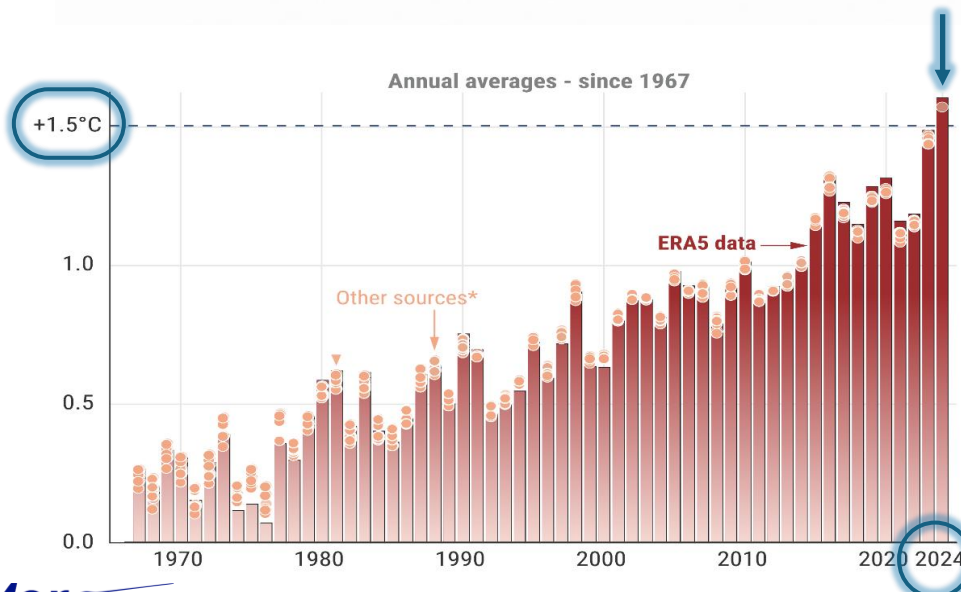
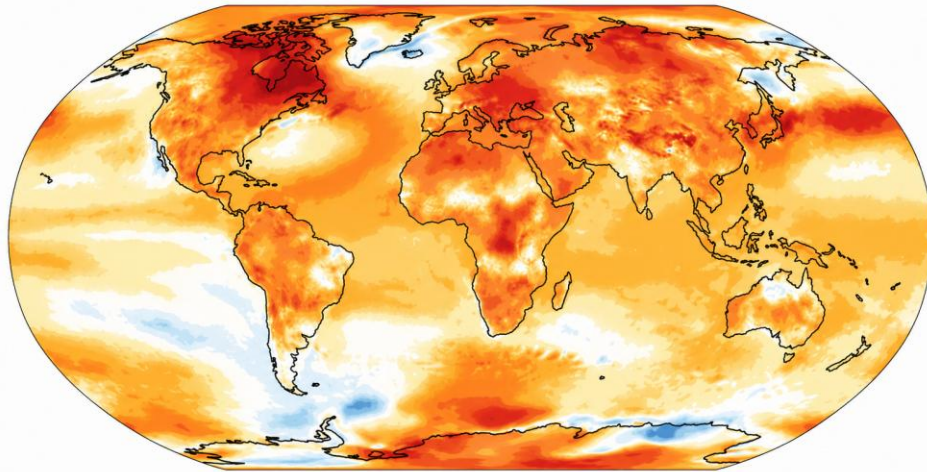


Aircraft Trajectory Optimization with Sustainable Aviation Fuel for Climate Impact Mitigation

PhD Student: Oumarou Moussa Bola
Supervisors: Abolfazl Simorgh, Manuel Soler

**Acknowledgments to grant N^o PIPF-2024/ECO-35509
Comunidad de Madrid**

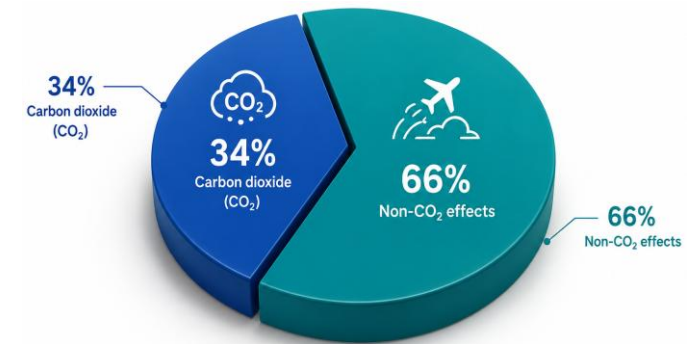
**PhD Aerospace Engineering UC3M
Doctoral Meetings 2026
2nd and 3rd June 2026**



❑ **Aviation** contributes to climate change by emitting various pollutants such as:

- Carbon dioxide (CO₂); **34%**
- Non-CO₂ effects; **66%**

e.g., Contrails, Nox-induced Ozone and CH₄, H₂O.....etc



❑ All in all, the sector currently accounts for approximately:



**10% OF TRANSPORT SECTOR
EMISSIONS**



**2-3% OF GLOBAL CO₂
EMISSIONS**



**3-5% OF TOTAL ANTHROPOGENIC
RADIATIVE FORCING (RF)**

Mitigation Measures

CO₂

Technological solutions

(Hybrid-) Electric aircraft



⋮

Hydrogen-powered aircraft



Alternative fuels

Sustainable aviation fuel



⋮

Hydrogen



Market-based measures

EU emission trading system



⋮

CORSIA



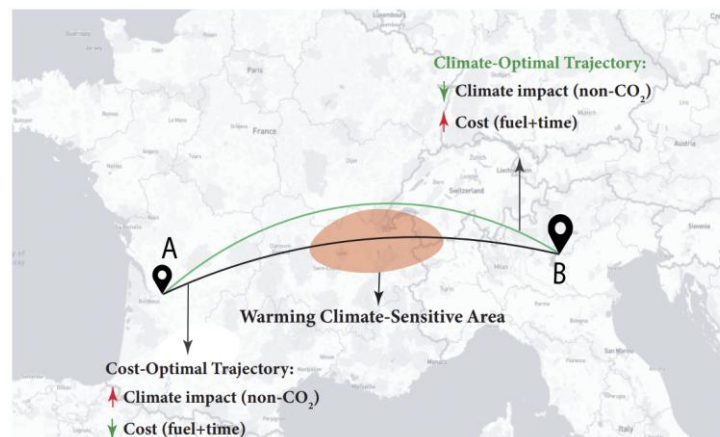
- Can be beneficial for non-CO₂ effects
- **Medium-to long-term** measures

