Artificial Neural Networks for the Detection of Contrails and Aviation Induced Cloudiness

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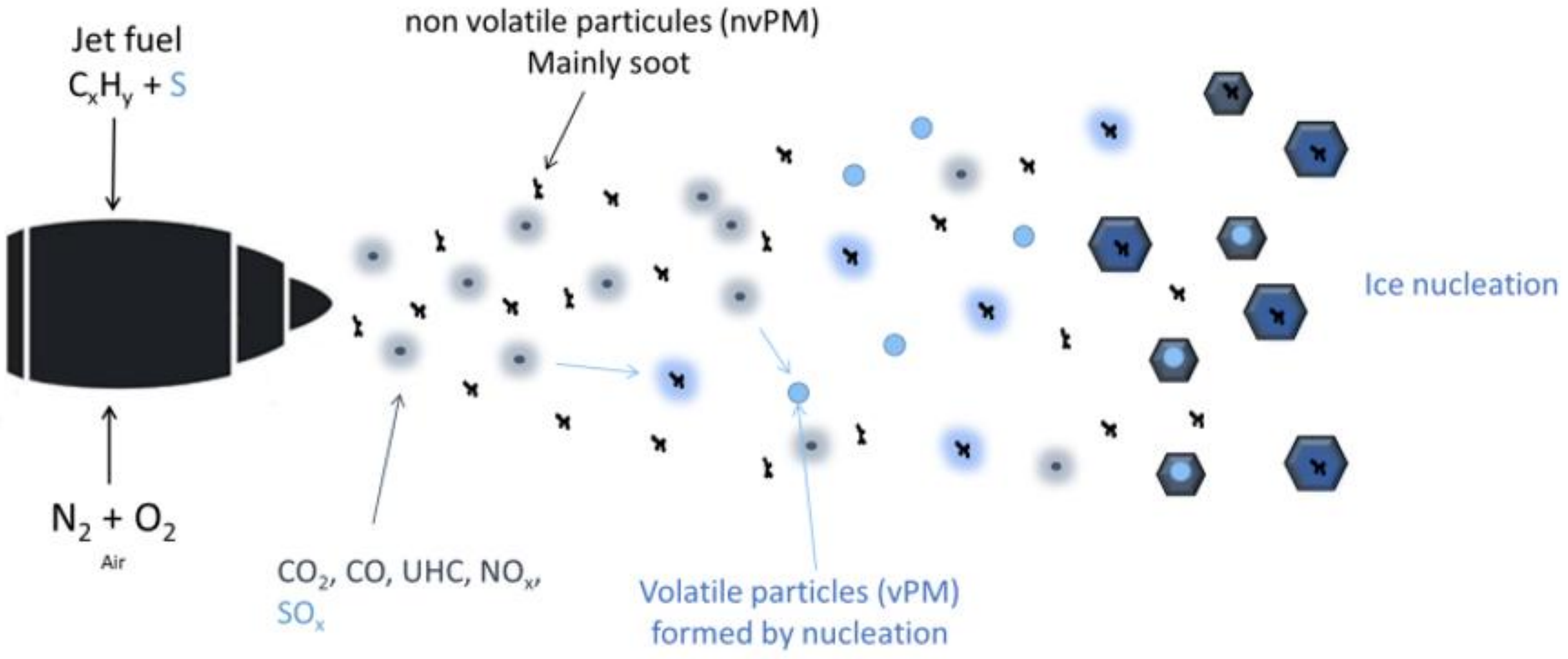
What are contrails?

Jet fuel combustion releases water vapour, gases and particles into very cold ambient air.



Combustion products

- Jet fuel + air → H_2O, CO_2, NO_x, SO_x, volatile particles, and soot

Particle and droplet formation

- Water condenses on exhaust particles and atmospheric particles already present in the ambient air.

