (SAF)	Soot particulates and contrail-cirrus
ATM	5. Avoidance of ice-supersaturated areas	Contrail-cirrus
	6. A climate charge	All (NO_X, water vapour, soot, sulphates, contrails)

FlyATM4E Climate-optimization of aircraft trajectories

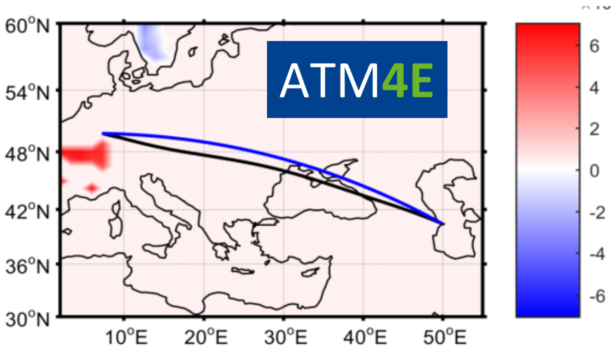
- Aviation is concerned by reducing climate impact of its operations. **Aviation climate impact** is caused by CO_2 and non-CO_2 emissions, comprising impacts of **contrails**, **nitrogen oxides** impacting ozone and methane, **water vapour**, and **aerosol effects**.
- **Non-CO_2 climate impacts** show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

Concept: Feasibility study



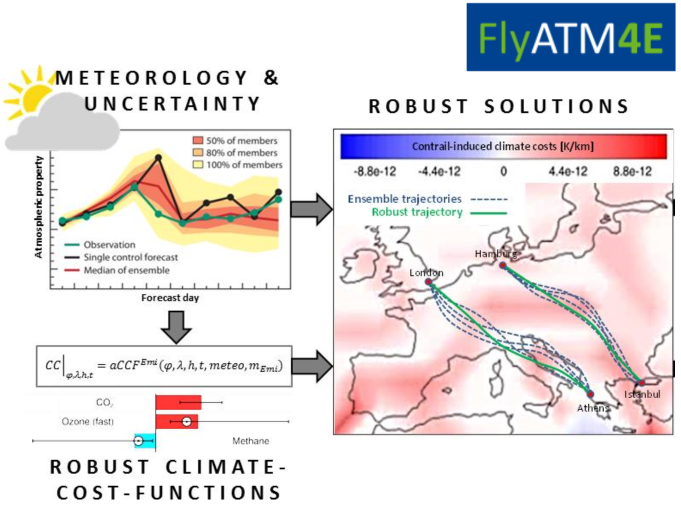
Matthes et al., 2012
Grewe et al., 2014a,b

European Application: Case study



Matthes et al., 2020

Uncertainties and robustness



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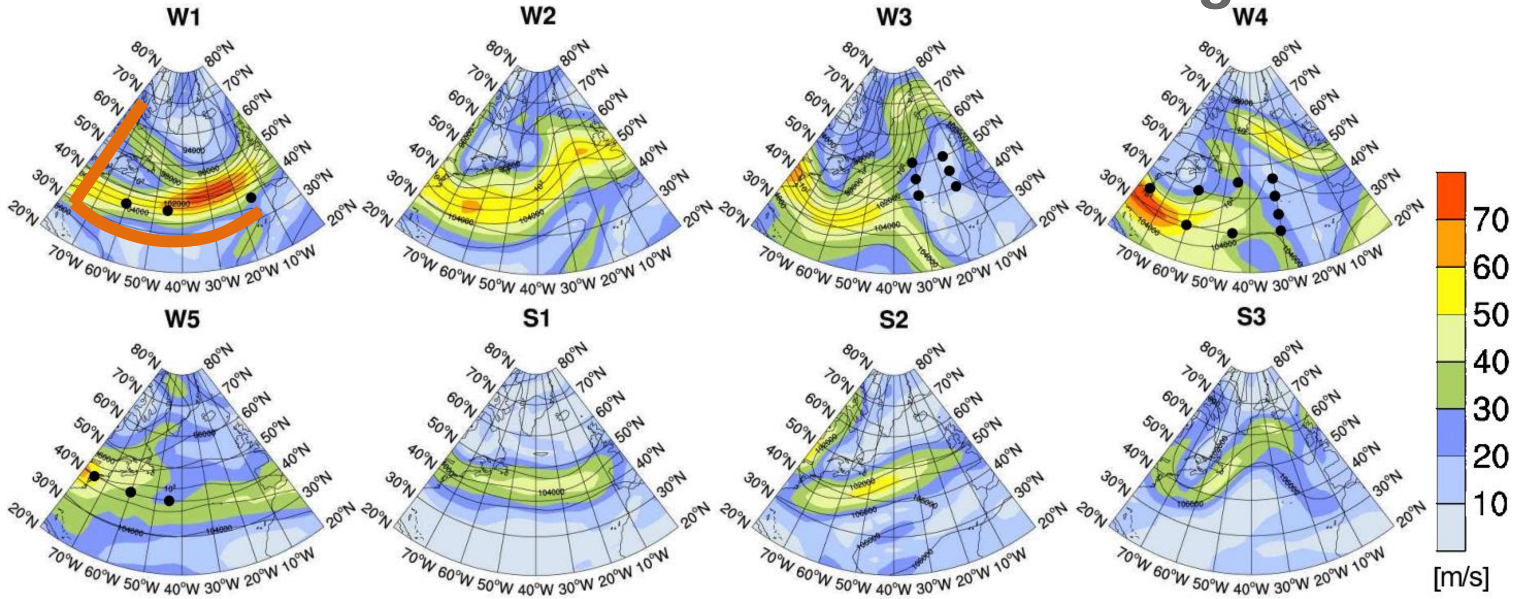
Weather data and Ozone Climate-Change-Functions



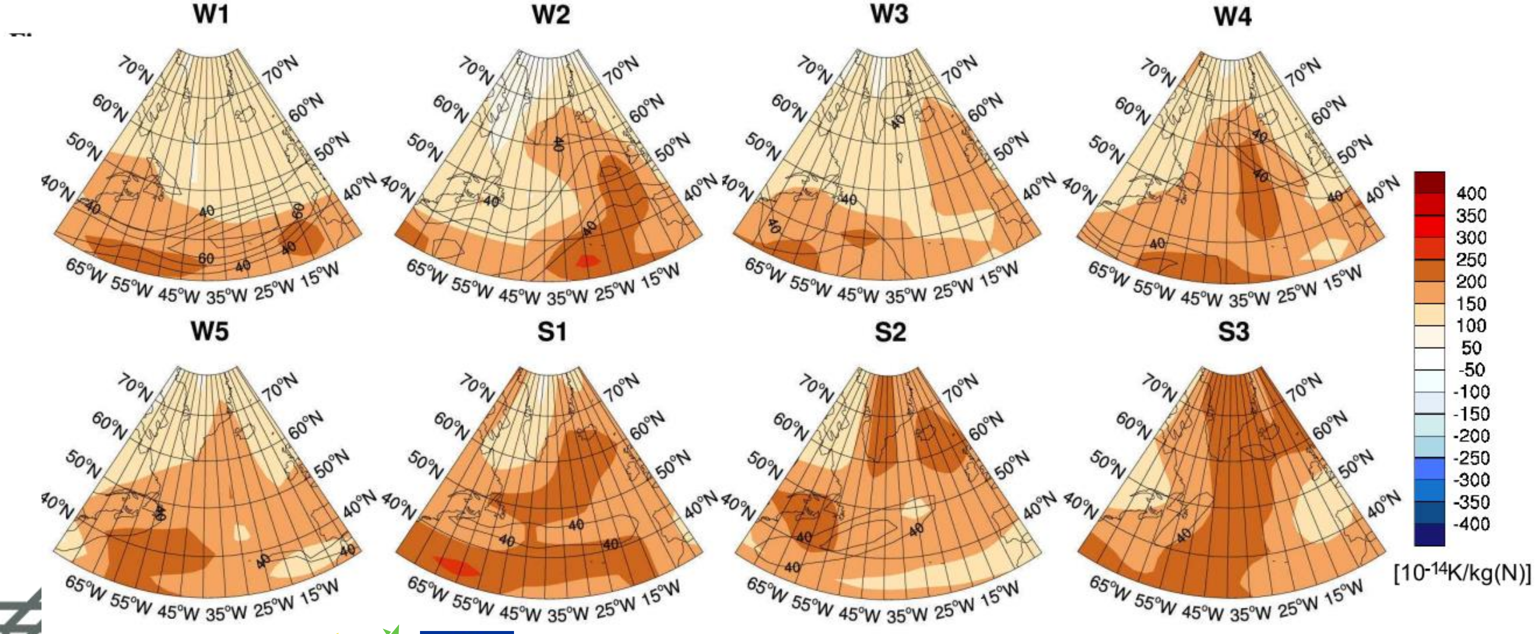
Climatology of aviation weather situations:

Winter W1-W5

Summer S1-S3

University Reading

Irvine et al. 2013



Frömming et al. 2021

Contribution of a local NO_x emission to climate change via ozone formation

Clear relationship between weather and CCFs

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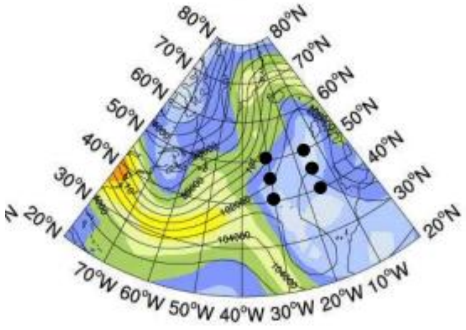
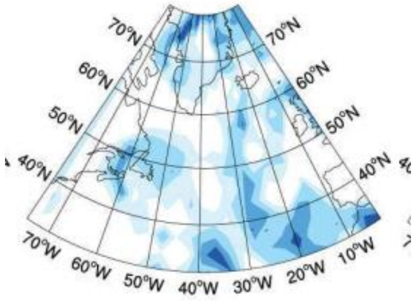
MET Service: Climate Change Functions (CCFs)

respresentative winter
weather situation,
250 hPa

Weather



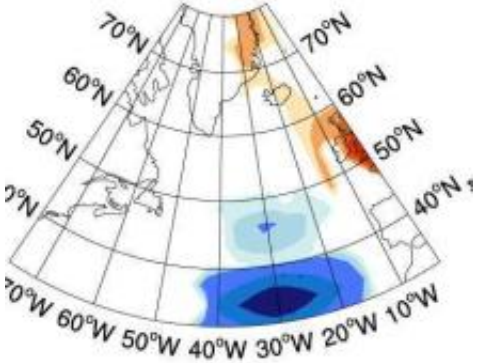
Potential contrail coverage



Frömming et al. 2021

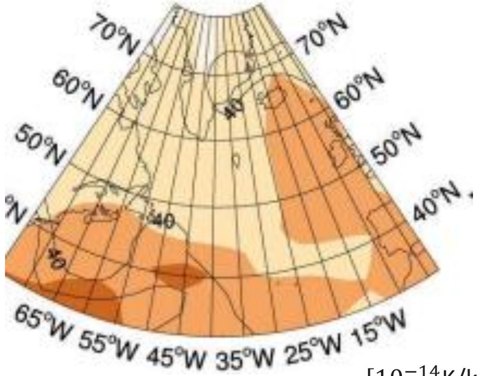
Climate Change Functions = four dimensional functions (space & time)

Contrail CCF



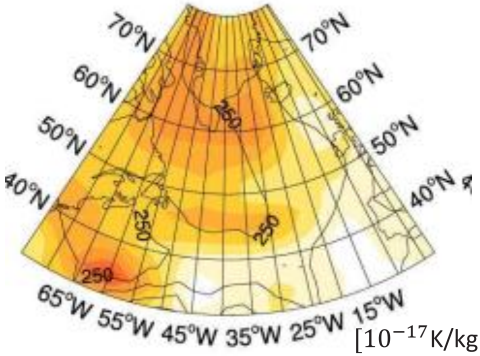
$[10^{-14}\mathrm{K/km(contrail)}]$

Ozone CCF



$[10^{-14}\mathrm{K/kg(N)}]$

Water vapour CCF



$[10^{-17}\mathrm{K/kg(fuel)}]$

- Climate change functions characterize sensitivity of the atmosphere to aviation emissions at specific location (position, altitude, time). ⇒ **MET products for climate-optimized trajectory planning** require spatially and temporally resolved climate impact information.

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Climate impact mitigation potentials of alternative routings

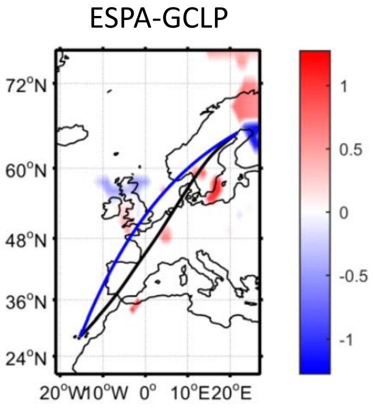
One Day Case Study of European Air Traffic on 18 December 2015

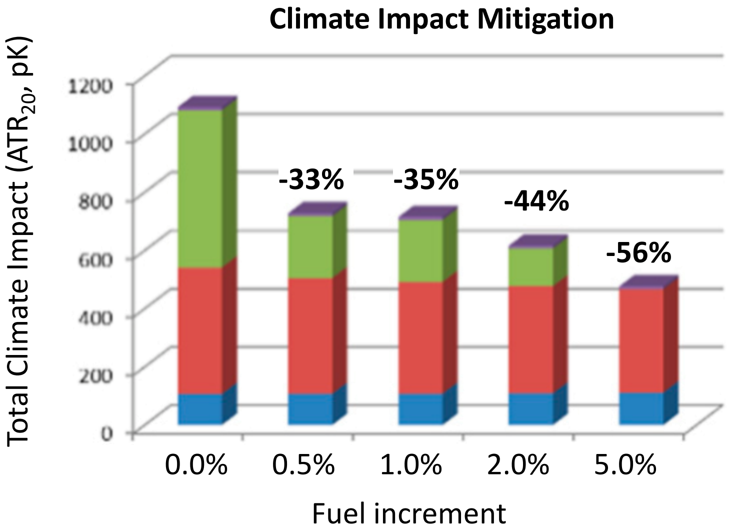
ATM4E

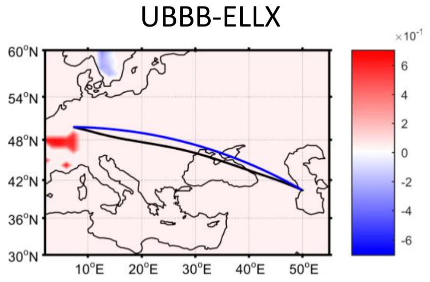
Matthes et al., 2020

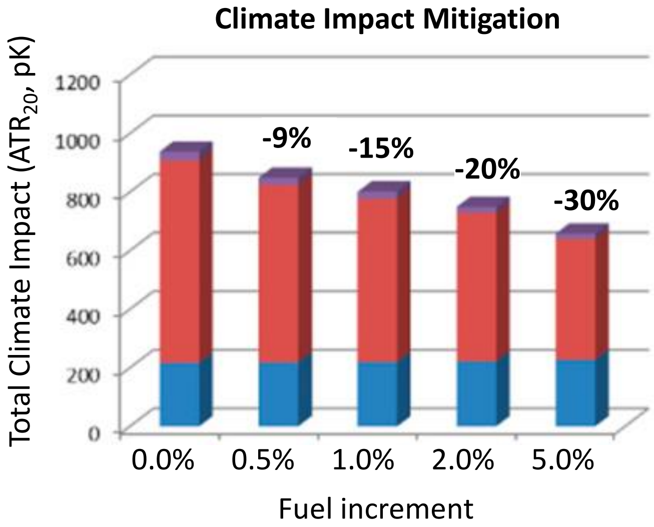
Example 1: Lulea – Gran Canaria (ESPA-GCLP)
Contrails-dominated climate impact