Non-CO₂

Operational measure

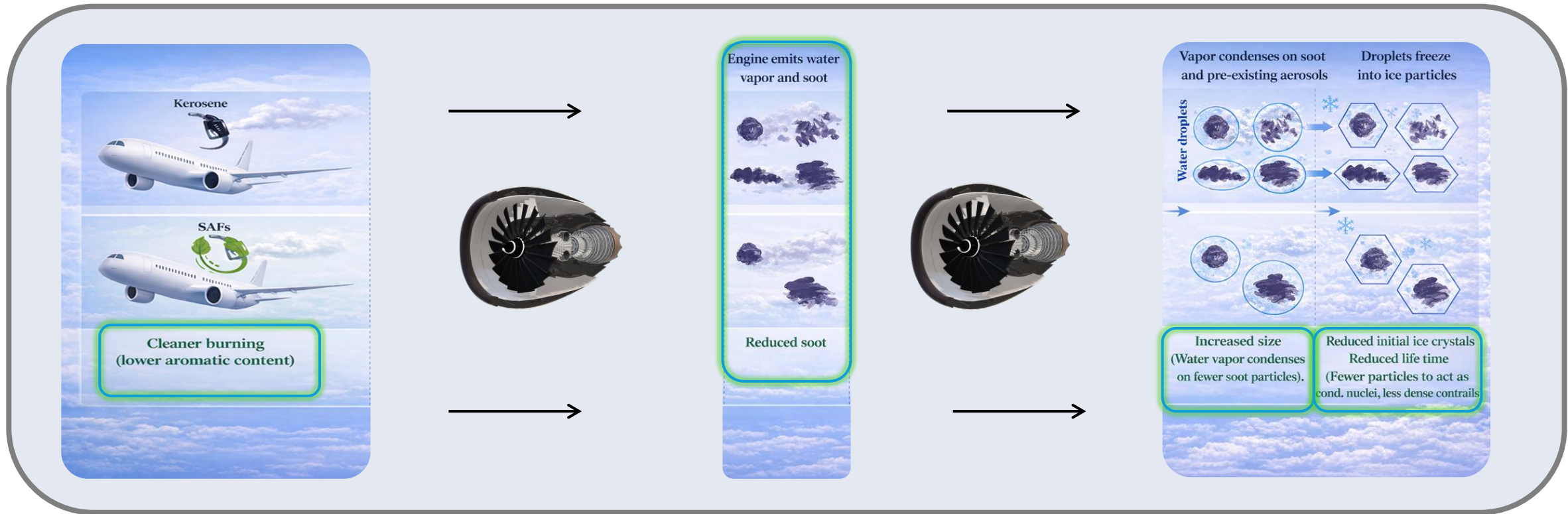
Flight Planning

“Non-CO₂ effects have a strong dependency on the time and Location of emissions”



- **Feasible** with existing infrastructures
- Relatively **short-term** measure
-  **Large-scale** flight rerouting may increase air traffic complexity and compromise operational feasibility.

SAF Benefits and Limitations



1

Up to 94% lifecycle CO₂ reduction

Compared to conventional kerosene on a well-to-wake basis.

2

Up to 2.5% fuel flow reduction

May reduce fuel flow and contribute to lower CO₂ emissions.

3

Mitigates non-CO₂ effects

Specifically reduces contrail formation and its climate impact.

4

Limited availability

More production-intensive than kerosene, leading to limited availability in the short term.

Literature review on trajectory optimization for climate impact mitigation

STUDY	FUEL	Climate effects	CONSIDERED FACTORS		FLIGHT PLANNING
	SAF	All using aCCF/CCFs model	Uncertainty		Methodology
(Matthes, Lührs et al., 2020)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	-		Direct opt. control
(Yamashita, Yin et al., 2020)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	-		Genetic algo.
(Yamashita, Yin et al., 2021)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	-		Genetic algo.
(Lührs, Linke et al., 2021)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	-		Direct opt. control
(Niklass, Grewe et al., 2021)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	-		Direct opt. control
(Vitali, Battipede et al. 2021)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	-		Direct opt. control
(Yin, Grewe et al. 2023)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	-		Genetic algo.
(Castino 2023)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	-		Genetic algo.
(Simorgh, Soler et al. 2023)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	MET		Augmented Random Search
(Simorgh, Soler et al. 2024)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	MET		Direct opt. control
(Simorgh, Soler et al. 2025)	-	Contr., O ₃ , CH ₄ , H ₂ O, CO ₂	MET		Augmented Random Search
(Chevallier, Guitart et al. 2025)	-	Contr., CO ₂	MET		Fast Marching Tree
(Demouge, Guitart et al. 2026)	-	Contr., CO ₂	-		Fast Marching Tree

Research Gaps and Scientific Objectives



Research Gaps

- Existing studies on **Climate-Optimized Flight planning** are focused on **kerosene-based aircraft** operations;
- ↓
- Need** for accurate **SAF emissions quantification and climate impact estimation**;
- ↓
- No studies** have investigated the potential of **SAF** and **Flight planning** to address both **CO₂** and **non-CO₂** climate effects under operational and fuel availability constraints.



Research main objectives

- O.1:** Climate-optimized flight planning with SAF;
- ↓
- O.2:** Conducting large-scale analysis of the mitigation potential of SAF and climate-optimized flight planning to inform and support evidence-based policy decisions;
- ↓
- O.3:** Develop AI-Based aircraft trajectory optimization that increases the computational efficiency of the state-of-the-art optimizers.

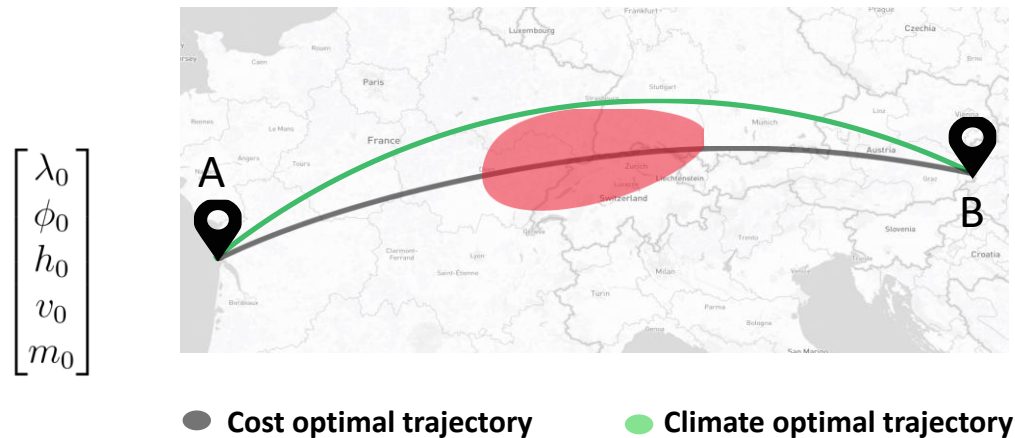
Research Question



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?

