Aircraft Trajectory Optimization & Sustainable Aviation Fuel towards Climate Impacts Mitigation

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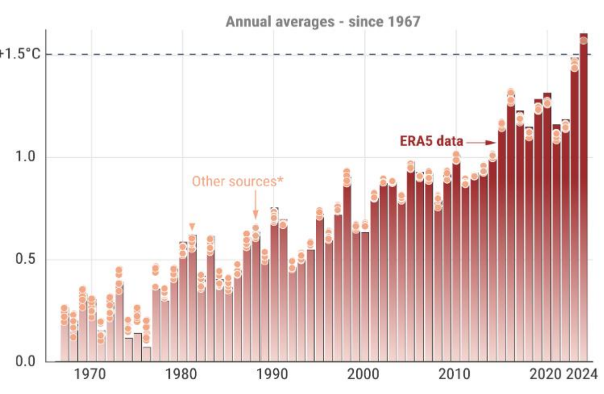
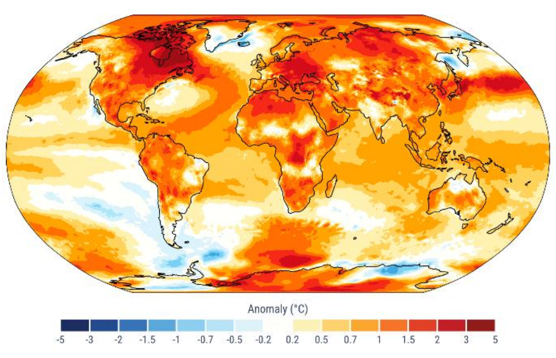
Motivation

2024 marked the first year with average temperatures clearly exceeding 1.5°C above pre-industrial levels.



Global surface temperature increase above pre-industrial



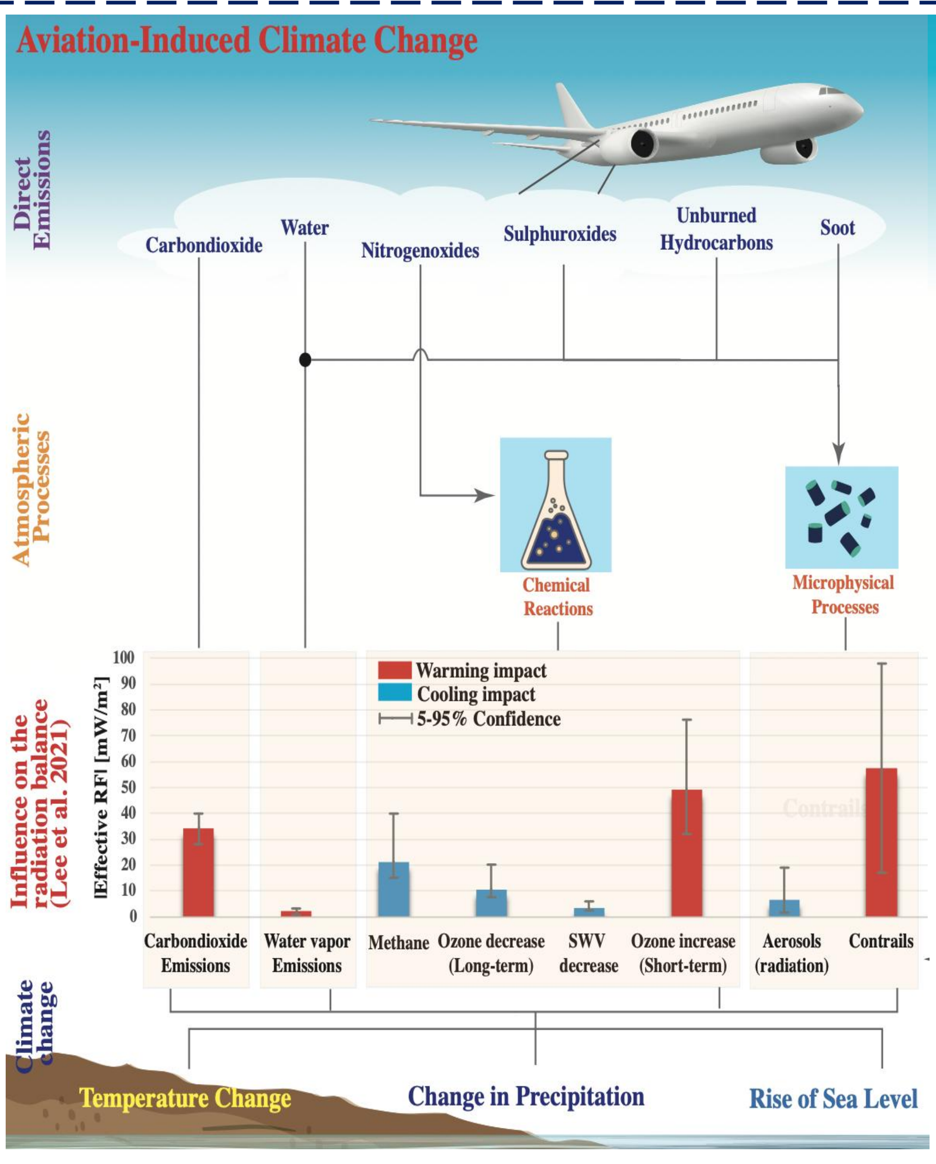
Surface air temperature anomalies in 2024

