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Robust Climate Optimal Aircraft Trajectory Planning within Structured Airspace

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Supervisor:
Prof. Manuel Soler (UC3M)

12th EASN International Conference

Overview

- Introduction
  - Motivation
  - Litrature review & Scientific gaps
- Robust climate optimal Aircraft trajectory planning [structured airspace]
  - Problem formulation
  - Solution approach
  - Simulation Results
    - Night-time scenario [warming contrails]
    - day-time scenario [cooling contrails]
- Future works

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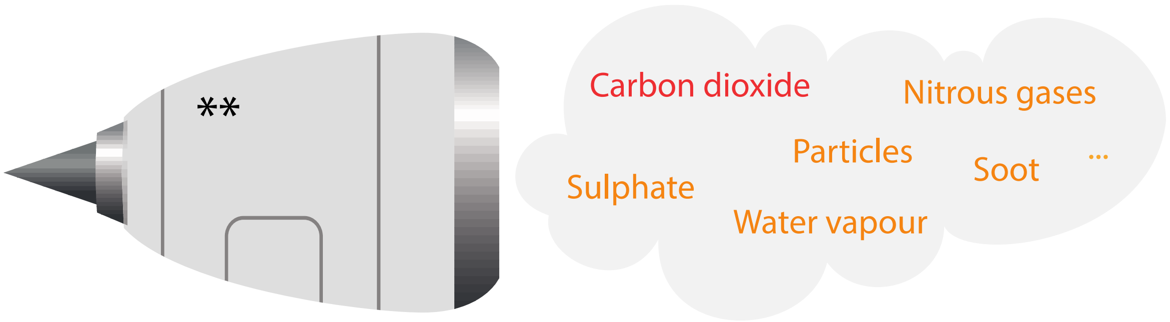
Motivation

- Aviation is responsible for about 3.5% of total global warming
- Aviation-induced climate impact consists of
  - carbon dioxide (CO_2)
  - non-CO_2 species (e.g., NO_x, contrails, water vapor, ...)

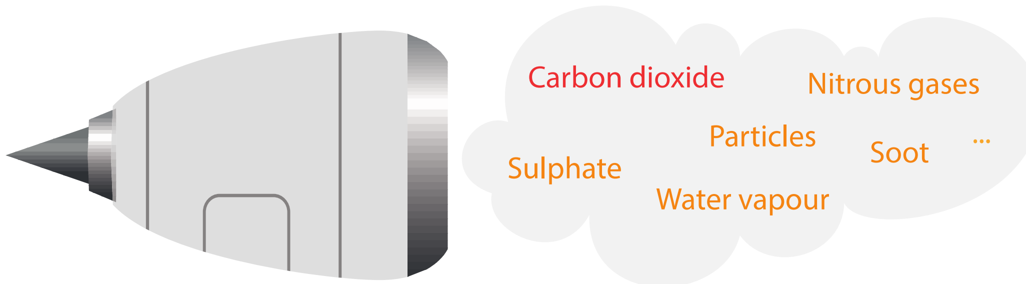


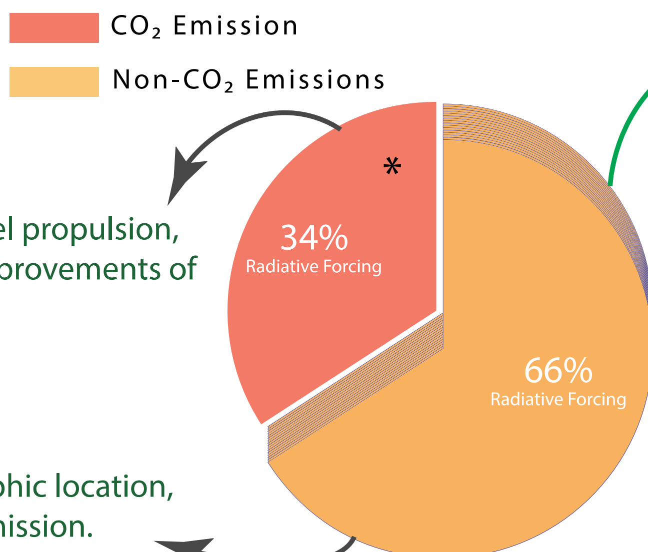
*** Feature: vecteezy.com.*

- An increase in global air traffic is foreseen in the coming decades (4.4% yearly)

Critical increase in climate impacts is expected

How to reduce aviation-induced climate impacts?

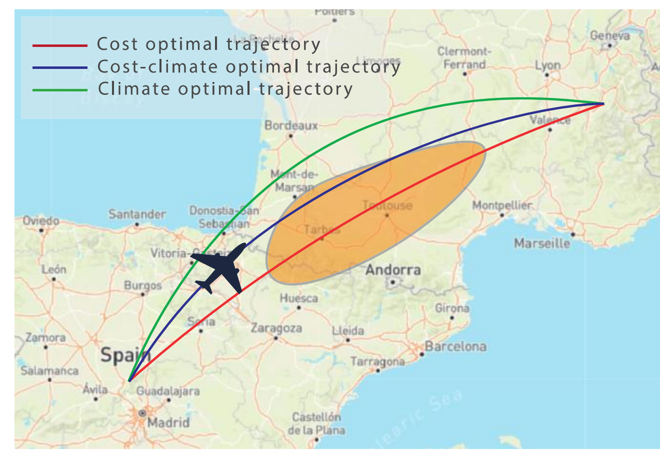




can be mitigated using novel propulsion, jet fuels, and continuous improvements of aircraft efficiency, ...

Mainly depends on geographic location, altitude, and time of the emission.

Thus, effects can be reduced by planning proper **climate-aware trajectories:**



** estimated by Lee, David S., et al. "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018." Atmospheric Environment 244 (2021).*

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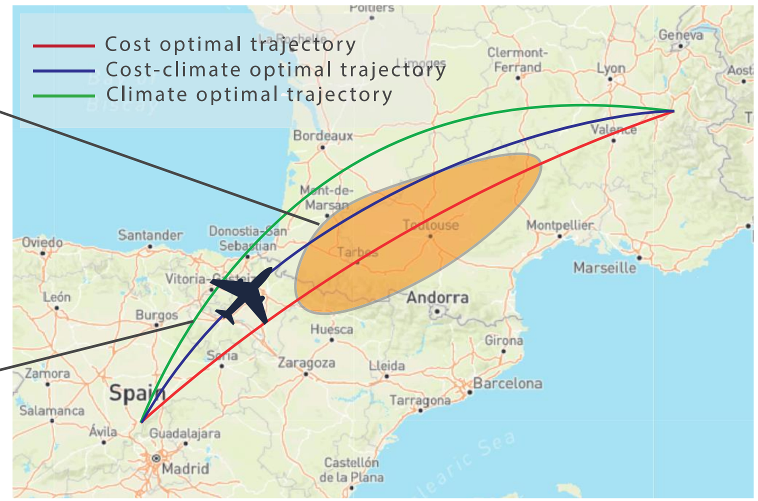
- Numerous studies in the literature have investigated the potentiality to mitigate climate impacts with aircraft path planning with different considerations of **climate impacts**, **operating cost**, and **trajectory planning method**.