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









- **Climate-optimized routings can mitigate the total climate impact significantly**
- **The total climate impact 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**

DLR FlyATM4E SESAR JOINT UNDERTAKING

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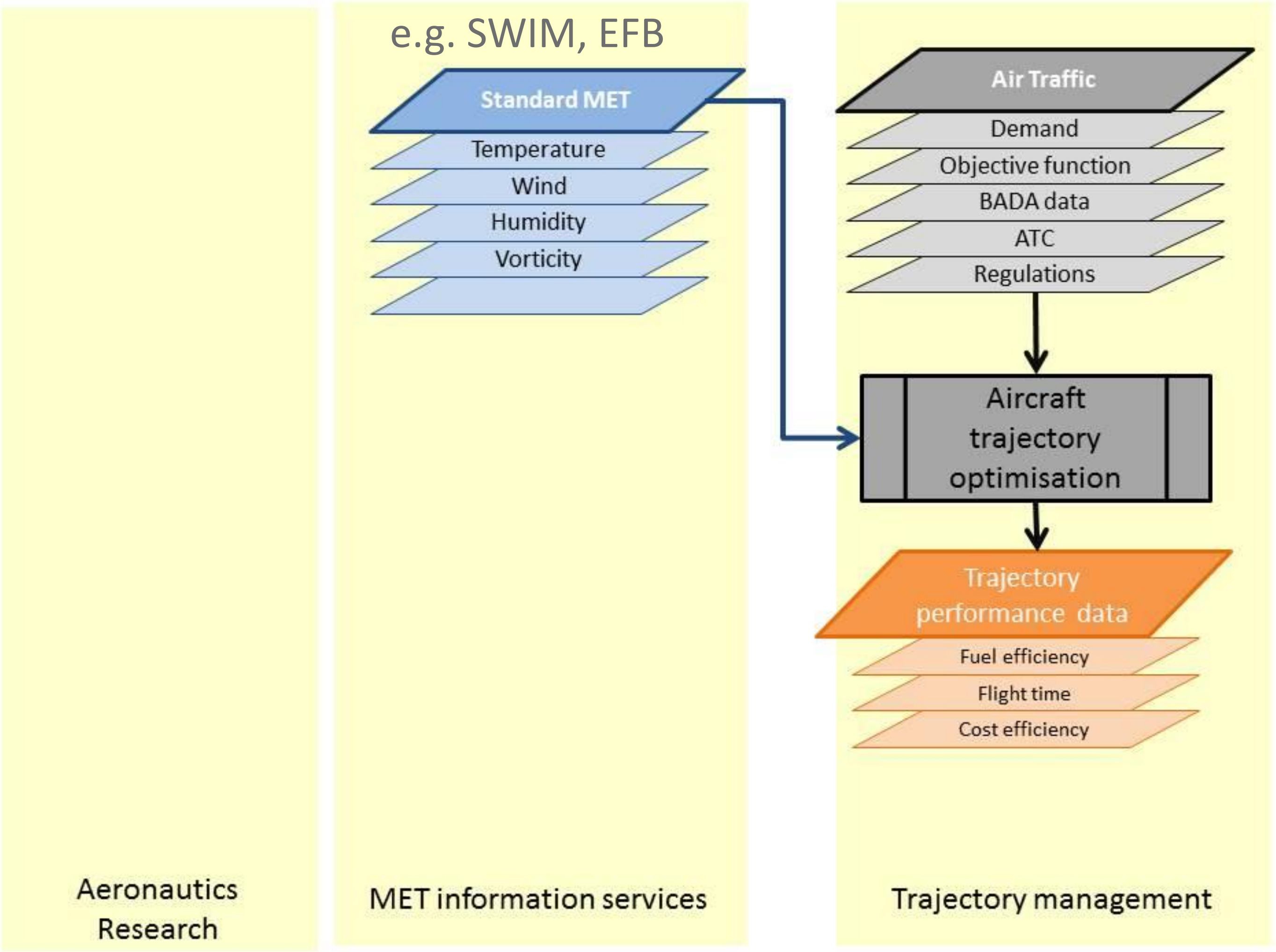
Air traffic management for environment

How to integrate climate change information (aCCFs) during flight planning

Schematic

ATM system



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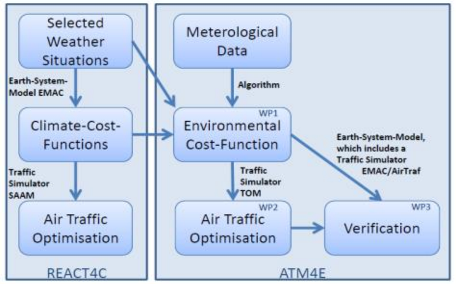
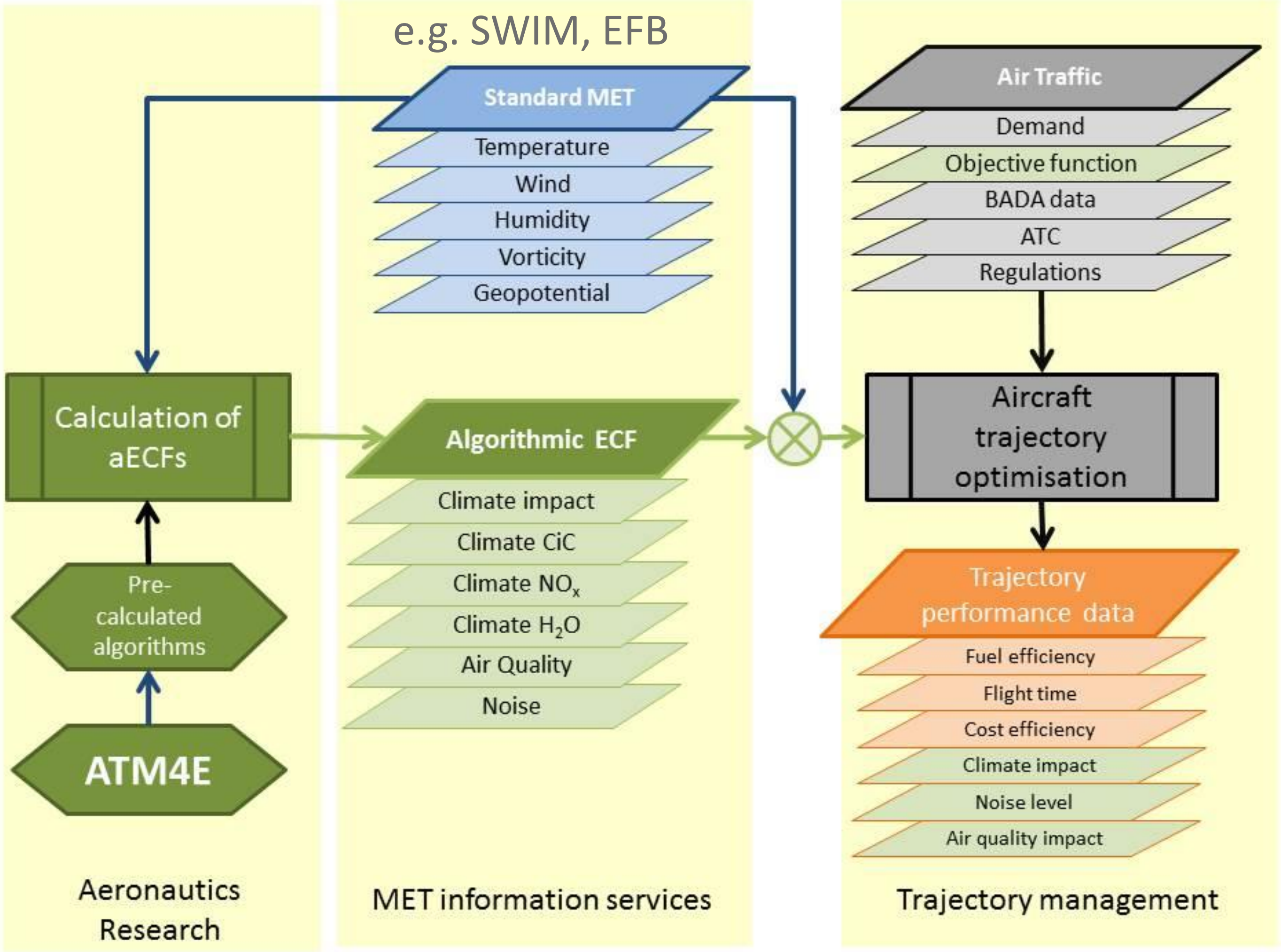