General Formulation Of the Problem

To generate feasible and efficient trajectories between origin and destination pairs:



$$\begin{bmatrix} \lambda_f \\ \phi_f \\ h_f \\ v_f \\ m_f \end{bmatrix}$$

Problem formulation

$$\min_{\mathbf{u}(t)} J = \mathbb{E} \left\{ M(t_0, t_f, \mathbf{x}(t_0), \mathbf{x}(t_f)) + \int_{t_0}^{t_f} L(\mathbf{x}(t, \delta), \mathbf{u}(t, \delta), \mathbf{z}(t, \delta), \zeta(\delta)) dt \right\}$$

$$\text{Subject to: } \dot{\mathbf{x}}(t) = \mathbf{f}(\mathbf{x}(t, \delta), \mathbf{u}(t, \delta), \mathbf{z}(t, \delta), \zeta(\delta))$$

$$\mathbf{x}(t_0) = \Psi_0(\zeta(\delta), t_0)$$

$$\mathbf{h}(\mathbf{x}(t, \delta), \mathbf{u}(t, \delta), \mathbf{z}(t, \delta), \zeta(\delta)) = 0$$

$$\mathbf{g}(\mathbf{x}(t, \delta), \mathbf{u}(t, \delta), \mathbf{z}(t, \delta), \zeta(\delta)) \leq 0$$

$$\mathbb{E} \{ \Psi(t_0, t_f, \mathbf{x}(t_0), \mathbf{x}(t_f)) \} = 0$$

$$T_{\mathbf{x}}(\mathbf{x}(t, \delta_1) - \mathbf{x}(t, \delta_2)) = 0, \forall \delta_1, \delta_2 \in \Delta$$

$$T_{\mathbf{u}}(\mathbf{u}(t, \delta_1) - \mathbf{u}(t, \delta_2)) = 0, \forall \delta_1, \delta_2 \in \Delta$$

$$T_{\mathbf{z}}(\mathbf{z}(t, \delta_1) - \mathbf{z}(t, \delta_2)) = 0, \forall \delta_1, \delta_2 \in \Delta$$

Flight Planning objectives

- **Operating Cost:** $= \psi_t \cdot \text{Exp. Flight Time} + \psi_m \cdot \text{Exp. Fuel Burn}$
 $= \psi_t \cdot \mathbb{E}[t_f(\omega) - t_0(\omega)] + \mathbb{E}[m_0(\omega) - m_f(\omega)]$
- **Climate Impacts Estimates: aCCF, CoCiP**

$$\mathbb{E}[\text{ATR}] := \mathbb{E} \left[\int_{t_0}^{t_f} \sum_{i=1}^5 \psi_{\text{ATR}, i} \text{ATR}_i(t, \mathbf{x}(t), \mathbf{u}(t), \zeta) dt \right], \text{ for } i \in \{\text{CH}_4, \text{Cont.}, \text{O}_3, \text{H}_2\text{O}, \text{CO}_2\}$$

Aircraft Dynamical Model

$$\frac{d}{dt} \begin{bmatrix} \phi \\ \lambda \\ h \\ v_{\text{tas}} \\ m \end{bmatrix} = \begin{bmatrix} (v_{\text{tas}} \cos(\gamma) \cos(\chi) + w_y) (R_M(\phi) + h)^{-1} \\ (v_{\text{tas}} \cos(\gamma) \sin(\chi) + w_x) ((R_N(\phi) + h) \cos(\phi))^{-1} \\ v_{\text{tas}} \sin(\gamma) \\ (T(C_T) - D(C_L)) m^{-1} - g \sin(\gamma) \\ -f_c(C_T) \end{bmatrix}$$