Climate-Sensitive Reigons (CSR)

1. How to determine CSR?
2. How to quantify the climate impact of emissions in these regions? With which metrics?

Climate-aware trajectory planning

1. How to include CSR in trajectory planning?
2. Which approach to determine climate-aware trajectories?
   # trajectory optimization
   # non- trajectory optimization
3. Which trajectory optimization methods?
   # optimal control
   # non-optimal control



Review

A Comprehensive Survey on Climate Optimal Aircraft Trajectory Planning

Abolfazl Simorgh [1,*], Manuel Soler [1], Daniel González-Arribas [1], Sigrun Matthes [2], Volker Grewe [2,3], Simone Dietmüller [2], Sabine Baumann [2], Hiroshi Yamashita [2], Feijia Yin [3], Federica Castino [3], Florian Linke [4], Benjamin Lührs [5] and Maximilian Mendiguchia Meuser [5]

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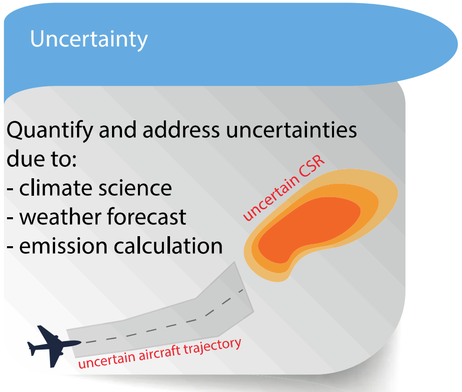
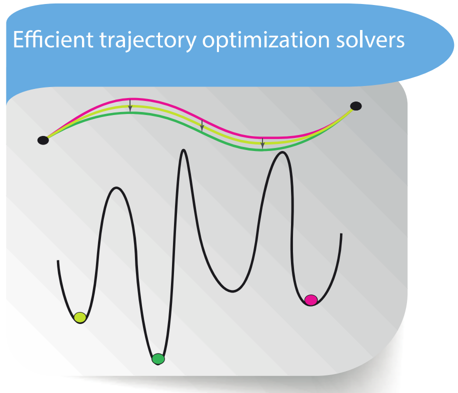
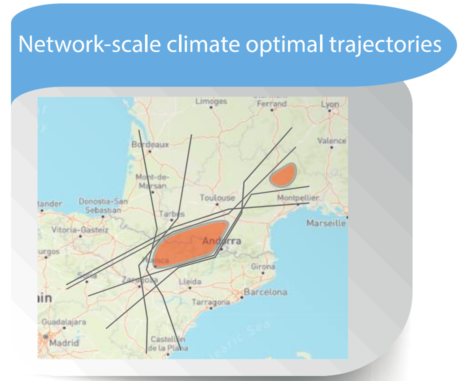
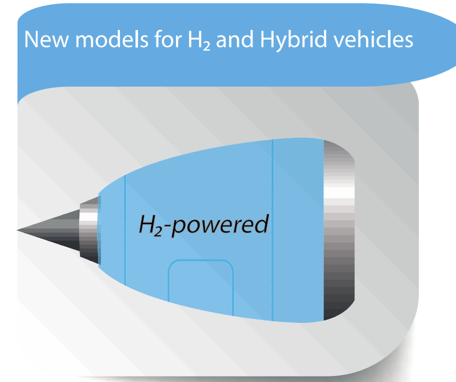
Open problems









Source	***Climate variable***	***Optimization method***	***Type***	***Routing***
Soler et al. (2014)	CO_2, Contrails	Multiphase mixed-integer optimal control	Deterministic	Free-routing
Hartjes et al. (2016)	Contrails	Direct optimal control	Deterministic	Free-routing
Lührs et al. (2016)	NO_x, H_2O, CO_2, Contrails	Direct optimal control	Deterministic	Free-routing
Lim et al. (2017)	Contrails, CO_2	Nonlinear programming	Deterministic	Free-routing
Matthes et al. (2017)	NO_x, H_2O, CO_2, Contrails	Direct optimal control	Deterministic	Free-routing
Niklaß et al. (2017)	NO_x, H_2O, CO_2, Contrails	Direct optimal control	Deterministic	Free-routing
Yin et al. (2018b)	Ozone	Genetic algorithm	Deterministic	Free-routing
Yin et al. (2018a)	Contrails	Genetic algorithm	Deterministic	Free-routing
Niklaß et al. (2019)	NO_x, H_2O, CO_2, Contrails	Direct optimal control	Deterministic	Free-routing
Yin et al. (2022)	NO_x, H_2O, CO_2, Contrails	Genetic algorithm	Deterministic	Free-routing
Yamashita et al. (2020)	NO_x, H_2O, CO_2, Contrails	Genetic algorithm	Deterministic	Free-routing
Matthes et al. (2020)	NO_x, H_2O, CO_2, Contrails	Direct optimal control	Deterministic	Free-routing
Lührs et al. (2021)	NO_x, H_2O, CO_2, Contrails	Direct optimal control	Deterministic	Free-routing
Yamashita et al. (2021)	NO_x, H_2O, CO_2, Contrails	Genetic algorithm	Deterministic	Free-routing

The aim of the conducted study is to address the following challenges:

- Consideration of **uncertainty** in planning climate-aware trajectories
- Development of efficient **robust trajectory optimizers**
- Consideration of currently structured airspace

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Climate optimal trajectory planning problem formulation

Main Requirments:

- **Quantifying climate impact of aircraft emissions**
  - Algorithmic climate change functions are employed
- **Quantifying uncertainty**
  - Meteorological uncertainty is only considered
  - Ensemble weather forecast is employed to characterize uncertainty in weather variables
- **Aircraft dynamical model (and other physical and operational constraints)**
  - Full 4D aircraft dynamical model
- **Objective function:**
  - Weighted sum of operating cost and climate impact

Quantification of Climate impact

Algorithmic climate change functions (aCCFs):
take instantaneous weather data at the time and location of emission to approximate its climate impact in terms of the Average Temperature Response over different time horizons.

For this purpose, a python library has been developed in collabaration with our coleagues wthin EU-projects **FlyATM4E and ALARM**

- The CLIMaCCF is publicly accessible on GitHub: https://github.com/dlr-pa/climaccf

CLIMaCCF Documentation

Release V1.0

Deutsches Zentrum für Luft und Raumfahrt (DLR)
Universidad Carlos III de Madrid (UC3M)
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Delft University of Technology (TUD)

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CLIMaCCF Library

What is CLIMaCCF?

The Python Library CLIMaCCF is a software package developed by UC3M and DLR. The main idea of CLIMaCCF is to provide an open-source, easy-to-use, and flexible software tool that efficiently calculates spatially and temporally resolved climate impact of aviation emissions by using algorithmic climate change functions (aCCFs). The individual aCCFs of water vapour, NOx-induced ozone and methane, and contrail-cirrus and also merged aCCFs that combine the individual aCCFs can be calculated.