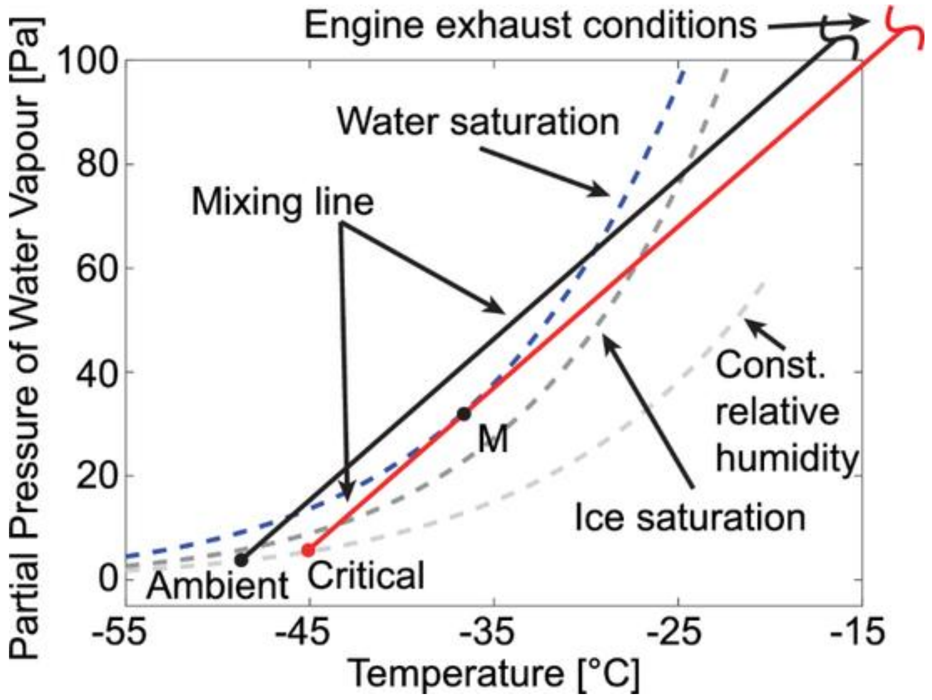
Ice crystals

- At temperatures below ~ −40 °C, water droplets freeze rapidly, producing contrail ice crystals.

What are contrails?