Flight Envelope Limitations

$$v_{\text{CAS, stall}} \leq v_{\text{CAS}}(v) \leq v_{\text{CAS, max}}$$

$$C_{T, \min} \leq C_T \leq C_{T, \max}$$

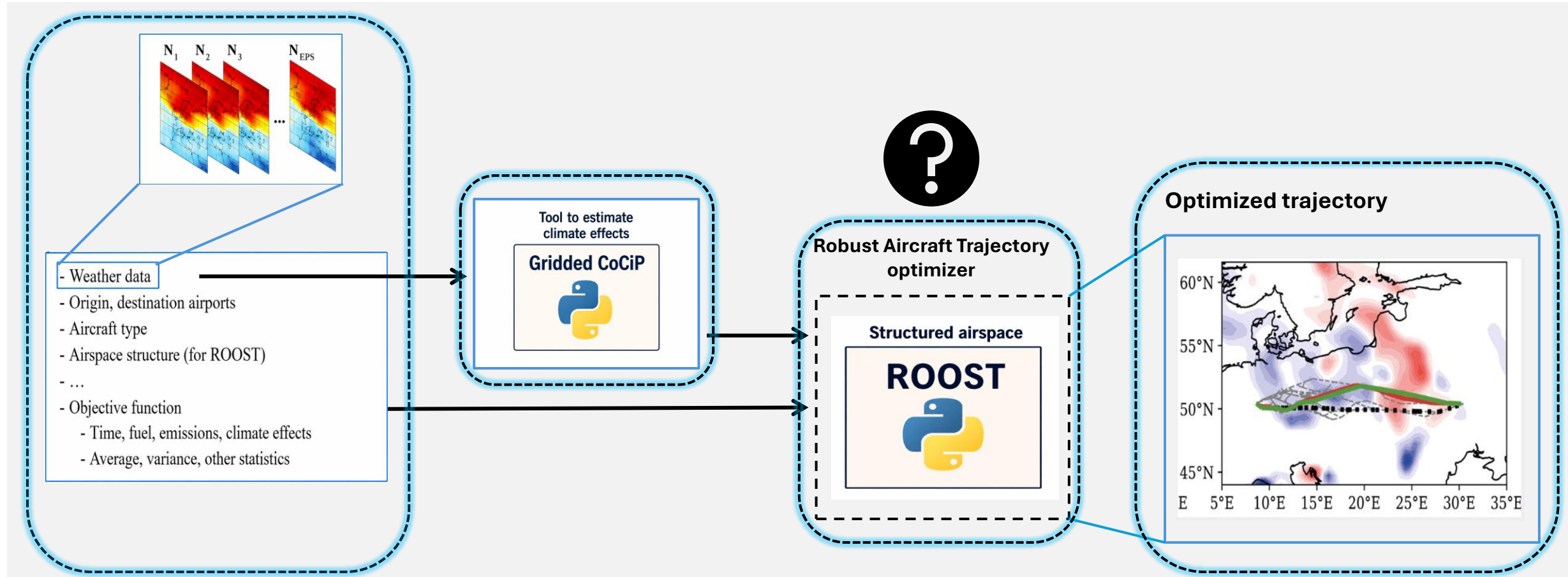
$$M(v_{\text{tas}}) \leq M_{\max}$$

$$C_L \leq C_{L, \max}$$

$$h \leq h_{\max}$$

Single Case Analysis: Methodology

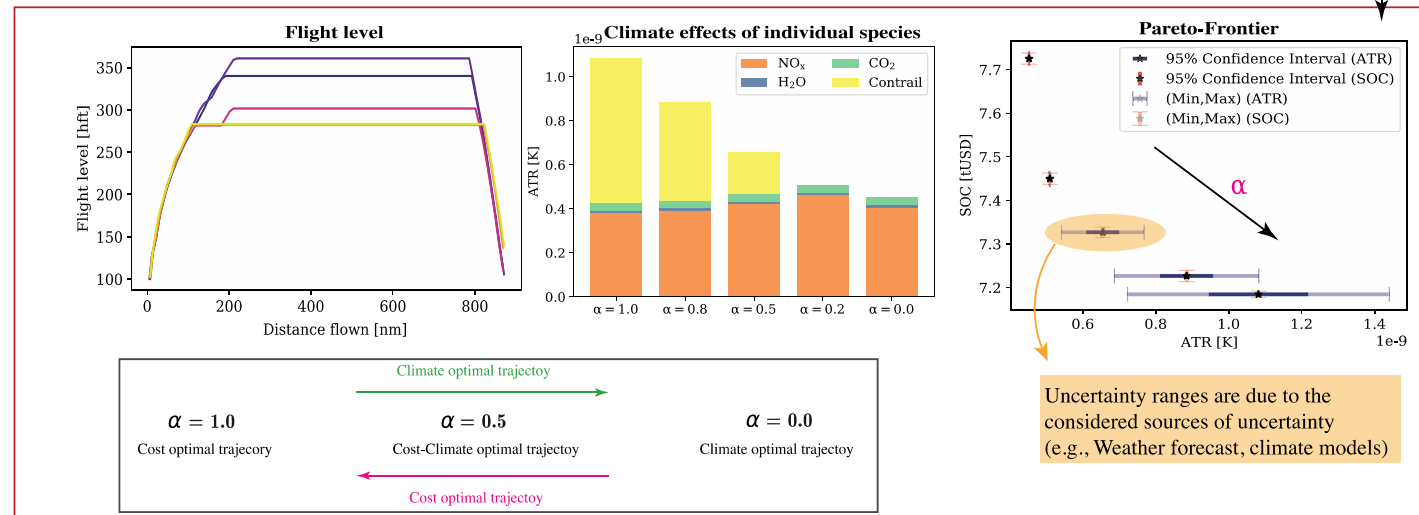
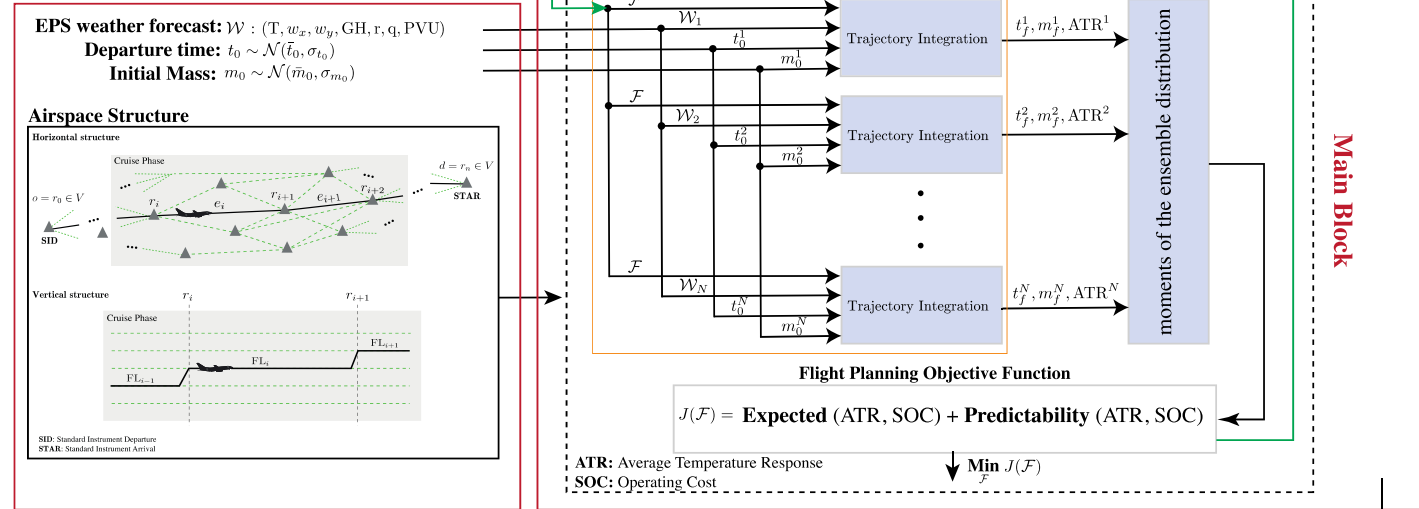
0.1: Climate-optimized flight planning with SAF;



Robust Optimization Of Structured Trajectories: ROOST

Features:

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



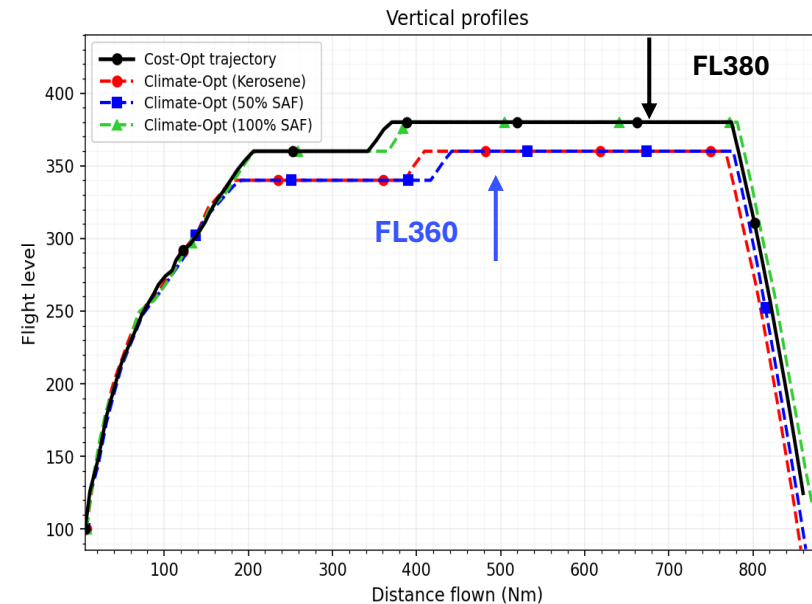
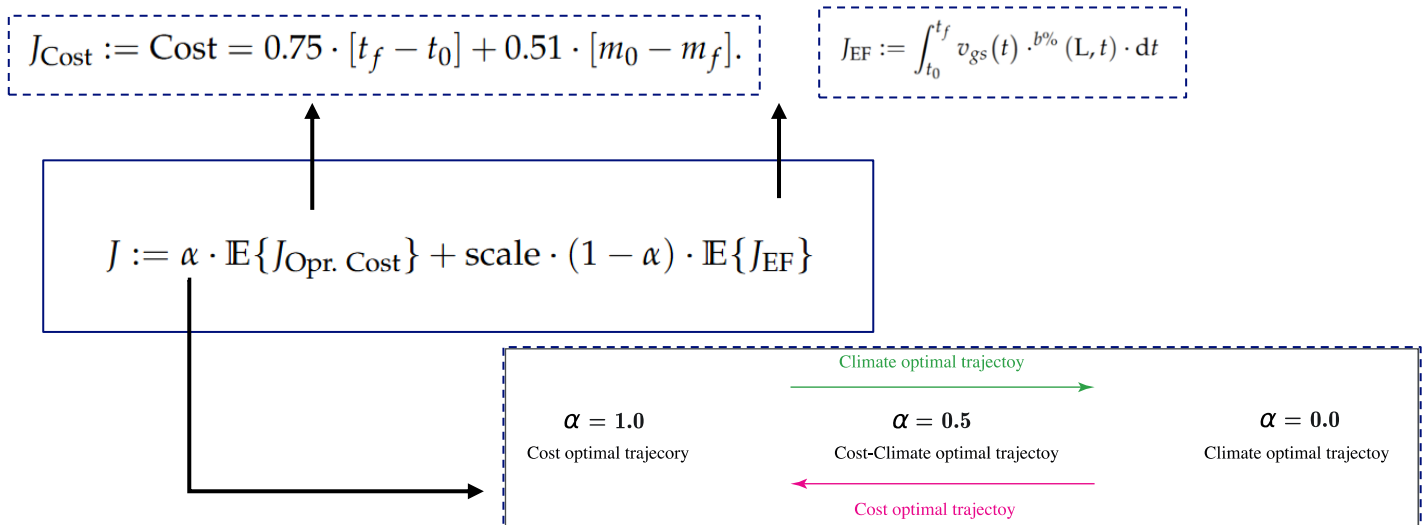
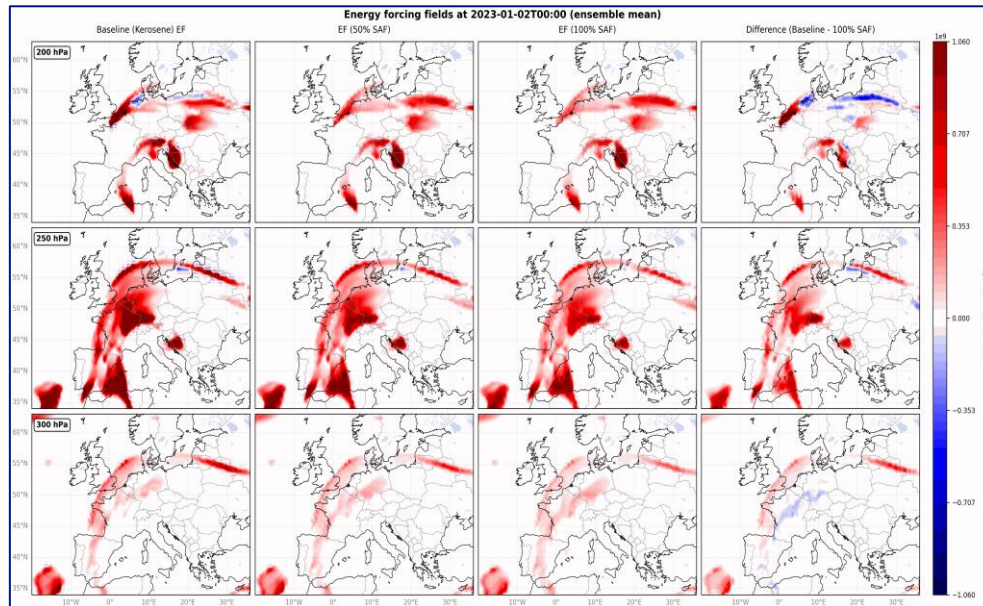
<https://github.com/Aircraft-Operations-Lab/roost>