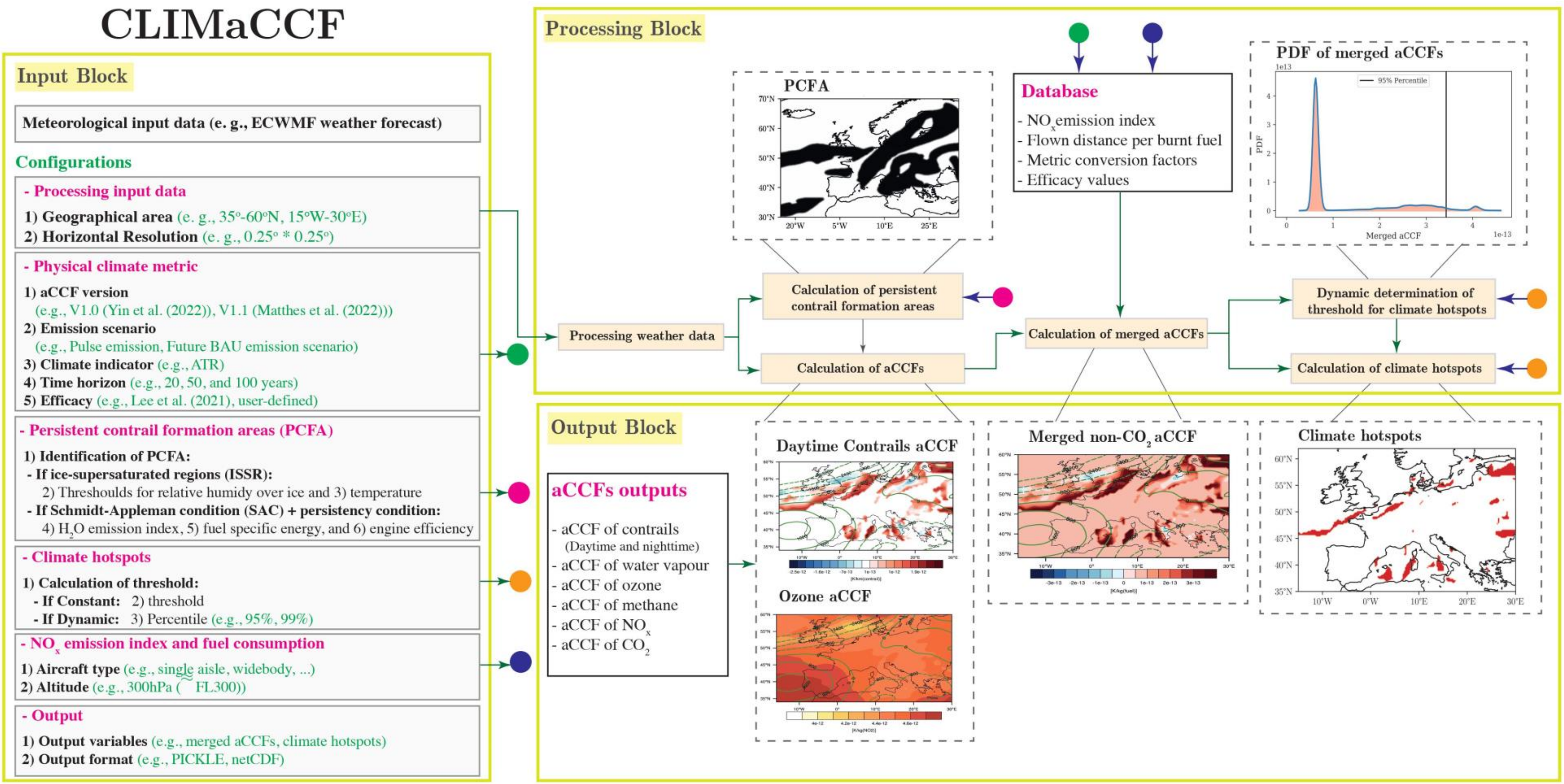
License: CLIMaCCF is released under GNU Lesser General Public License v3.0 (LGPLv3). Citing the Software Documentation Paper (Dietmüller et al. 2022) together with CLIMaCCF software DOI (doi: 10.5281/zenodo.6977273) and version number will serve to document the scientific impact of the software. You should consider this an obligation if you have taken advantage of CLIMaCCF.

Citation info: Dietmüller, S. Matthes, S., Dahlmann, K., Yamashita, H., Simorgh, A., Soler, M., Linke, F., Lührs, B., Meuser, M. M., Weder, C., Grewe, V., Yin, F., Castino, F. (2022): A python library for computing individual and merged non-CO2 algorithmic climate change functions: CLIMaCCF V1.0, GMDD.

Support: Support of all general technical questions on CLIMaCCF, i.e., installation, application, and development, will be provided by Abolfazl Simorgh (abolfazl.simorgh@uc3m.es), Simone Dietmüller (Simone.Dietmueller@dlr.de), and Hiroshi Yamashita (Hiroshi.Yamashita@dlr.de).

Core developer team: Abolfazl Simorgh (UC3M), Manuel Soler (UC3M), Simone Dietmüller (DLR), Hiroshi Yamashita (DLR), Sigrun Matthes (DLR).

Structure of CLIMaCCF:



Uncertainty

The current study focuses on uncertainty in meteorological variables obtained from standard weather forecasts as well as initial flight conditions

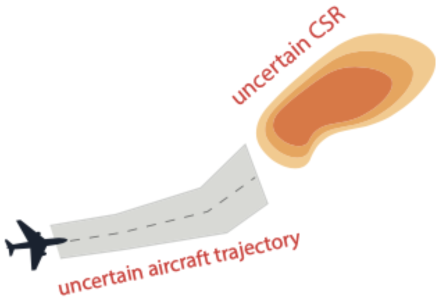
Motivation

- Dynamic of aircraft relies on some meteorological variables such as components of wind
  - uncertainty in components of wind affects ground speed, which determines the time at which the aircraft will overfly each waypoint in the route, as well as how much time the aircraft will spend at each leg (thus influencing fuel burn)

Aircraft trajectories are affected by Meteorological uncertainties

- non-CO_2 climate impacts highly depend on meteorological conditions.
  - Uncertainty in relative humidity affects the determination of persistent contrail formation areas
  - Uncertainty in temperature and geopotential affect the climate impact of Ozone
  - . . .