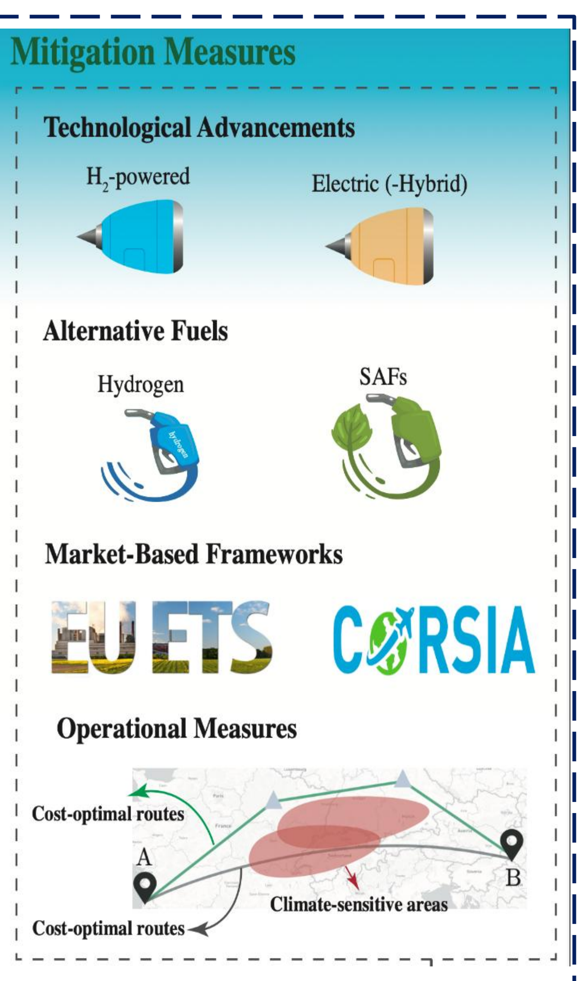
Aviation plays a significant role in climate change and needs urgent and effective solutions to meet global climate goals.

- ❑ **CO_2 emissions $\simeq$ 1/3**
- ❑ **Non-CO_2 effects $\simeq$ 2/3 (e.g., contrails and NOx-induced effects)**

This thesis focuses on the most immediate measures to address aviation-induced climate change, i.e., the integration of:

- ❑ **Aircraft Trajectory Optimization (effective for non-CO_2)**
- ❑ **Sustainable Aviation Fuels (effective for CO_2 and non-CO_2)**





Long-term sol.: Tech. advancement
Medium/short term solutions:

- ❑ Operations
- ❑ SAF

Introduction

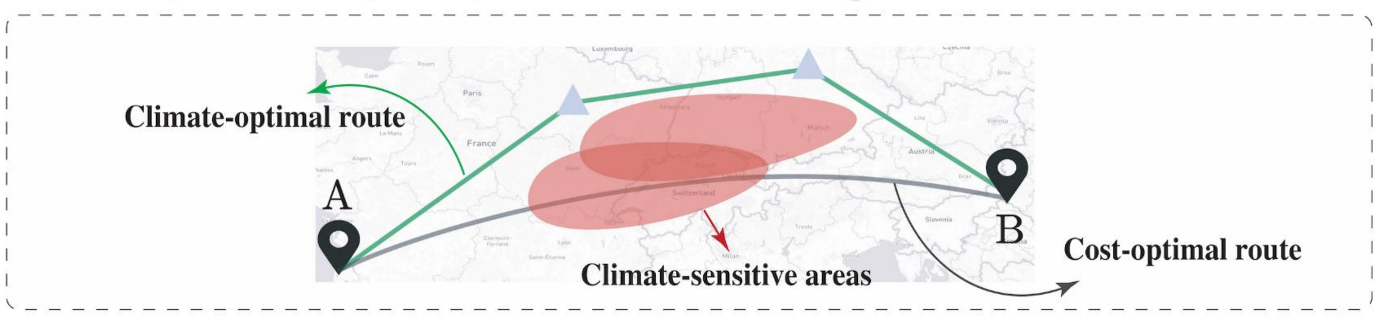
Climate-Optimized Flight Planning:

- ❑ Effective mitigation of **non-CO_2** climate impacts due to the spatiotemporal dependency of these effects.
- ❑ Rerouting of many flights can lead to operational infeasibility, resulting in increased air traffic complexity.