Simorgh, A., Soler, M., González-Arribas, D., Linke, F., Lührs, B., Meuser, M.M., Dietmüller, S., Matthes, S., Yamashita, H., Yin, F. and Castino, F., 2023. Robust 4D climate-optimal flight planning in structured airspace using parallelized simulation on GPUs: ROOST V1.0. *Geoscientific model development*, 16(13), pp.3723-3748.

González-Arribas, D., Baneshi, F., Andrés, E., Soler, M., Jardines, A., & García-Heras, J. (2023). Fast 4D flight planning under uncertainty through parallel stochastic path simulation. *Transportation Research Part C: Emerging Technologies*, 148, 104018.

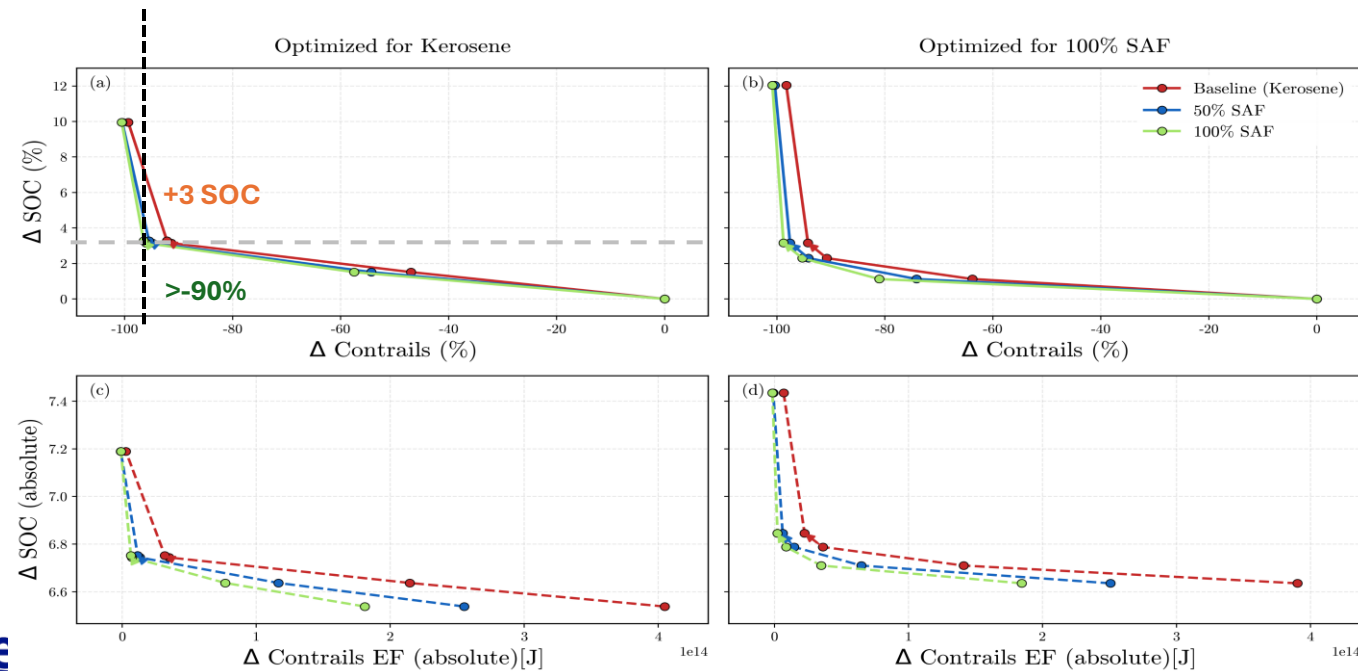
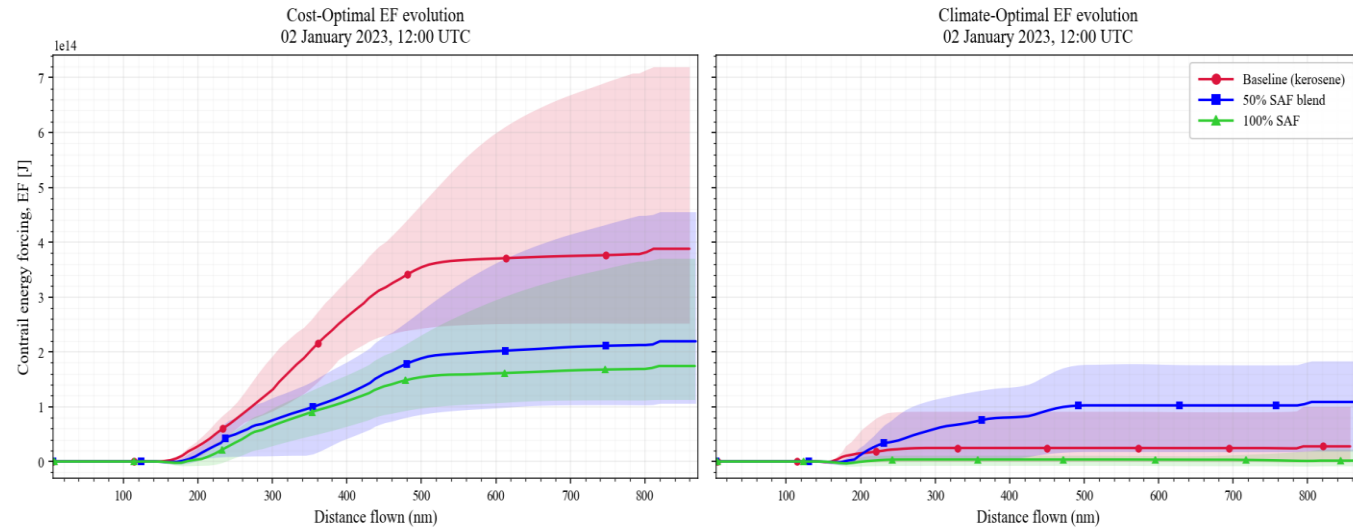
Midday Assessment: Departure @ UTC 12h00