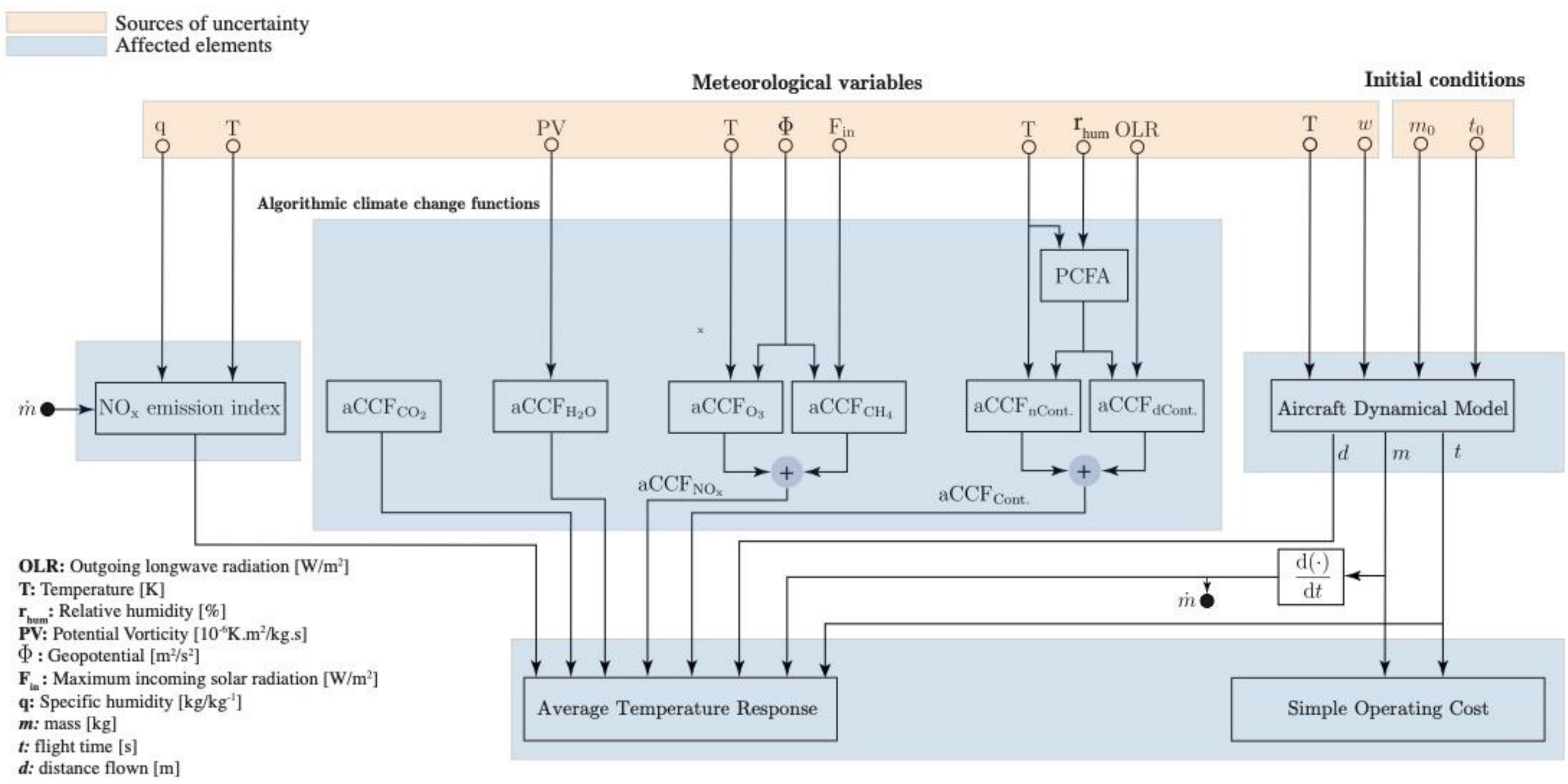
Climate impacts are affected by Meteorological uncertainties



Ensemble Prediction System (EPS), providing n different forecast is employed to characterize uncertainty in weather forecast.

Uncertainty

Propagation of the uncertainty (associated with initial flight conditions and meteorological variables) within climate optimal aircraft trajectory planning:



Dynamical model and objective function

4D aircraft Dynamical model:

$$\begin{bmatrix} \dot{\phi} \\ \dot{\lambda} \\ \dot{h} \\ \dot{v} \\ \dot{m} \end{bmatrix} = \begin{bmatrix} (v\cos\gamma\cos\chi + w_y)\left(R_M(\phi)+h\right)^{-1} \\ (v\cos\gamma\sin\chi + w_x)\left((R_N(\phi)+h)\cos\phi\right)^{-1} \\ v\sin\gamma \\ (T(C_T) - D(C_L))m^{-1} - g\sin\gamma \\ -FF(C_T) \end{bmatrix},$$

$$\text{State variables } (\mathbf{x}) : \begin{bmatrix} \phi & \lambda & h & v & m \end{bmatrix}^T,$$

$$\text{Control variables } (\mathbf{u}) : \begin{bmatrix} C_T & \chi & \gamma \end{bmatrix}^T.$$

Objective function:

$$\text{Objective function} = \psi_{\text{CST}} \cdot \text{Operating cost} + \psi_{\text{CLM}} \cdot \text{Climate impact}$$

$$J = \psi_{\text{CST}} \left[\psi_t \cdot \text{ Exp. Flight time} + \psi_m \cdot \text{Exp. Fuel burnt} \right] + \psi_{\text{CLM}} \cdot \text{Exp. ATR}$$

$$\text{Exp. Flight time} : \mathbb{E}\{\text{FT}\} := \mathbb{E}\{t_f - t_0\}$$

$$\text{Exp. Fuel burnt} : \mathbb{E}\{\text{FB}\} := \mathbb{E}\{m_0 - m_f\}$$

$$\text{Exp. ATR} : \mathbb{E}\{\text{ATR}\} := \mathbb{E}\{ \int_{t_0}^{t_f} \sum_{i=1}^{5} \psi_{\text{ATR},i} \cdot \text{ATR}_i(t, \mathbf{x}(t), \mathbf{u}(t), \zeta) \text{d}t \}$$

$$\text{for } i \in \{\text{CH}_4, \text{Cont.}, \text{O}_3, \text{H}_2\text{O}, \text{CO}_2\}:$$

$$\text{ATR}_{\text{O}_3}(t, \mathbf{x}, \mathbf{u}, \zeta) = 10^{-3} \times \text{aCCF}_{\text{O}_3}(t, \mathbf{x}, \zeta) \cdot \dot{m}_{nox}(t)$$

$$\text{ATR}_{\text{CH}_4}(t, \mathbf{x}, \mathbf{u}, \zeta) = 10^{-3} \times \text{aCCF}_{\text{CH}_4}(t, \mathbf{x}, \zeta) \cdot \dot{m}_{nox}(t)$$

$$\text{ATR}_{\text{Cont.}}(t, \mathbf{x}, \zeta) = 10^{-3} \times \text{aCCF}_{\text{Cont.}}(t, \mathbf{x}, \zeta) \cdot v_{gs}(t)$$

$$\text{ATR}_{\text{H}_2\text{O}}(t, \mathbf{x}, \mathbf{u}, \zeta) = \text{aCCF}_{\text{H}_2\text{O}}(t, \mathbf{x}, \zeta) \cdot \dot{m}(t)$$

$$\text{ATR}_{\text{CO}_2}(t, \mathbf{x}, \mathbf{u}, \zeta) = \text{aCCF}_{\text{CO}_2} \cdot \dot{m}(t)$$

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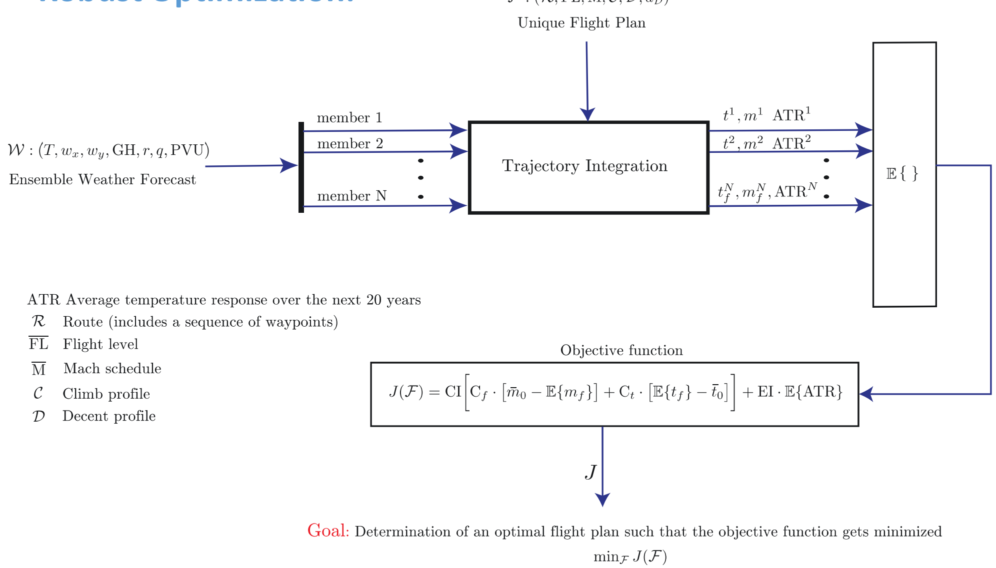
Robust 4D Climate Optimal Flight Planning in Structured Airspace