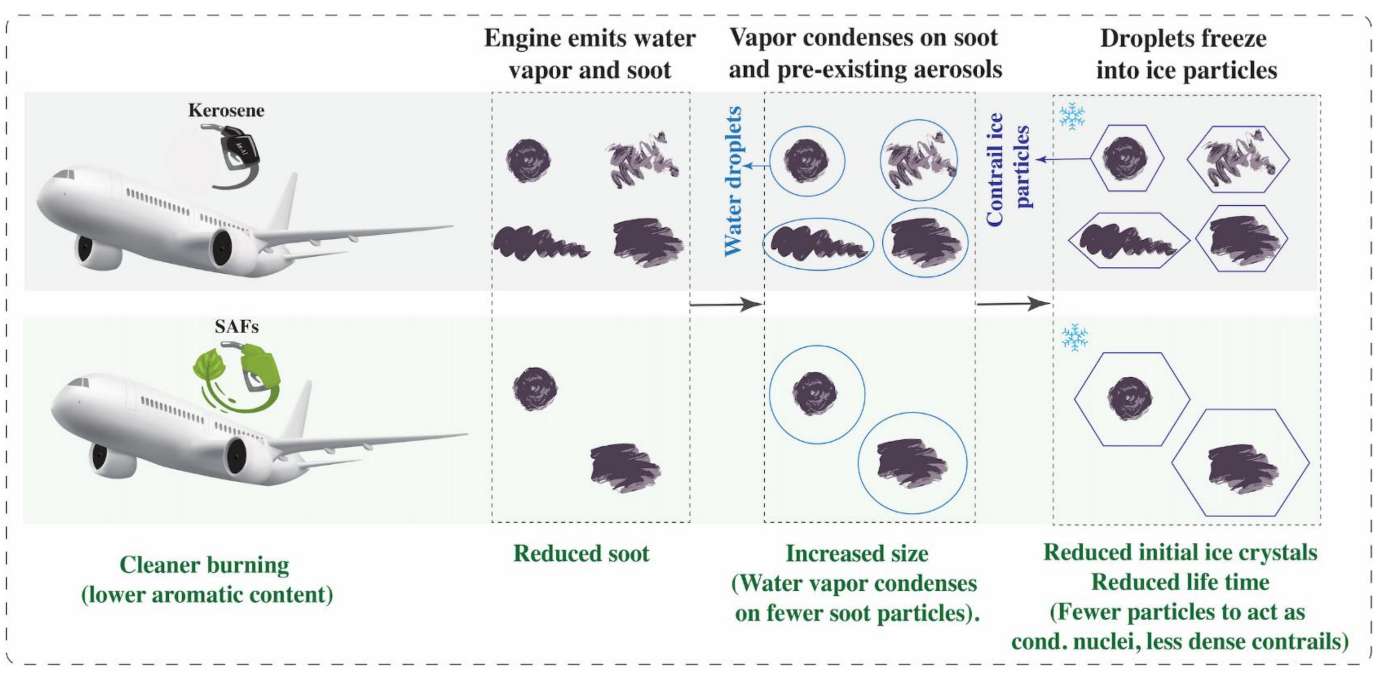
Sustainable Aviation Fuel:

- ❑ Can mitigate **"well-to-wake"** CO_2 equivalent emissions by up **to 94%.**
- ❑ May reduce fuel flow by up to 2.5%, contributing to cutting down its **CO_2** emissions.
- ❑ Can potentially mitigate specific non-CO_2 effects, more precisely contrails, though it requires a better understanding.
- ❑ More production-intensive and costly than kerosene, leading to limited availability in the short term.

I) Climate-optimized routing to mitigate aviation-induced non-CO_2 climate effects



II) Sustainble aviation fuels to reduce warming impact of contrails



Problem Statement

How can we effectively utilize SAF and climate-optimal flight planning to maximize climate benefits while ensuring operational feasibility and accounting for current SAF limitations?

State-of-the-art

All studies in the literature on climate-optimized flight planning are focused on conventional kerosene-based aircraft.