- ❑ **Date:** Jan 2nd, 2023
- ❑ **Optimization Framework:** ROOST
- ❑ **Flight:** Frankfurt → Kiev
- ❑ **Fuel types:** Kerosene, 50% Kerosene - SAF Blend, 100% SAF
- ❑ **Aircraft:** A320-231 (engine: V2500-A1)
- ❑ **Climate Impacts:** Gridded CoCiP

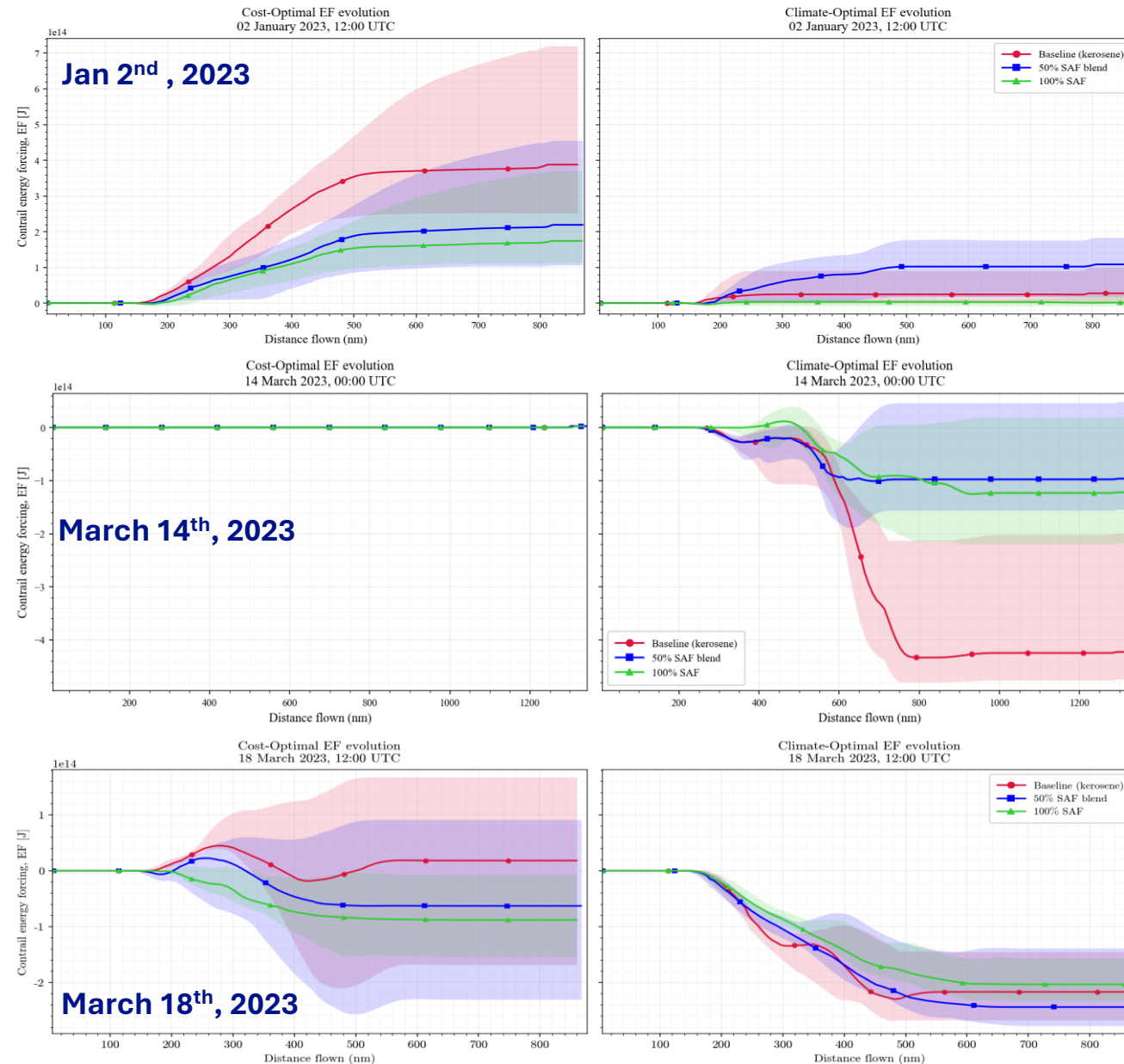


For this specific scenario of flight, day and departure time, the vertical profile shows:

- Higher cruise altitude for the Cost Optimal trajectory and the **climate-optimal** trajectory of **100% SAF** operation;
- The flights operated with **50% SAF** and **full kerosene** tend to fly at slightly lower altitude.