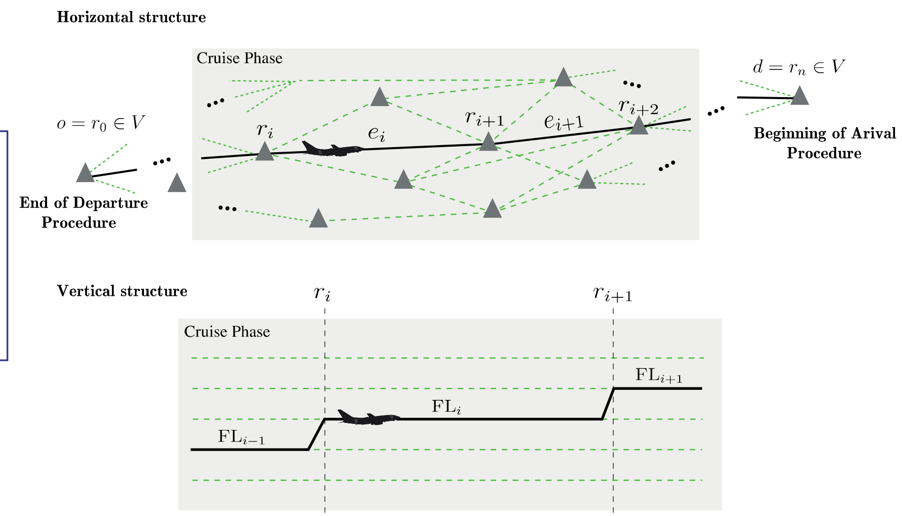
Features

- A technique for flight planning that Integrates **horizontal** and **vertical** decision-making
- **Fast** performance thanks **to GPU-based parallelization**
- Considers **climb**, **cruise** and **descent** phases
- Incorporate **uncertainty** in **meteorological variables**, as well as **initial flight time and initial flight mass**

Robust Optimization:



Airspace Structure:



Reference

- **Robust 4D Climate Optimal Flight Planning in Structured Airspace using Parallelized Simulation on GPUs.** Abolfazl Simorgh, Manuel Soler, et al.. *Geoscientific Model Development (under-review).*

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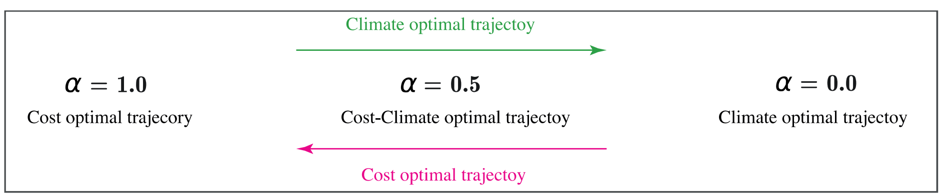
Case studies

- **Date:**
  - 13th of June 2018 – 0000UTC
  - 20th of Dec 2018 – 12000UTC.
- **Flight:**
  - Frankfort to Kyiv
- **Uncertainties:**
  - Initial flight time (Gaussian variable)
  - Initial flight mass (Gaussian variable)
  - Weather variables (10 ensemble members)
- **NOx emission:** BFFM2
- **Aircraft:** A320-214 (CFM56-5B4)

Flight Planning Objective = α * Simple Operting Cost + $(1 - \alpha)k$ * Average Temperature response



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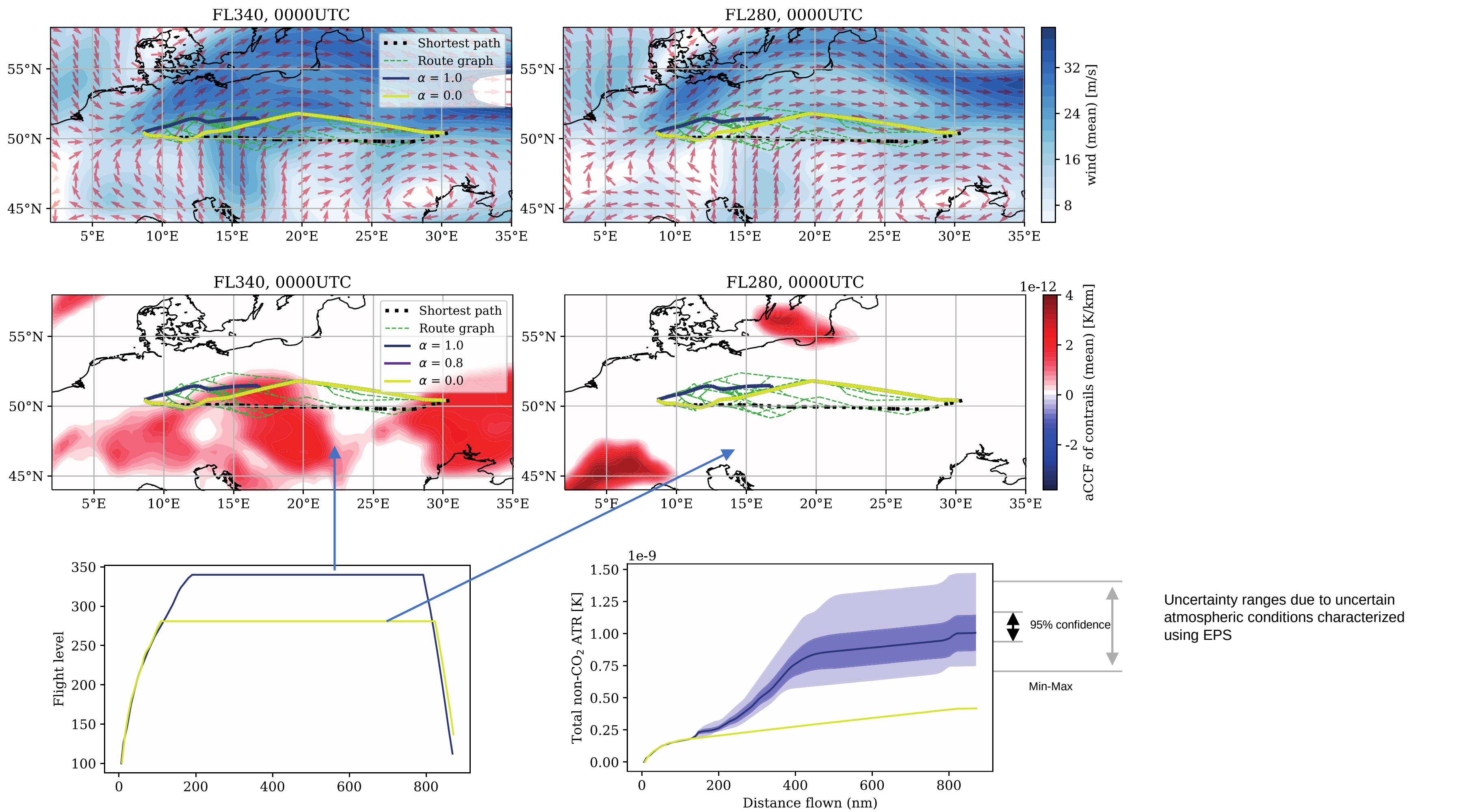
Flight: Frankfurt to Kyiv