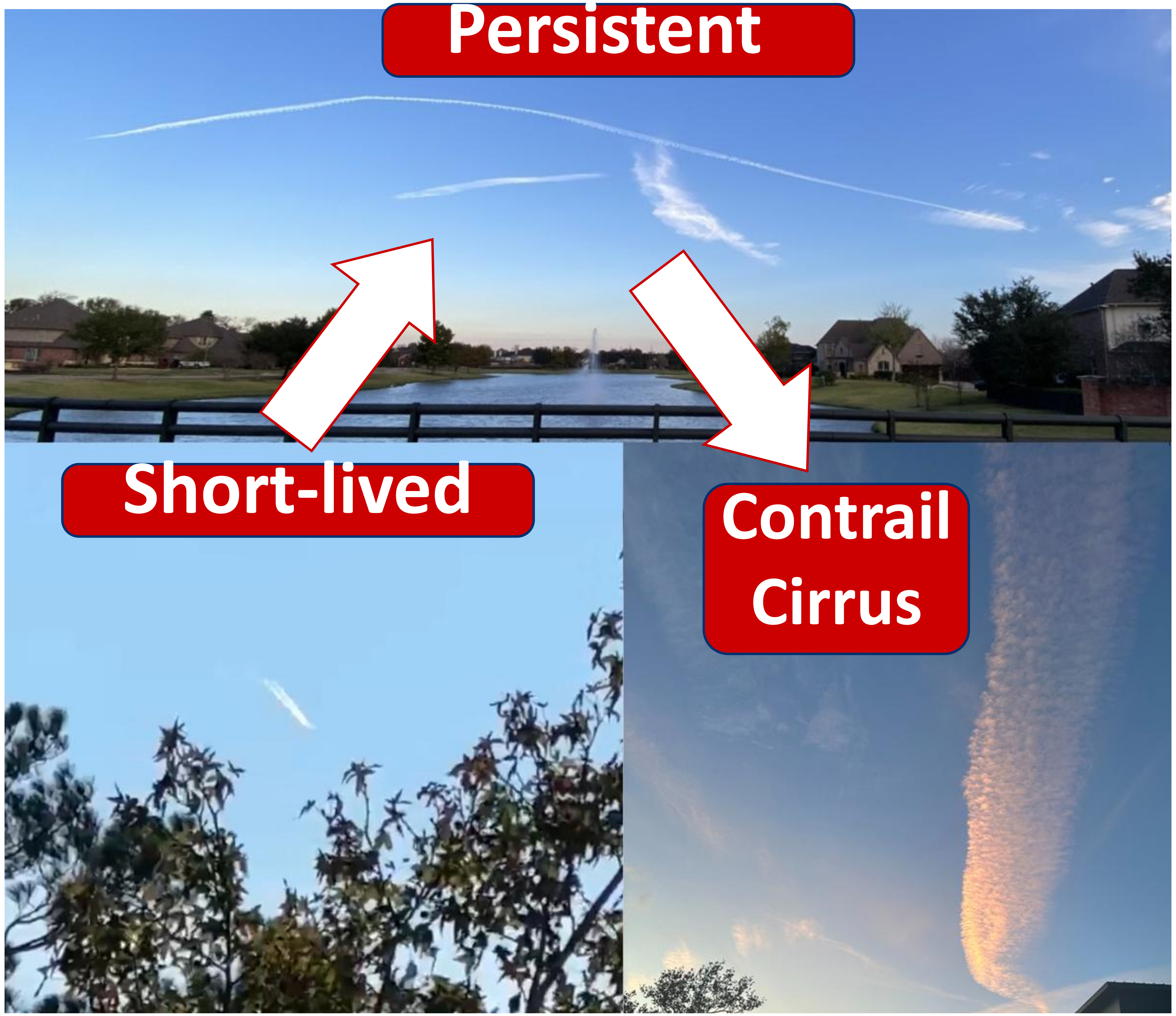
Formation and lifetime depend on atmospheric conditions

Schmidt–Appleman criterion: Hot moist exhaust + cold ambient air → water saturation reached → contrail formation



(Callard et al., 2026)

- In **ice-subsaturated air**, crystals quickly sublimate, producing short-lived contrails.
- In **ice-supersaturated air**, they persist, grow, and spread into contrail cirrus.