Contribution of ATM4E



ATM4E

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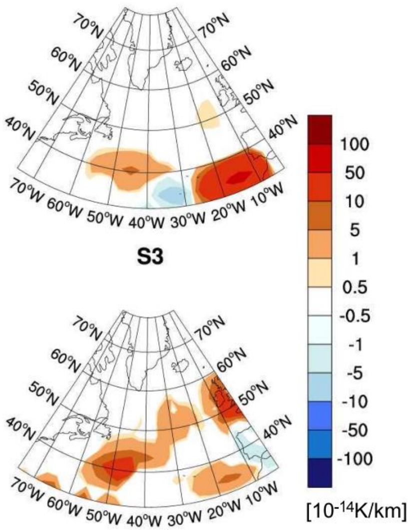
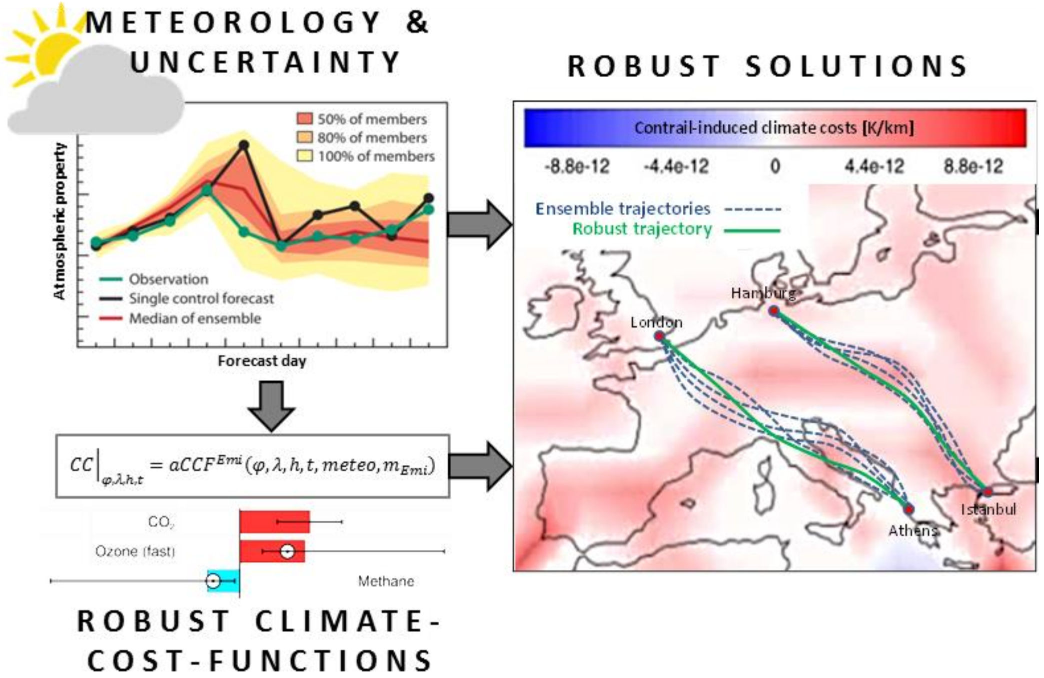
Feasibility study: Step towards robustness of climate-optimized trajectories Using algorithmic Climate Change Functions ECFs (MET service)

- FlyATM4E developed a concept to **identify climate-optimised aircraft trajectories** which enables a robust and **eco-efficient** reduction in aviation's climate impact, quantifying non-CO_2 **mitigation potentials**.
- FlyATM4E **identified those weather situations** and aircraft trajectories, which lead to a **robust climate impact reduction** despite **uncertainties.** Methods on robust decision making under uncertainty conditions are currently under development, resulting in quantitative estimates of robust mitigation potentials.

NAFC



Frömming et al. 2021



- FlyATM4E further identified those weather situations having a **large potential to reduce the climate impact** with only little or even no cost changes ("**Cherry-Picking**") and those situations where both, climate impact and costs can be reduced ("**Win-Win**").
- FlyATM4E **formulates recommendations** how to implement these **strategies in meteorological (MET) products**

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

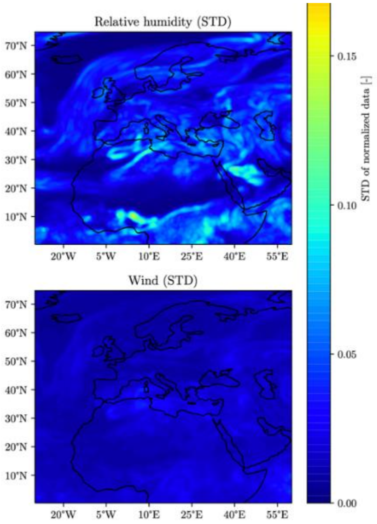
Prevailing uncertainties need to be characterized and **mathematical concepts** for a risk assessment on how to integrate identified uncertainties in the overall climate effects assessment need to be introduced.

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

Quality of the meteorological forecast

Ensemble Prediction System (EPS)

Statistical analysis of key parameters in individual ensemble members, e.g. humidity, temperature, wind.