13 June 2018, midnight (Formation of persistent contrails during nighttime)



Cost optimal ($\alpha = 1.0$):

- Higher altitudes (FL 340 for cruise)
- Flies through warming contrails
- Deviates from the shortest path to benefit from stronger tailwinds
- The net ATR is uncertain

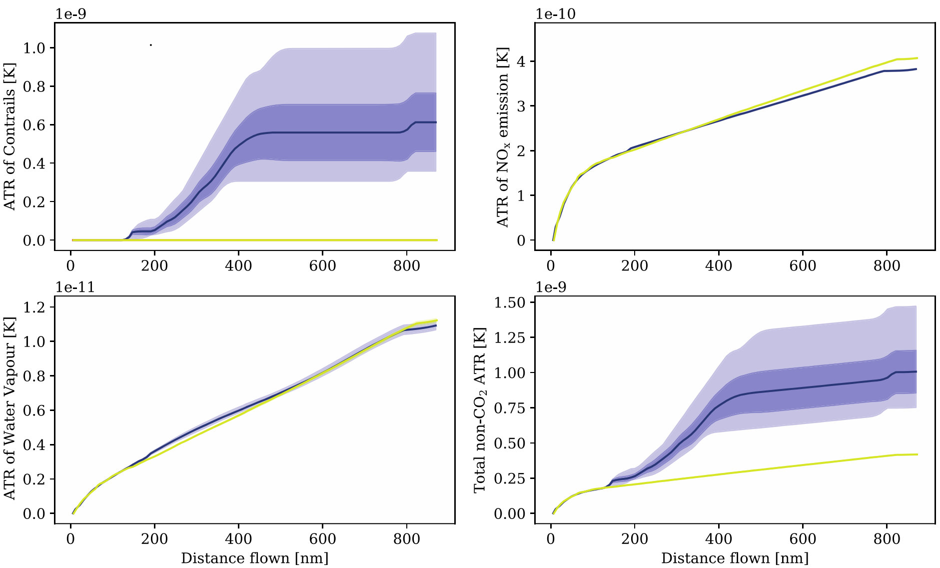
Climate optimal ($\alpha = 0.0$):

- Lower altitudes (FL 280 for cruise)
- Avoids formation of persistent contrails
- The net ATR is almost deterministic

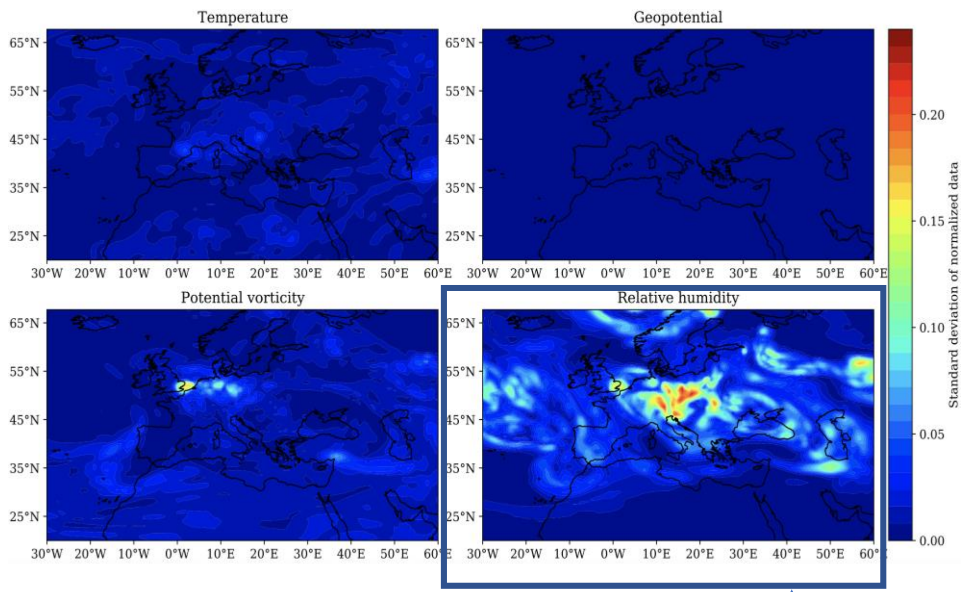
Flight: Frankfurt to Kyiv

13 June 2018, midnight (Formation of persistent contrails during nighttime)

Contribution of each non-CO_2 species to net ATR:



Standard deviation of Meterological variables:

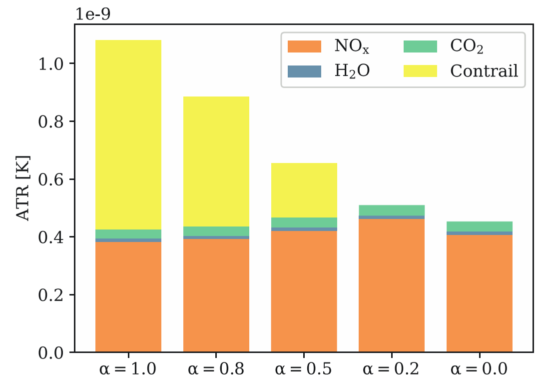


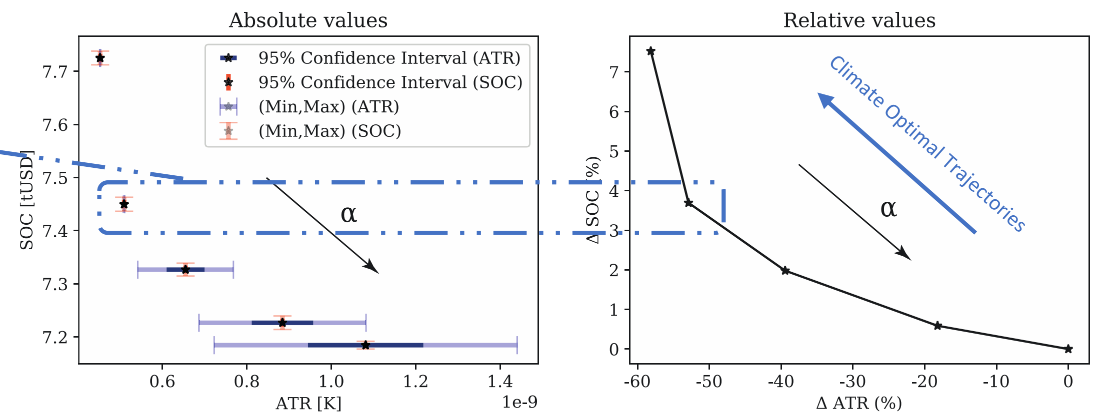
- The contrails have the largest climate impact.
- The uncertainty in the net ATR is mainly related to the relatively high uncertainty in contrails’ climate impact.
- The high uncertainty in contrails' climate impact is related to the high variability among the ensemble members of relative humidity provided by the EPS required to determine the areas favorable for forming persistent contrails.