Contrails have a Climate Impact

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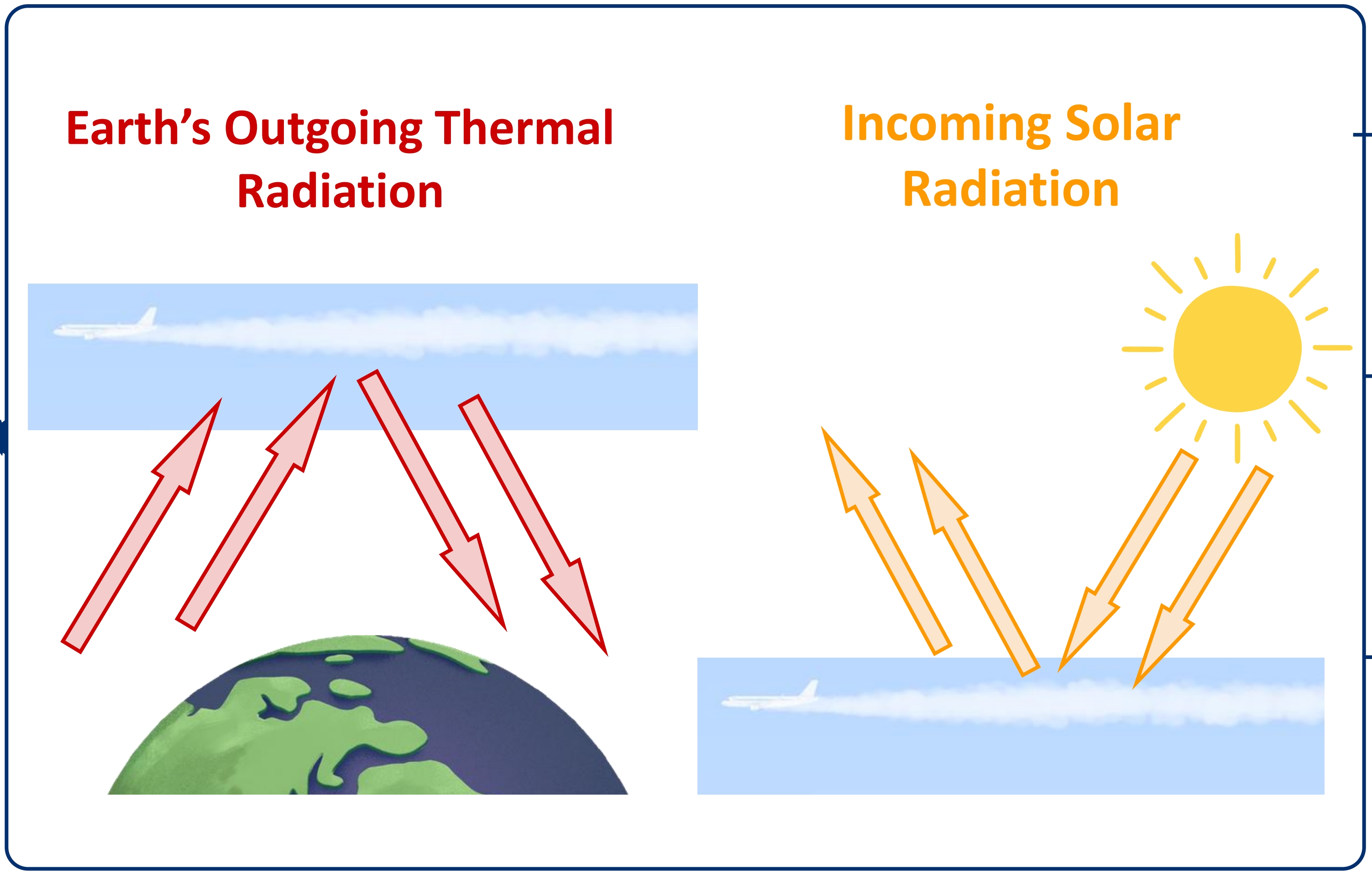
The magnitude and sign of contrail radiative forcing are highly sensitive to microphysical and optical properties, which control net warming / cooling effects.

Key controlling properties

1. Ice crystal size / habit
2. Optical depth
3. Cloud height and temperature
4. Particle number concentration
5. Vertical extent

Radiative pathway



Impact

- Higher optical depth increases SW scattering and LW trapping
- Crystal size and habit modify scattering and absorption efficiency
- Contrail altitude and temperature influence longwave trapping and atmospheric lifetime.