Simorgh et al. 2022
Dietmüller et al., 2022

Representation atmospheric processes

Physical climate metrics

Development aCCFs

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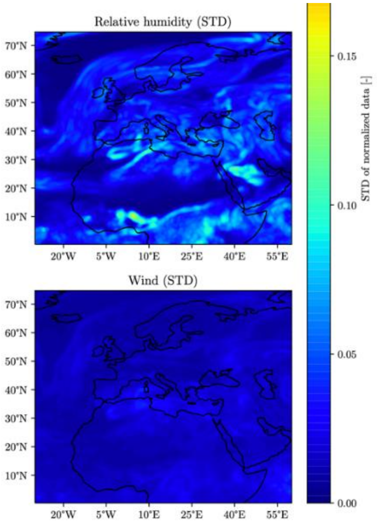

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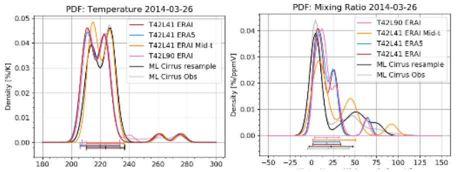
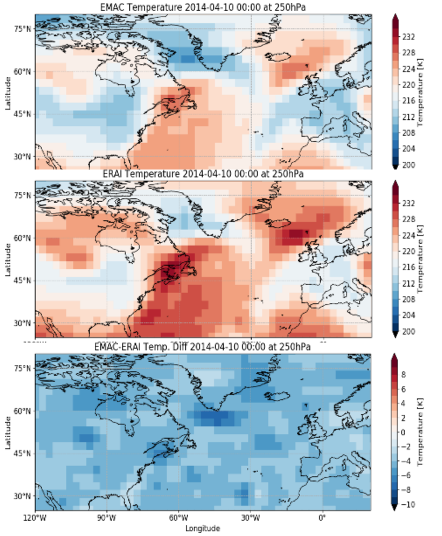
Representation atmospheric processes

Nudged simulations in chemistry-climate model EMAC



Temperature **Water vapour**

Systematic evaluation of chemistry-climate model EMAC with reanalysis and observation data to determine uncertainty.



Peter et al. 2022

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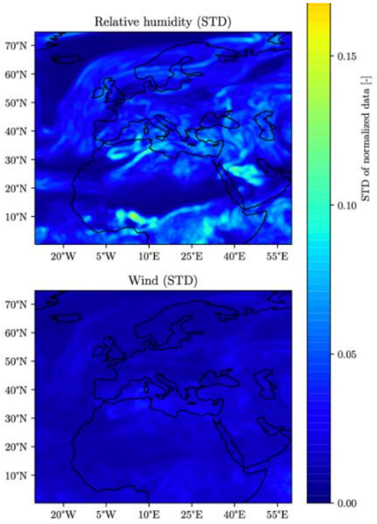

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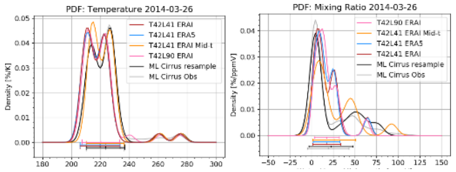

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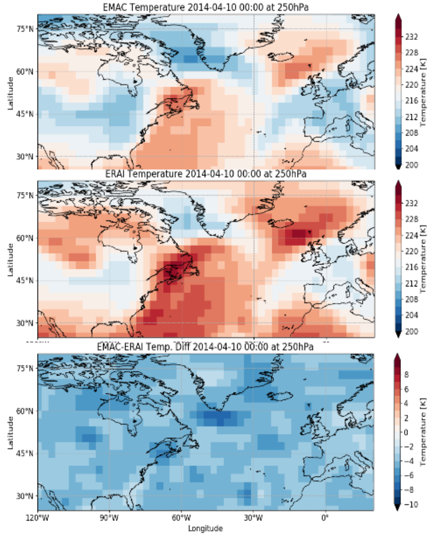

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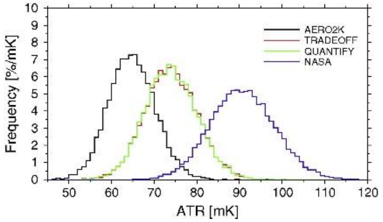
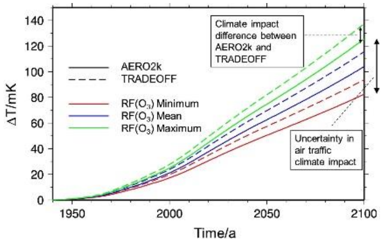
Peter et al. 2022

Physical climate metrics

Climate metrics are calculated with climate response model AirClim





Calculation of temperature change of CO_2 and non-CO_2 effects requires a physical metric definition, as well as assumptions on background conditions, resulting in uncertainty ranges identified by Monte Carlo simulations.

Dahlmann et al. 2016

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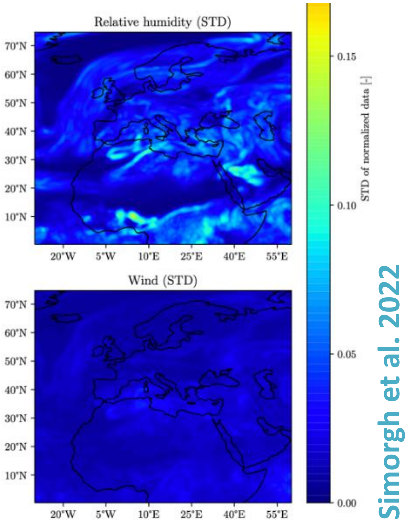

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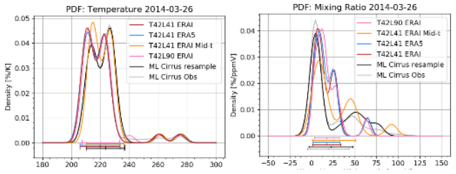

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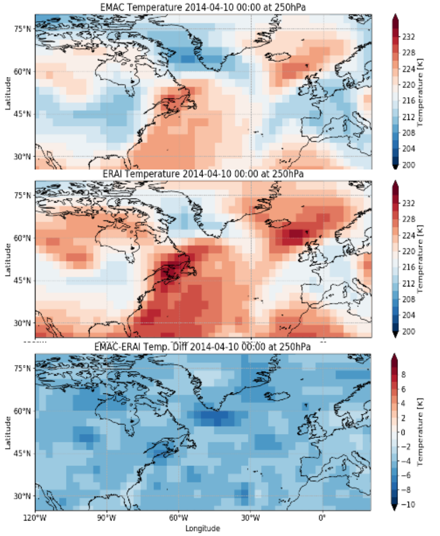

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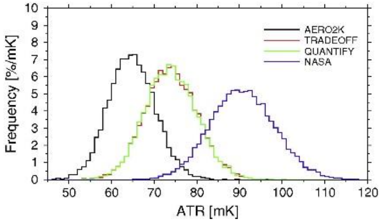

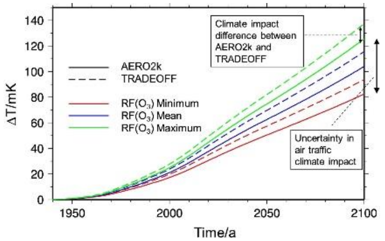

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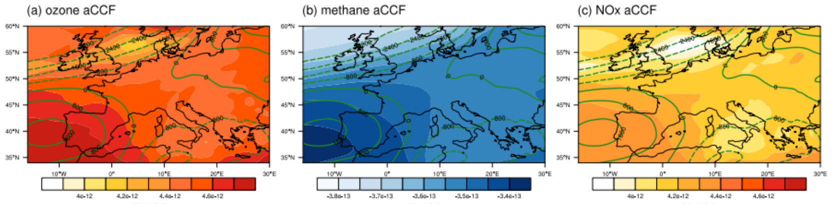
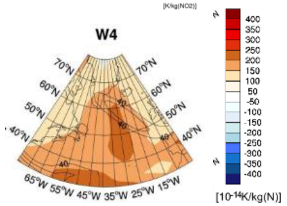
Dahlmann et al. 2016