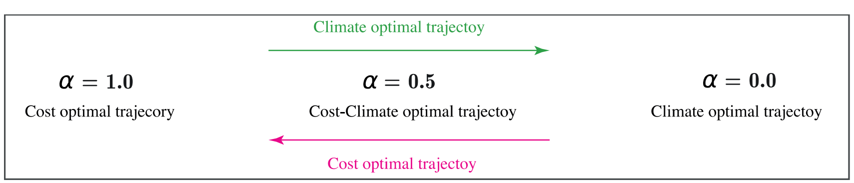
Flight: Frankfurt to Kyiv

13 June 2018, midnight (Formation of persistent contrails during nighttime)

- Persistent contrails have the largest climate effects
- Mitigation potential is achieved mainly by avoiding contrail-sensitive areas
- Since the climate impact associated with contrails has high uncertainty, by avoiding areas sensitive to form persistent contrails, the uncertainty of the net ATR decreases
- For a specific case, climate impact can be reduced by 55.0% by accepting an increase of 4.0% in cost (mean values)







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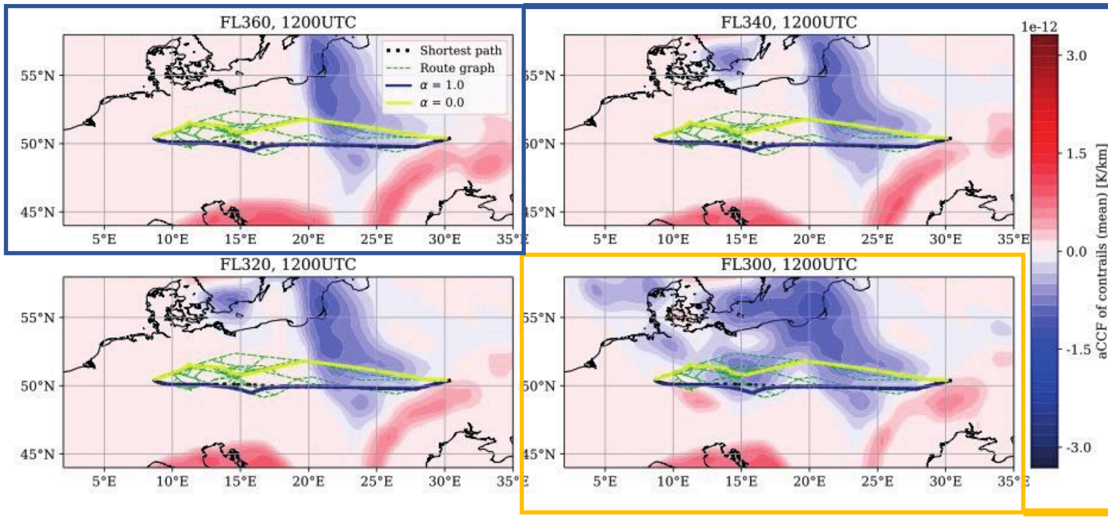
Flight: Frankfurt to Kyiv

20 December 2018, midday (Formation of persistent contrails during nighttime)

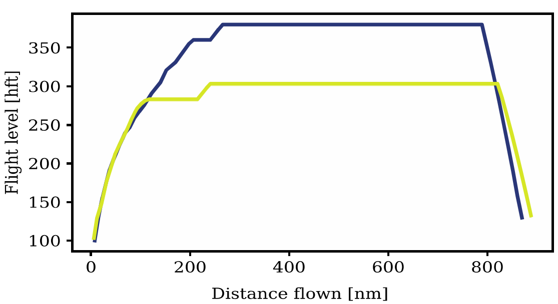


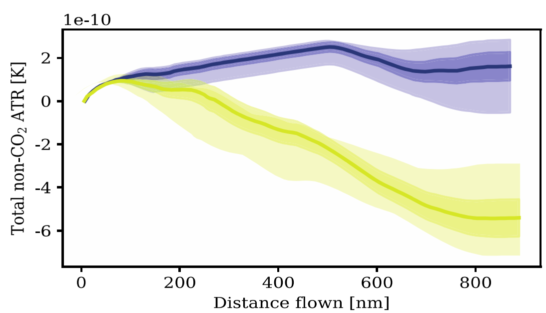
Cost optimal ($\alpha = 1.0$):

- Higher altitudes (FL 360 for cruise)
- The net ATR is positive (warming)

Climate optimal ($\alpha = 0.0$):

- Lower altitudes (FL 300 for cruise)
- Generates cooling contrails
- The net ATR is negative (Cooling)
- The net ATR is uncertain due to the tendency to fly in areas favorable to forming persistent contrails



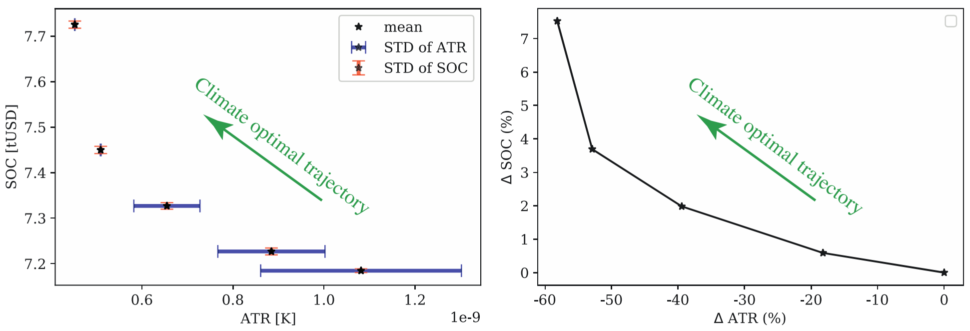


flight: Frankfurt to Kyiv

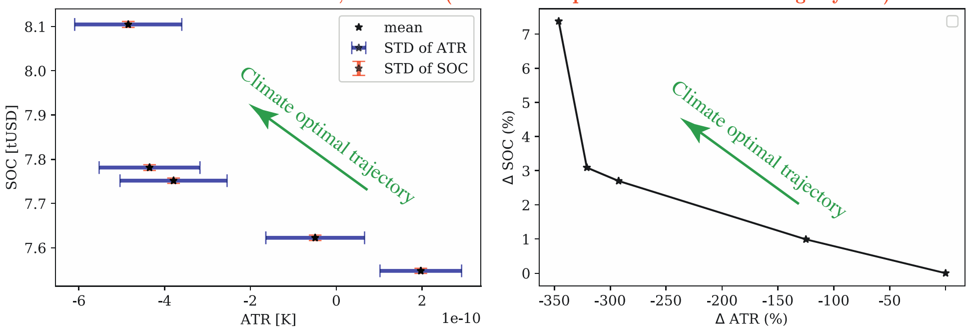
Night-time VS Day-time

- The mitigation potentials for scenarios with contrails effects (warming or cooling) are higher due to dominant climate impact and non-smooth spatial behavior of contrails.
- The generation of cooling contrails is associated with high uncertainty as the aircraft tends to fly within uncertain persistent contrail formation areas.
- The results are almost deterministic for the scenarios with no contrails or the cases where aircraft trajectories avoid the formation of contrails.