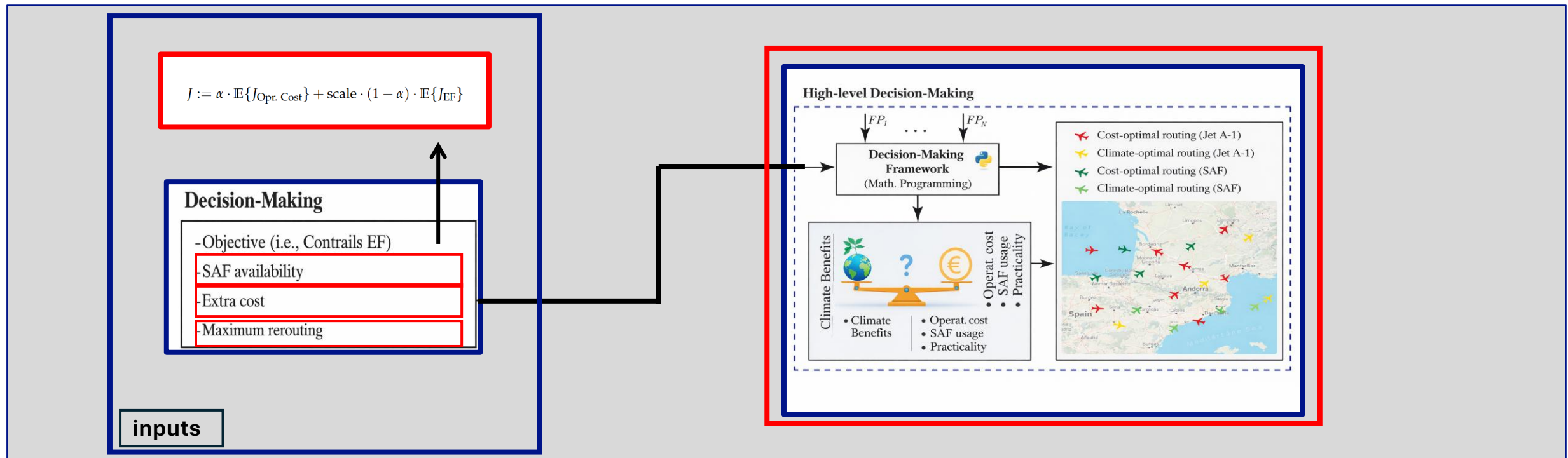
Results & Insights Phase 1: Single-flight experiments (2023)



Insights:

- Within each individual case, increasing SAF blending tends to reduce contrail energy forcing when the effect of the contrail in that specific flights (which dependent on the atmospheric conditions, locations and time of Emission) is warming.
- We can see a substantial reduction in the contrail Energy forcing as SAF blends increases for warming contrails
- And that for both cost and climate optimal trajectories
- It is clear that climate-optimal routings lead to noticeable differences in contrail forcing compared to cost-optimal trajectories.
- However, in case the effect is cooling, the benefits is reduced given that the initial number of ice water concentration is reduced and in turn it shortens the lifetime of the formed persistent contrails.

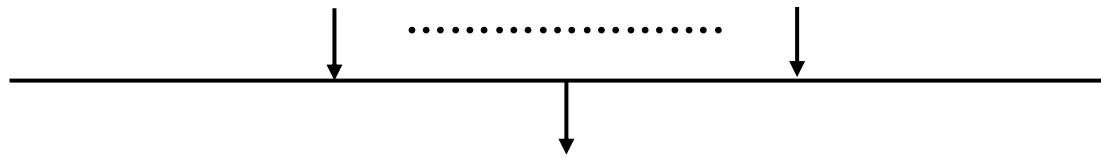
Decision Making Framework



Considering optimizing N flights using the proposed approach, for each flights several alternative exists for both routing options and blending ratios:

$$B := \{0\%, 50\%, 100\%\}$$

$$FP_k = [FP_k^{0,0\%}, \dots, FP_k^{n_k,0\%}, \dots, FP_k^{n_k,100\%}]$$



$$FP_k^{r,b\%} := [Fuel-S_k^{r,b\%}, Fuel-K_k^{r,b\%}, Cost_k^{r,b\%}, EF_k^{r,b\%}]$$

Decision Making Framework

For the optimal selection of one alternative per flight based on the criteria discussed earlier, we define a vector of binary decision variables for all alternatives across all flights, i.e.,

$$\mathbf{x} := [\mathbf{x}_1, \dots, \mathbf{x}_N];$$

$$\mathbf{x}_k := [x_k^{0,0\%}, \dots, x_k^{n_k,0\%}, \dots, x_k^{n_k,100\%}]$$

where $x_k^{r,b\%} \in \{0,1\}$ is a binary variable that indicates whether the k^{th} flight adopts routing option r with a blending ratio of $b\%$.

Based on these definitions, the decision-making problem is simply stated as follows:

$$\begin{aligned} \min_{\mathbf{x}} \quad & \sum_{k=1}^N \sum_{r=1}^{n_k} \sum_{b \in B} x_k^{r,b\%} \cdot EF_k^{r,b\%}, \\ \text{w.r.t.} \quad & \frac{1}{\text{Cost}_{\text{BAU}}} \left(\sum_{k=1}^N \sum_{r=1}^{n_k} \sum_{b \in B} x_k^{r,b\%} \cdot \text{Cost}_k^{r,b\%} \right) \leq P_c, \\ & \frac{1}{\text{Fuel}_{\text{net}}} \left(\sum_{k=1}^N \sum_{r=1}^{n_k} \sum_{b \in B} x_k^{r,b\%} \cdot \text{Fuel-S}_k^{r,b\%} \right) \leq P_{\text{saf}}, \\ & \sum_{r=1}^{n_k} \sum_{b \in B} x_k^{r,b\%} = 1; \quad \text{for } k = 1 \dots N, \\ & \frac{1}{N} \left(\sum_{k=1}^N \sum_{b \in B} x_k^{1,b\%} \right) \geq P_r, \end{aligned}$$

Max increase in operating cost

SAF capacity constraints

Allowable rerouting

With:

$$\text{Cost}_{\text{BAU}} := \sum_{k=1}^N \text{Cost}_k^{1,0\%}$$

$$\text{Fuel}_{\text{net}} := \sum_{k=1}^N \sum_{r=1}^{n_k} \sum_{b \in B} x_k^{r,b\%} \cdot (\text{Fuel-S}_k^{r,b\%} + \text{Fuel-K}_k^{r,b\%}).$$