Development aCCFs

Comprehensive Lagrangian simulations in chemistry-climate

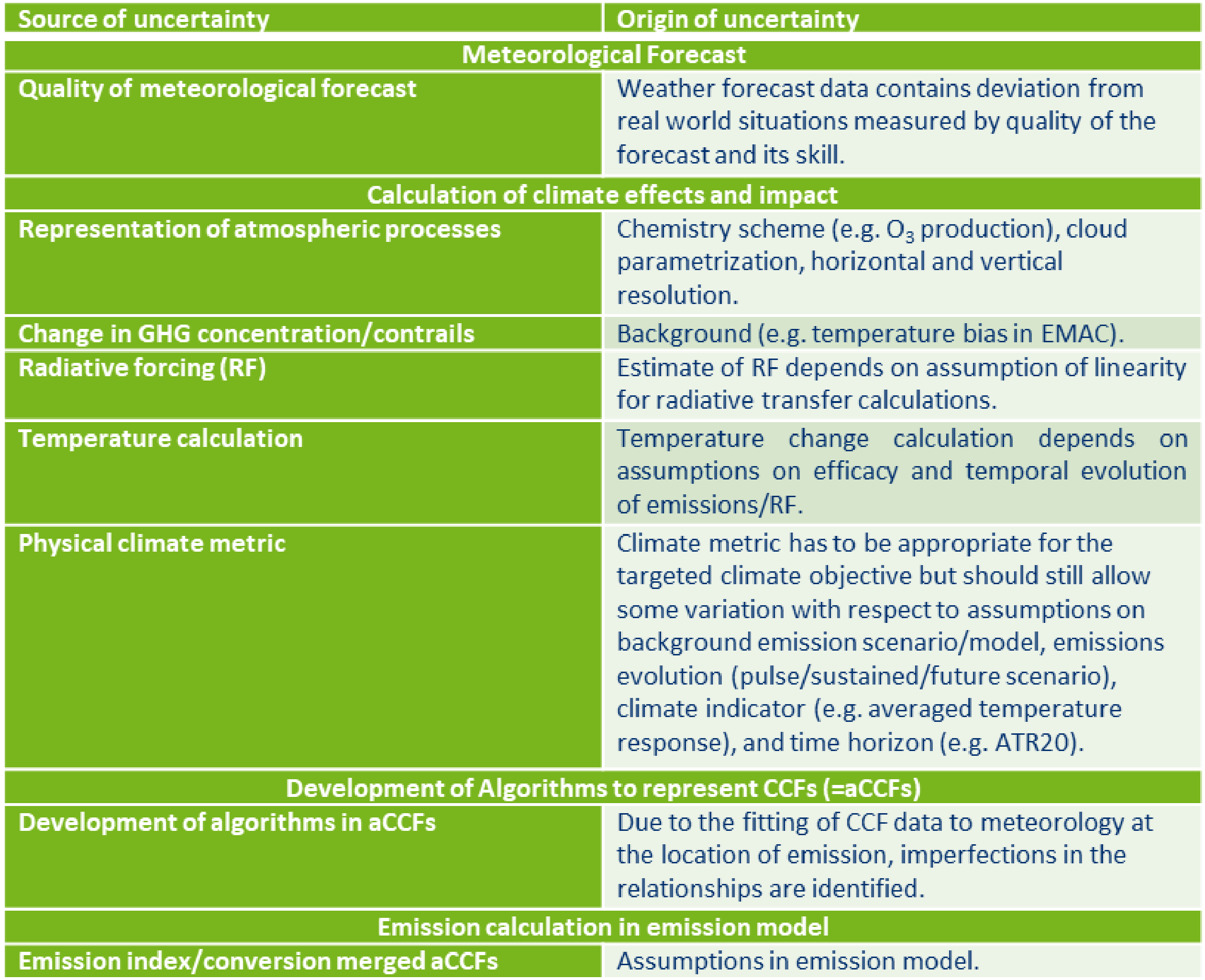




Correlation and fitting of aCCFs to MET data represents effects with imperfections. Strongly depends on season and region, requiring evaluation.

Frömming et al. 2021, Yin et al. 2022, Dietmüller et al., 2022

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.

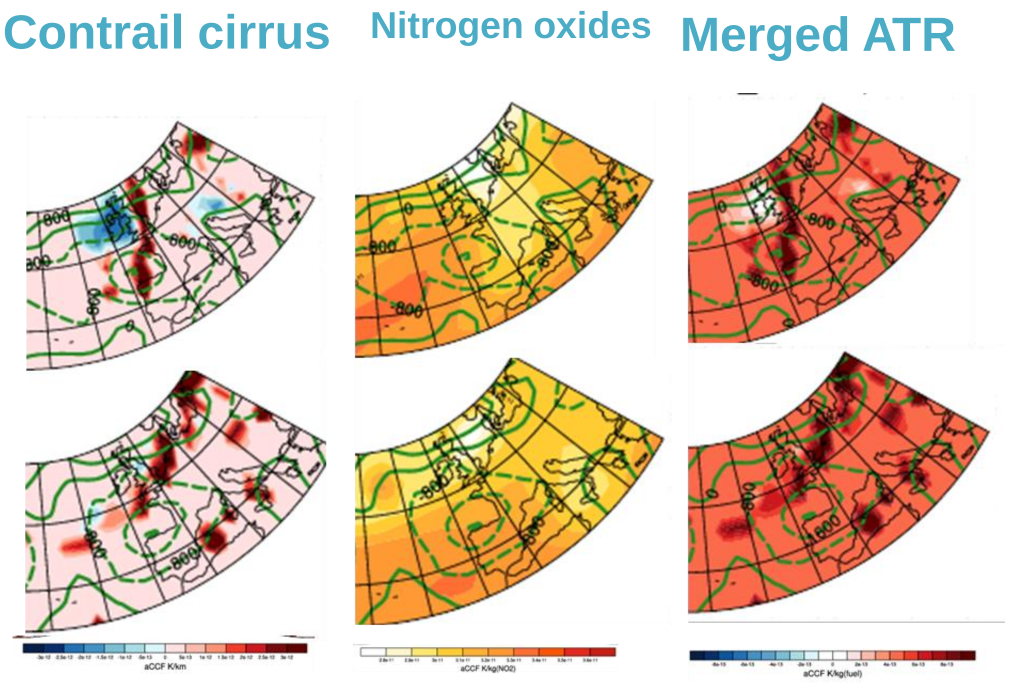
This is a prerequisite in order to **characterize robustness** of alternative **climate-optimized aircraft** trajectories.

This methodology has been applied in a **case study** (summer & winter, 2018) for aircraft movements in the European Airspace where **mitigation potentials due to climate-optimized routing** have been identified (Matthes et al., 2022, *in prep.)* and their associated **uncertainty ranges** have been quantified.

Feasibility study: Step towards robustness of climate-optimized trajectories (1/3)

- Spatial and temporal distribution of **climate effects** by climate change functions
- Expanded **environmental performance assessment** (climate metrics, sensitivity)
- **Physical climate metric**: average temperature response

- Case studies of European Air Traffic (2018) to **identify climate-optimized aircraft trajectories** quantifying total climate impact and non-CO_2 **mitigation potentials**.
- Two aircraft **trajectory optimization** tools (TOM, ROOST) and Earth System climate model (EMAC/DLR,TUD)
- **Cooling effects due** to contrail cirrus influences mitigation potentials



Yin et al., 2022 (in prep.)
Dietmüller et al. 2022 (in prep)

This project has received funding from the SESAR Joint Undertaking under grant agreements No 699395 and No 891317 under European Union's Horizon 2020 research and innovation programme.

Feasibility study: Step towards robustness of climate-optimized trajectories (2/3)

Implementation of prototype climate change functions

Reanalysis data in order to identify mitigation potentials in real weather situtations

Assessing weather situations and their mitigation potentials shows strong variation of climate effects with synoptic situation, season and geographic region of flight.