13th of June 2018, 0000 UTC (Formation of persistent contrails during nighttime)



20th of December 2018, 0000 UTC (Formation of persistent contrails during daytime)



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- **Conclusions & Future works**

Conclusion

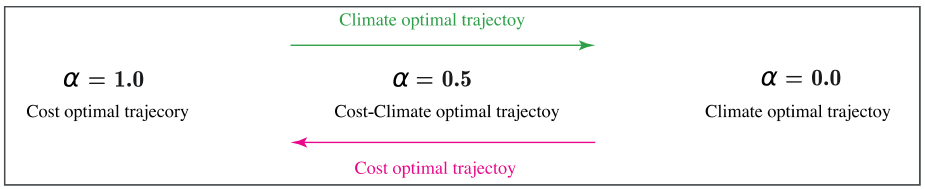
- There is a potential to mitigate aviation-induced climate impact by climate-aware trajectory planning.
- Such mitigation potential is associated with uncertainty (e.g., climate science, emission calculation, and meteorological condition).
- Relative humidity provided by ensemble prediction systems is highly uncertain.
- Uncertainty in relative humidity leads to high uncertainty in the quantification of contrails climate impact.
- During night-time, reducing climate impact could also reduce the uncertainty ranges.
- However, during the day-time, mitigation of climate impact was associated with high uncertainty.

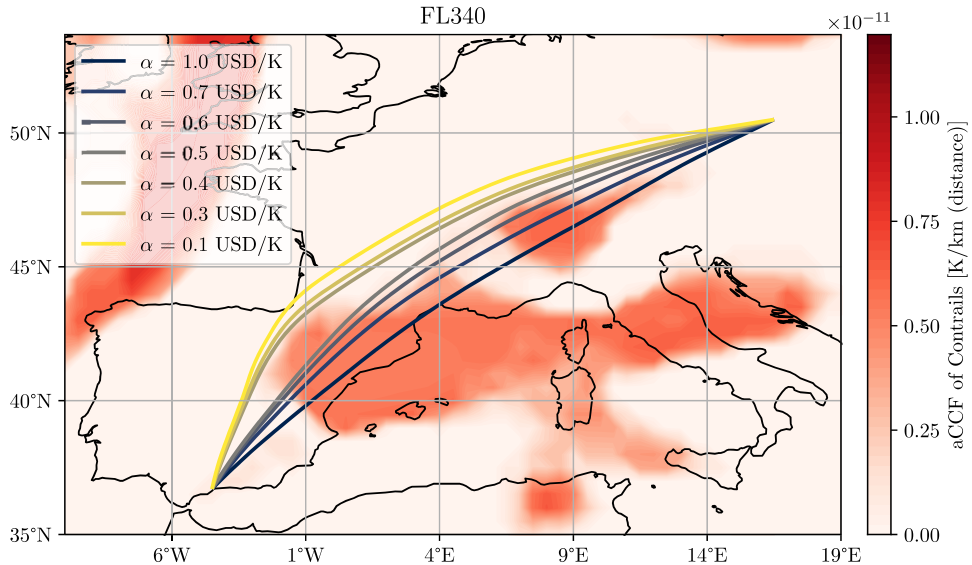
Future works

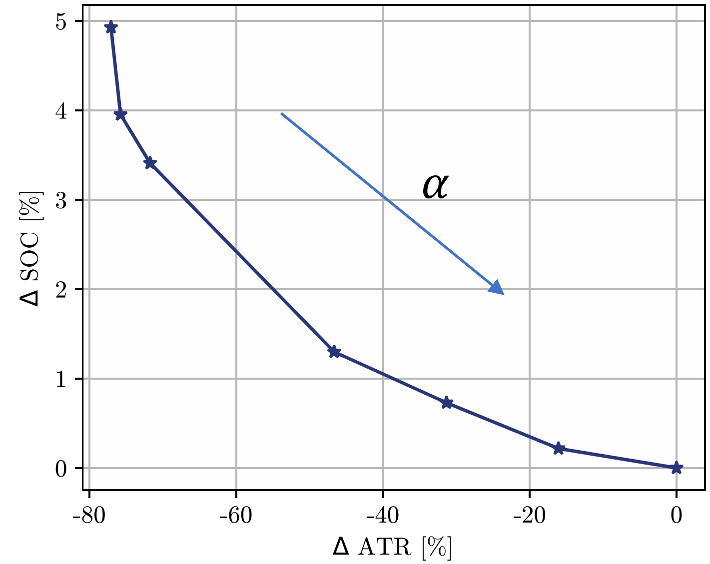
- Robustness of climate optimal trajectories in the presence of cooling contrails (during day-time)
- Robust 4D climate optimal trajectory planning in the free-route airspace

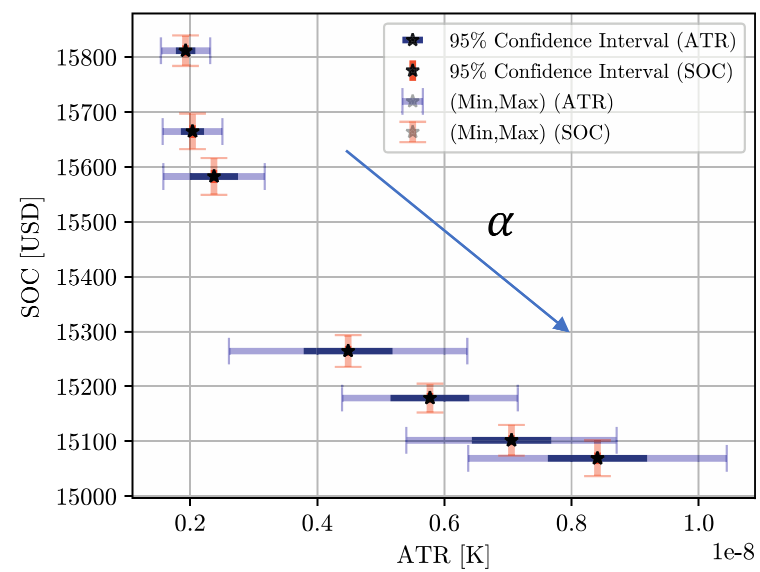
Robust 2D climate optimal trajectories in Free-route airspace

- **Date**: 21^{th} of May 2018 – 0000 UTC
- **Flight**: Malaga to Wroclaw
- **Uncertainties**: Weather variables (50 ensemble members, weather forecast 3 hours in advance from ECMWF)
- **NOx emission**: Boeing Fuel Flow Method 2 (BFFM2)
- **Aircraft**: A320-231 (engine: V2500-A1)
- **Flight level**: FL340 ($\approx$ 10358.5m)
- **Optimization method**: Direct Optimal Control (transcription: trapezoidal, NLP solver: IPOPT, Node: 80)









- ***Simorgh, A.**, Soler, M., González-Arribas (2022). Robust Climate Optimal Aircraft Trajectory Planning Considering Uncertainty in Weather Forecast . 6th CEAS Conference on Guidance, Navigation and Control (EuroGNC).*

Thank YOU

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