Scientific gaps:

- ❑ There is a need to quantify and estimate SAF-powered aircraft emissions, as well as the induced CO_2 and non-CO_2 effects.
- ❑ There is a need for climate-optimized flight planning considering SAF-powered aircraft.
- ❑ There is a need to investigate the combined mitigation potential of SAF usage and flight planning under operational and fuel availability constraints. This requires large-scale analysis supported by high-fidelity, fast-time flight planning tools.

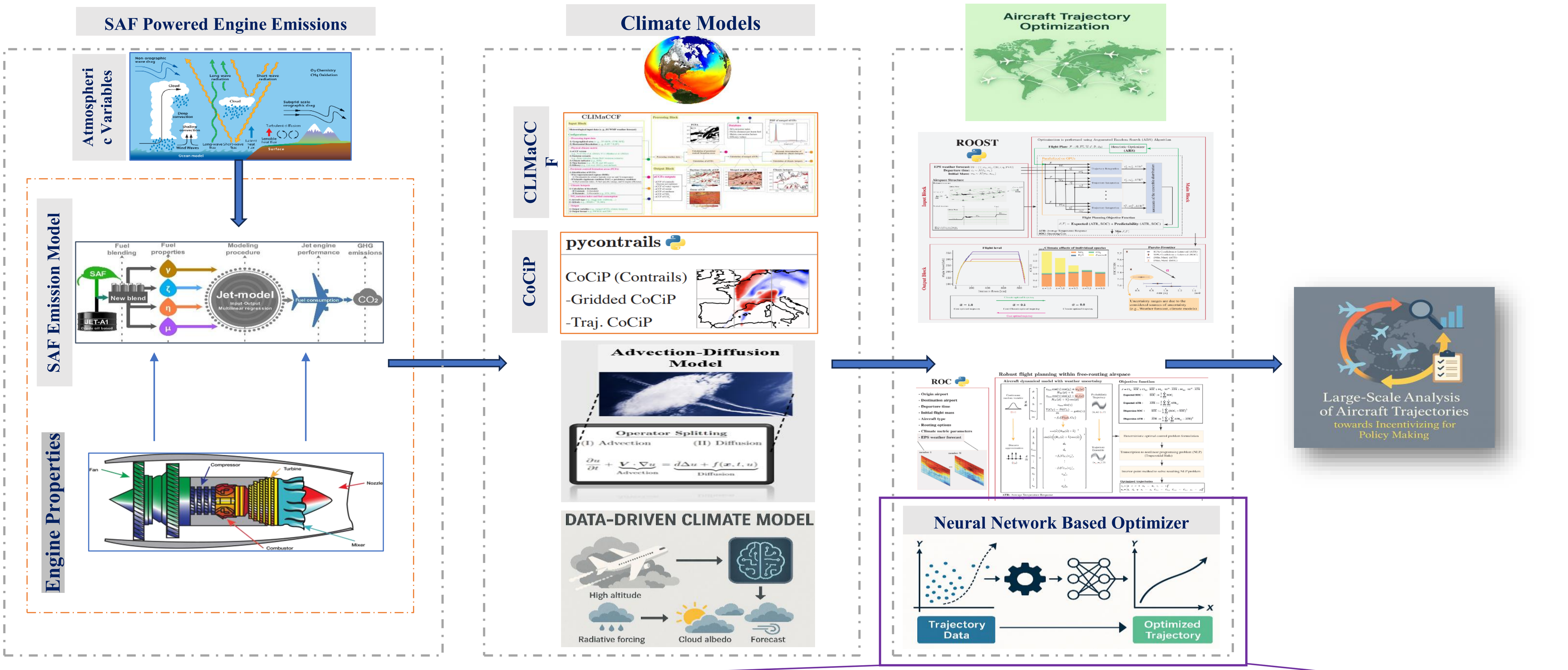
Scientific Goals

SG1: Developing climate impact estimation models for SAF-powered aircraft

SG2: Bridging AI and optimal control to develop data-driven aircraft trajectory optimization to increase the computational efficiency

SG3: Conducting large-scale analysis of the mitigation potential of SAF and climate-optimized flight planning to inform and support evidence-based policy decisions.