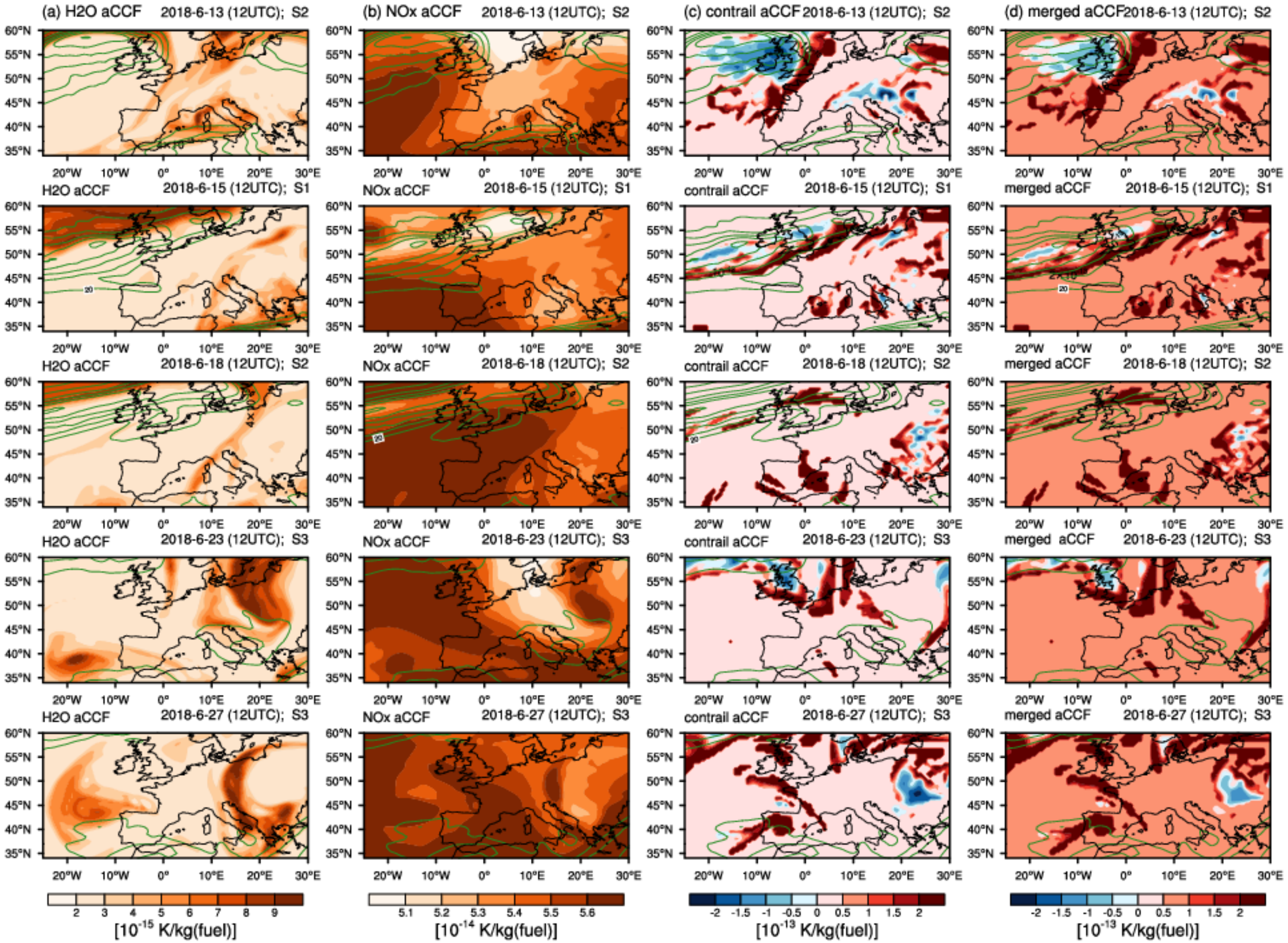
Further research is needed in order to consolidate estimates of climate effects and mitigation gains. However, feasibility studies on possible implementation are required in order to prepare for future implementation.

From earlier comprehensive climate chemistry simulations for summer and winter algorithmic climate change functions have been derived.

Applying these algorithms to reanalysis data allows to quantify anticipated climate effect for a given geographic position and time of flight.

Climate metrics (ATR) were calculated with climate response model AirClim

Individual non-CO_2 climate effects show different type of granularity, strength and temporal variation of regions with high impact.

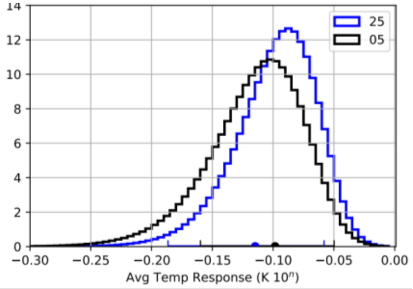


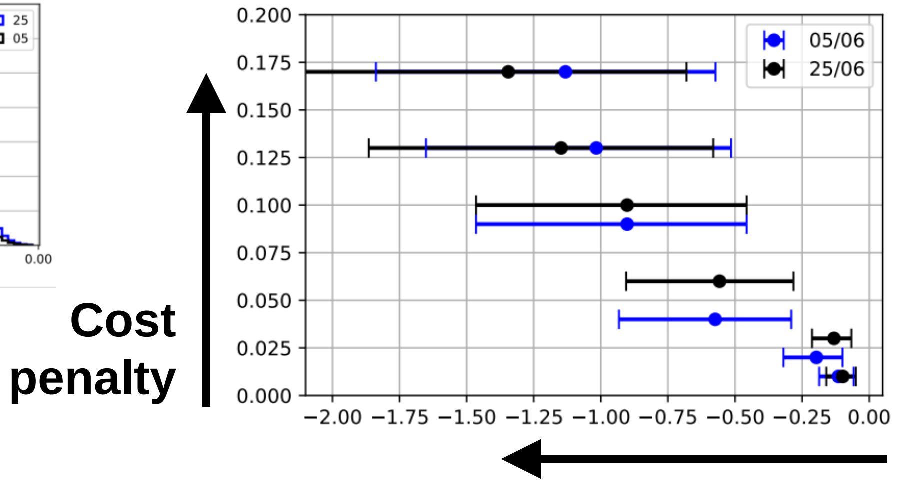
Matthes et al. 2022

Feasibility study: Step towards robustness of climate-optimized trajectories (3/3)

- **Pareto front** of optimized solutions
- **Mitigation potential & Uncertainty** depends on synoptic situation.
- **Monte-Carlo** risks assessment to assess robustness of identified mitigation options
- Strategies for **efficient solutions** from a system approach **rely on marginal costs**

Uncertainty analysis (normal & lognormal)



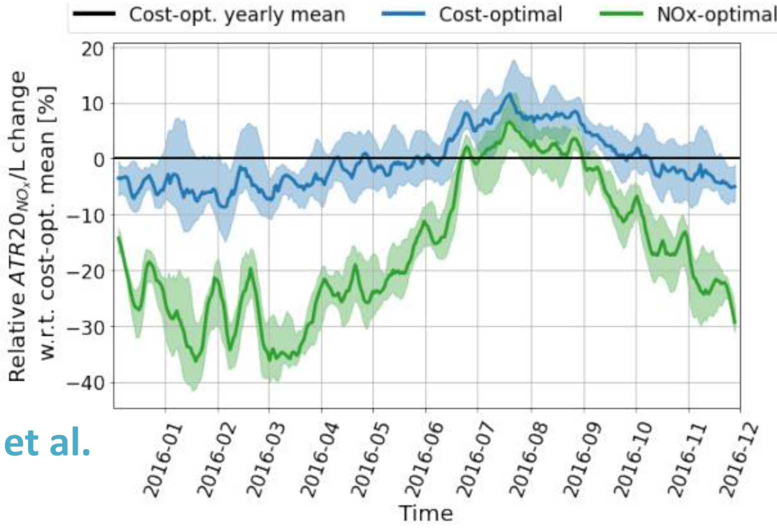


Cost penalty

Reduction in climate effects

Matthes et al. 2022

NO$_x$ effects of European Air Traffic (Jan-Dec)