Aggregated Analysis: Results

Research Question

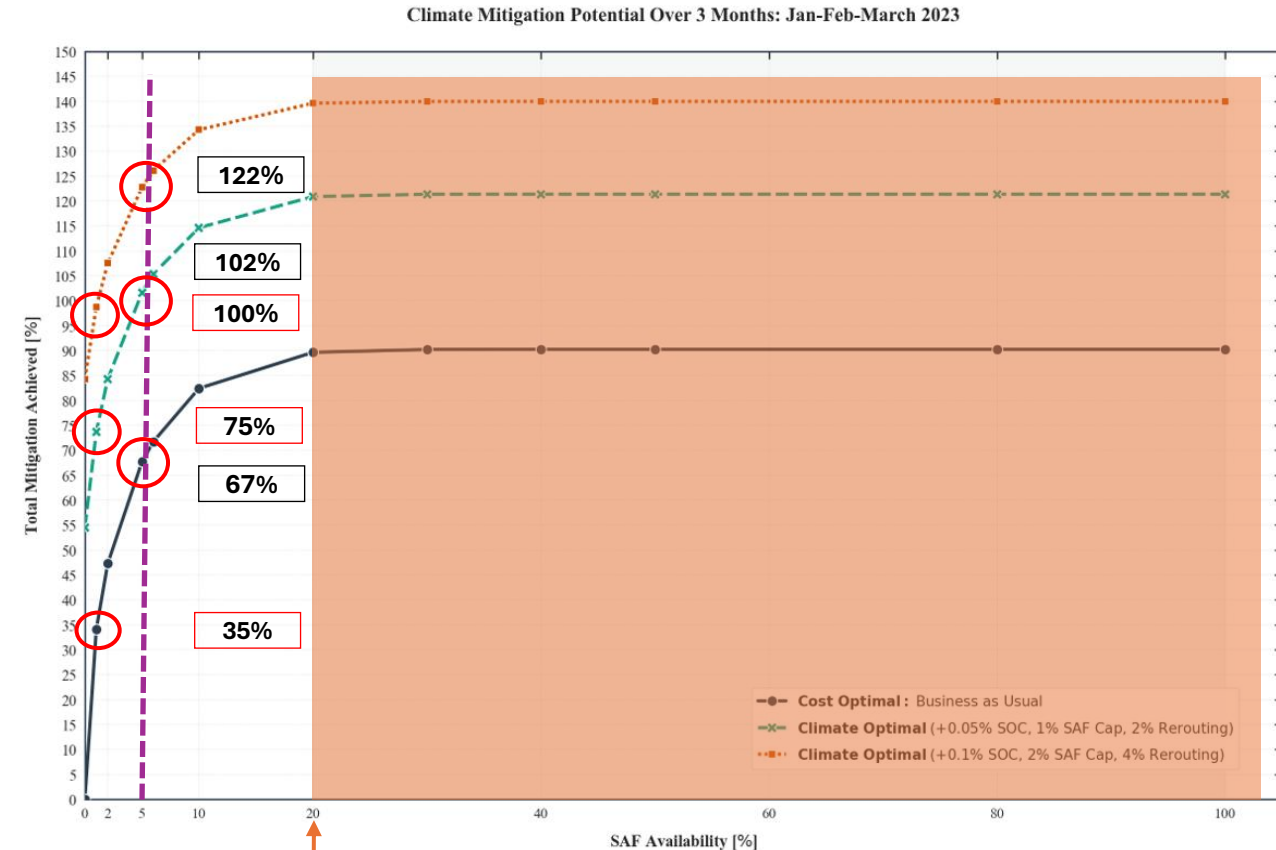


How can we effectively utilize SAF and climate-optimal flight planning to maximize climate benefits while ensuring operational feasibility and accounting for current SAF limitations?

Monthly Assessments: Departure @ 00h00 UTC & 12h00 UTC

- ❑ **Date:** 1st Jan – 31st March
- ❑ **Optimization Framework:** ROOST
- ❑ **Flight:** Top 10 European routes
- ❑ **Fuel types:** Kerosene, 50% Kerosene - SAF Blend, 100% SAF
- ❑ **Aircraft:** A320-231 (engine: V2500-A1)
- ❑ **Climate Impacts:** Gridded CoCiP

- **Climate optimal 1:** +0.05% SOC, 1% SAF Cap, 2% Max Rerouting
- **Climate optimal 2:** +0.1% SOC, 2% SAF Cap, 4% Max Rerouting



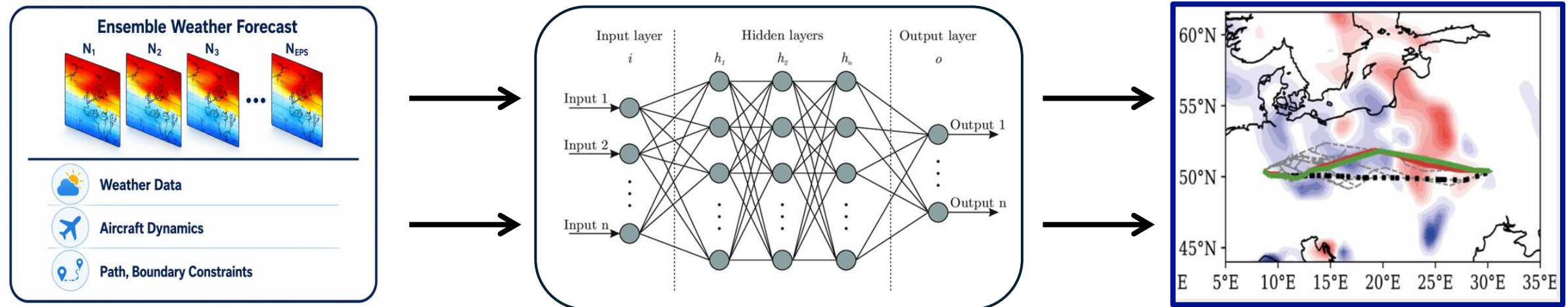
- From **20% SAF Availability** onwards, increasing the production of SAF does not translate in any additional climate benefits.

Ongoing Work: Proposed Solution Based on PiNNS

- ❖ **O.3:** Develop AI-Based aircraft trajectory optimization that increases the computational efficiency of the state-of-the-art optimizers.

Main Limitation of the Current Optimizers:

- The limitation of the current optimizer are essentially the computation cost when performing large scale analysis over several years and for thousands of flight,
- To overcome** this challenge, we aim to develop an AI-driven framework capable of significantly accelerating climate-optimal trajectory generation while maintaining high solution quality.





1. Research Outputs

• Manuscripts

- **Moussa-Bola, O.**, Simorgh, A., & Soler, M. “A Monthly Analysis of Optimal Aircraft Trajectories under Conventional and Sustainable Aviation Fuel Blends.” Target: *Transportation Research Part D* (In preparation).



2. Scientific Dissemination

• Conferences:

- Simorgh, A., **Moussa-Bola, O.**, & Soler, M. “Climate-Optimized Flight Planning & Sustainable Aviation Fuels.” Poster presented at: *TSAS Toulouse Conference, 28-30 Jan 2025*.
- Simorgh, A., **Moussa-Bola, O.**, et al. “Robust Climate-Optimal Flight Planning with Probabilistic Algorithmic Climate Change Function (paCCF) of Ozone.” Presented at: *5th ECATS Conference, 27-29 Jan 2026, Brussels, Belgium*.



3. Research Collaborations & Recognition

• Scholarships

- Comunidad de Madrid Predoctoral Research Fellowship 2024 (Grant No. PIPF-2024/ECO-35509)

• Mentorship Program

- SPARK KIMIYYA – Mentor: Dr. F. Maina (NASA Goddard Space Flight Center). (2025–2026).

• Participation in European projects and research initiatives

- F4ECLIM project
- REFMAP project



4. Courses & Workshops Attended

- PhD Course: “From Optimal Control to Learning-Based Control” – Dr. M. A. Mendez (von Karman Institute). UC3M, Jun 2026.
- “Control and Machine Learning” – Prof. E. Zuazua & Prof. M. Lasar. EECI International Graduate School on Control (Dubrovnik, 2025).
- “Optimization, Optimal and Predictive Control” – AIMS Research & Innovation Centre (Online, May 2025)
- “Advanced Sustainable Aviation Technologies” – TU Braunschweig (Online, 2025)
- Exchange Workshop: Reference Management & Note-Taking Best Practices (UC3M, 10th Jun, 2025).
- “Integrated Environmental Modelling for Sustainable Aviation and Urban Air Mobility” – EUROCONTROL (Online, 2026).
- “Contrail Management: progressing towards risk-informed decision making” – IATA & RAeS (Online, 9-10 March 2026).

Thank you!
Questions?

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