Methodology



Optimal Control Problem Formulation

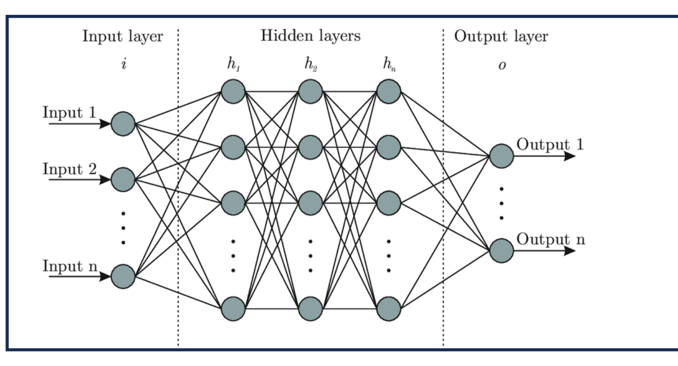
$$\min_{u\in U} J(t_0,t_f,x,u) = M(t_0,t_f,x,x(t_0),x(t_f)) + \int_{t_0}^{t_f} L(x(t),u(t),p,t)\,dt$$

$$\text{s.t.:}\quad \dot{x}(t) = f(t,p,x(t),u(t)) \quad : \text{DAE}$$

$$h(x(t),u(t),p,t) = 0,$$

$$g(x(t),u(t),p,t) \le 0$$

$$\Psi(t_0,t_f,x,x(t_0),x(t_f)) = 0$$



$\forall \varepsilon > 0,\ \exists N \in \mathbb{N},\ \exists \alpha_i, b_i \in \mathbb{R}$, vectors $w_i \in \mathbb{R}^n$ for $i = 1,\dots,N$:

$$\hat{f}(x) = \sum_{i=1}^{N} \alpha_i \sigma(w_i^T x + b_i)$$

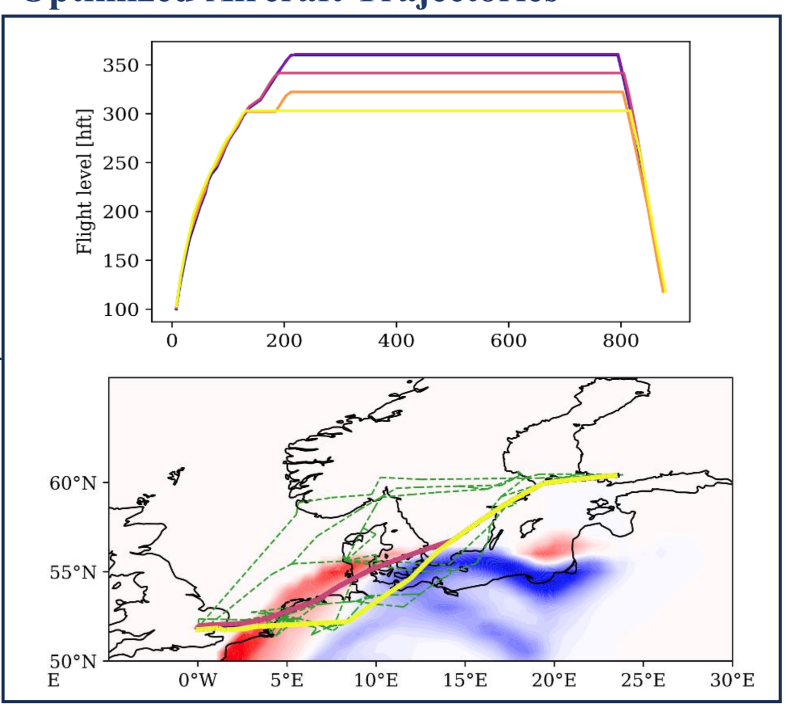
satisfies

$$|\hat{f}(x) - f(x)| < \varepsilon \quad \forall x \in K.$$

That is, $\hat{f}$ uniformly approximates f on K.

Optimization Approach (Supervised or unsupervised)

Optimized Aircraft Trajectories



References

[1] A. Simorgh and M. Soler, "Climate-optimized flight planning can effectively reduce the environmental footprint of aviation in Europe at low operational costs," Communications Earth & Environment, 2024

[2] D. S. Lee, D. Fahey, A. Skowron, M. Allen, U. Burkhardt, Q. Chen, S. Doherty, S. Freeman, P. Forster, J. Fuglestvedt, et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018," Atmospheric Environment, vol. 244, p. 117834, 2021.

[3] C. Voigt, J. Kleine, D. Sauer, R. H. Moore, T. Bräuer, P. Le Clercq, S. Kaufmann, M. Scheibe, T. Jurkat-Witschas, M. Aigner, et al., "Cleaner burning aviation fuels can reduce contrail cloudiness," Communications Earth & Environment, vol. 2, no. 1, p. 114, 2021.

[4] Simorgh, Abolfazl, and Manuel Soler. "Pathways to Sustainable Aviation: Aligning Flight Plans with Climate Goals." Communications Earth & Environment (2025).

Acknowledgments

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refmap HORIZON EUROPE F4EClim flying ATM for Environment Climate