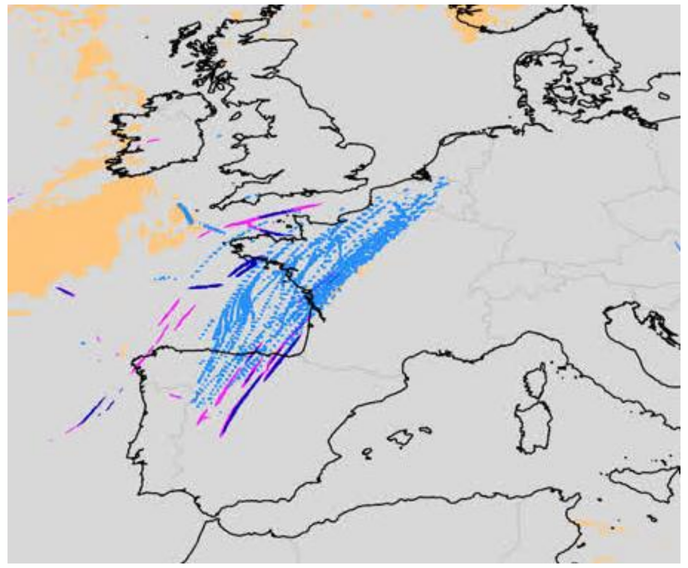
Presentation Outline

1. Research objectives
2. State of the Art
3. Achievements and Research Progress
4. Next Steps
5. Summary

1. Research Objectives

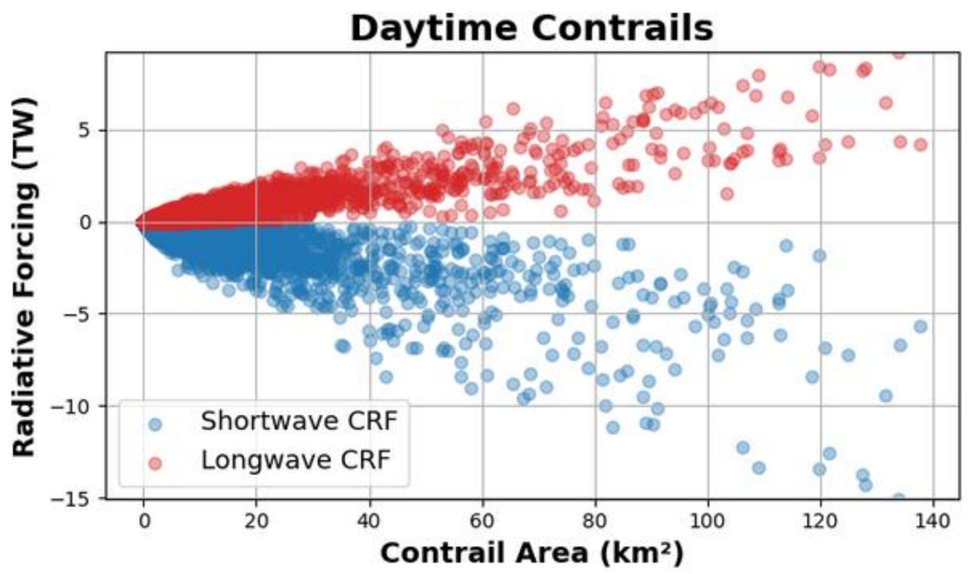
1

Develop advanced tools for contrail detection and monitoring



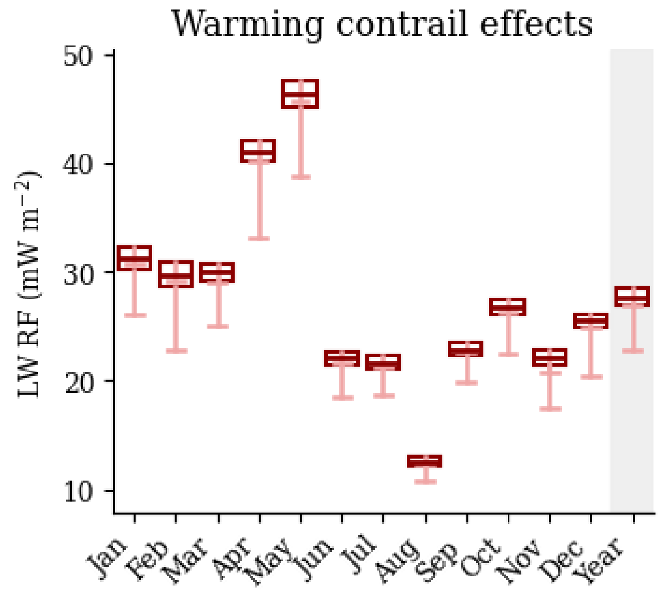
2

Investigate contrail formation, persistence, and radiative forcing



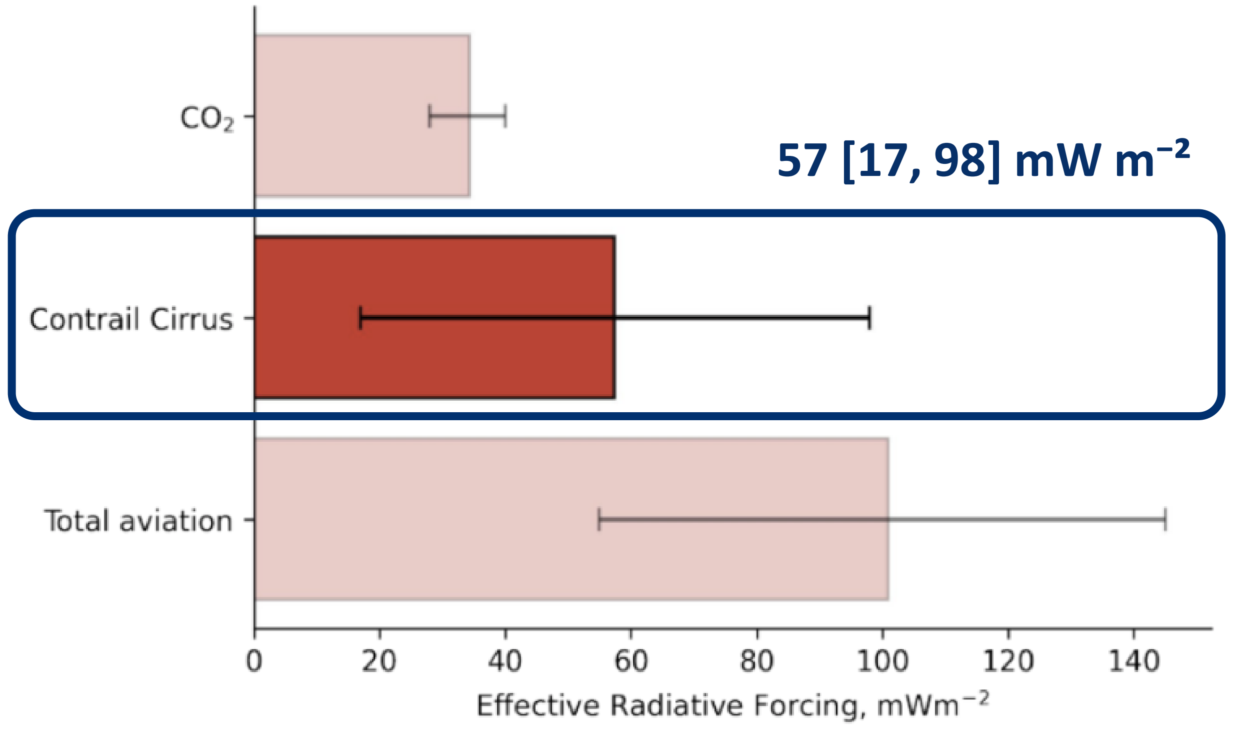
3

Constrain uncertainties in contrail climate forcing estimates



1. SoTA: Contrail Impacts

Main Aviation Climate Impact Contributions



(Lee et al., 2021)

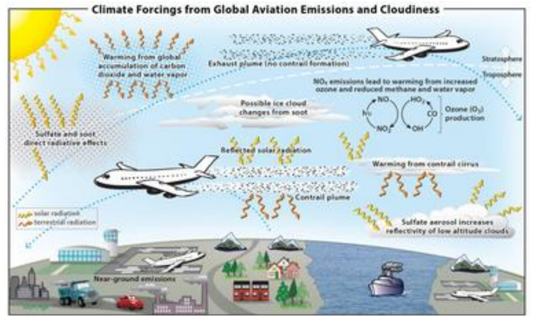
Contrails represent the **largest** and **most uncertain** aviation impact

How contrail climate impact is currently estimated

1 Global climate models

- Contrail-cirrus parameterizations
- Sensitivity studies and large-scale effective radiative forcing estimates