Castino et al. 2021

- Beyond two offline trajectory optimizers the Earth System Climate model **EMAC/AirTraf** is used for optimization
- **Pareto principle** confirms that e.g. 20% of the flights contribute about 80% of the reduction
- **Strong seasonal dependence** of mitigation potentials can be characterized leading to **optimization strategies**

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D-KULT: LuFo Projekt (2022-2025)

Zielsetzung

- **Nachweis der Machbarkeit ökoeffizienter Flugtrajektorien**

✈ im europäischen Luftraum (größere Möglichkeit zur Reduzierung der Klimawirkung, laterale Abweichungen leichter möglich, aber mehr Einrichtungen involviert),

✈ im deutschen Luftraum (potentiell mehr Zwangsbedingungen durch Start und Landung, leichtere reale Umsetzbarkeit durch einheitliche nationale Zuständigkeit).

Technische Ziele

✈ Die Bildung von persistenten Kondensstreifen und Kondensstreifen-Zirren für realen Luftverkehr vermeiden.

✈ Ein Flugplanungssystem für klima-freundliche (öko-effiziente) Flugtrajektorien auf der Basis von algorithmische Klimawirkungsfunktionen (aCCC) implementieren.

✈ Die Machbarkeit von klima-freundliche Flugtrajektorien demonstrieren.

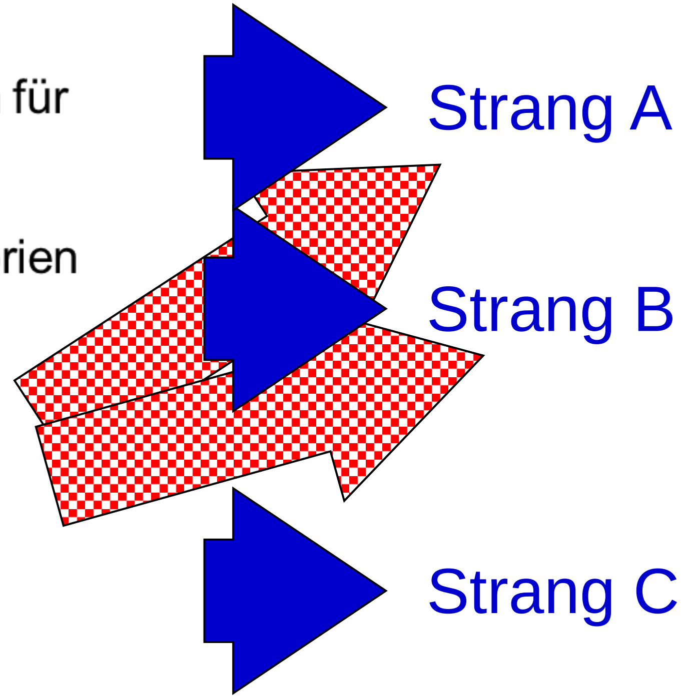
✈ Methoden für lärmarmen An- und Abflug unter Berücksichtigung der Klimawirksamkeit weiterentwickeln.

Sausen D-KULT Überblick

D-KULT: LuFo Projekt (2022-2025)

Umsetzung

- Die Bildung von persistenten Kondensstreifen und Kondensstreifen-Zirren für realen Luftverkehr vermeiden.
- Ein Flugplanungssystem für klima-freundliche (öko-effiziente) Flugtrajektorien auf der Basis von algorithmische Klimawirkungsfunktionen (aCCC) implementieren.
- Die Machbarkeit von klima-freundliche Flugtrajektorien demonstrieren.
- Methoden für lärmarmen An- und Abflug unter Berücksichtigung der Klimawirksamkeit weiterentwickeln.

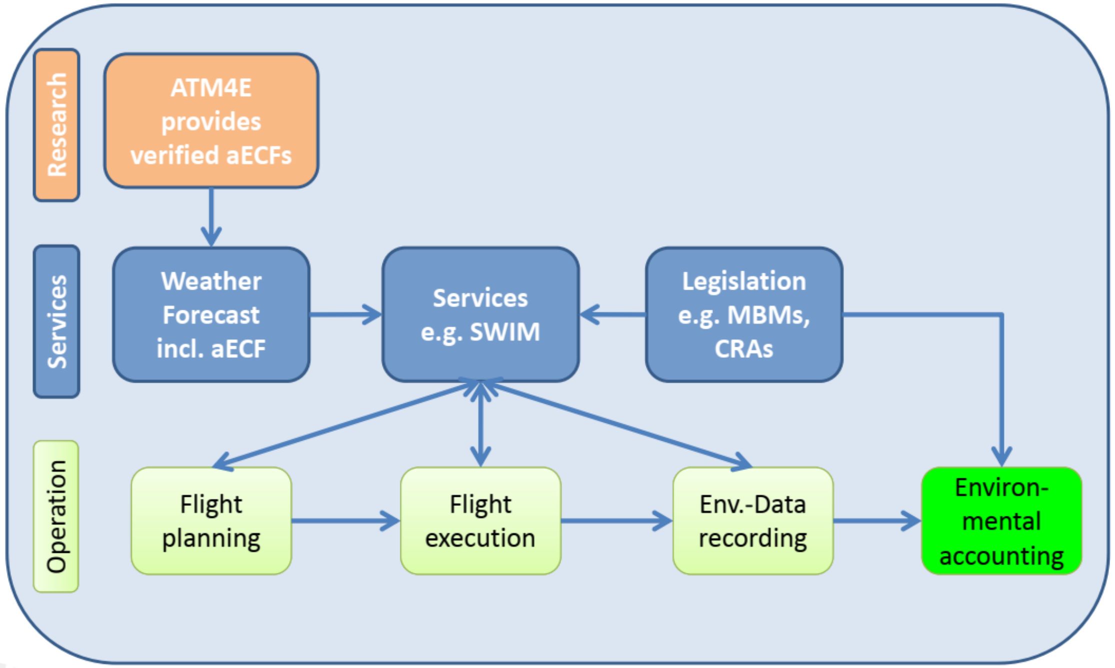

Strang A

Strang B

Strang C

Roadmap: Towards implementation of climate-optimized trajectories

- Implementation relies on **provision of climate change functions to ATM** (trajectory optimisation)
- Feasibility study performed on **infrastructure** comprising MET components – resulting in roadmap definition how to expand the current ATM system in order to **enable climate-optimized trajectories**
- Options on how to **develop and how to integrate such novel MET products** have been studied in earlier projects, e.g. DG Aeronautics (**REACT4C**, 2010-2013) and SESAR2020 (e.g. **ATM4E**, 2016-2018).
- Candidate solutions are proposed: enabling solution relying on aCCFs (**Sol-FlyATM4E-01**) and operational solution on climate optimized trajectories (**Sol-FlyATM4E-01**)
- Further options on how to expand current ATM and how to identify overall **mitigation potential by climate-optimized trajectories** are currently explored, e.g. ongoing SESAR2020 (Exploratory Research) FlyATM4E, ALARM, but also Aeronautics ClimOP and ACACIA.
- Concepts on how to deal with **prevailing uncertainties** are required for a **robust decision making**.



Matthes et al. 2017

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Danke für Ihr
Aufmerksamke

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https://flyatm4e.eu/

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