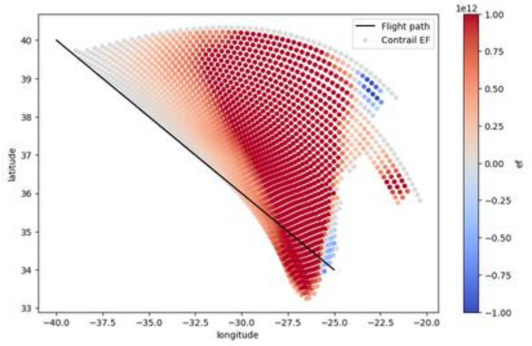
Burkhardt & Kärcher (2011); Chen & Gettelman (2013); Lee et al. (2021)



2 Plume-based contrail models

- Formation, persistence and spreading
- Microphysics and radiative forcing; CoCiP and related frameworks

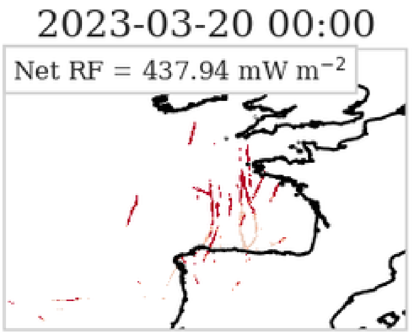
Schumann (2012); Teoh et al. (2020, 2024)



3 Observation-based quantifications

- Satellite observations of cover, lifetime, optical depth and radiative effect mainly from linear contrails
- Used to evaluate and constrain models

Minnis et al. (2004, 2013); Duda et al. (2019); Sonnabed et al, (2026)



Implication: stronger observation-based constraints are needed to reduce uncertainty in contrail occurrence, microphysical properties and radiative forcing.

1. SoTA: Observational studies

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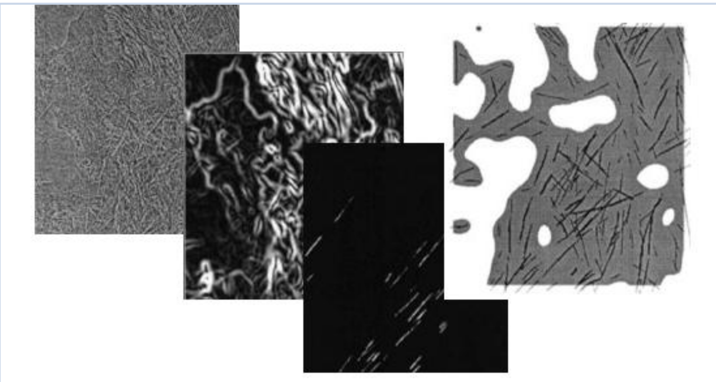
Over the last decades, remote sensing data have been increasingly used to develop tools for studying contrails.

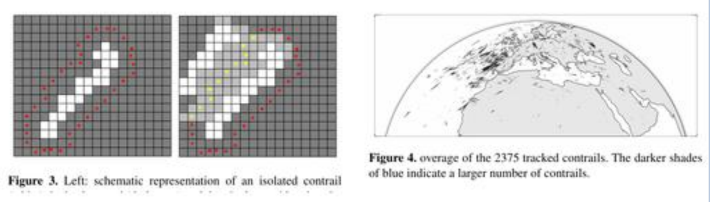
1 Early satellite studies



Automated detection of linear contrails using IR band differences, line filters and morphology.

Mannstein et al. (1999); Duda et al. (2013); Minnis et al. (2013)

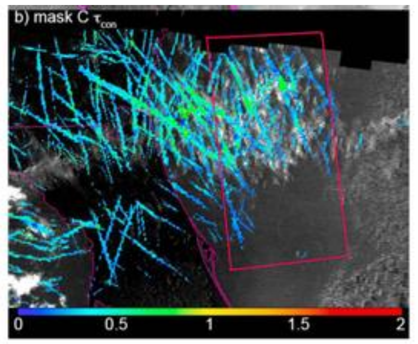
2 Detection and tracking of linear contrails



MSG/SEVIRI rapid-scan data enabled tracking of lifetime, spreading, width, altitude and some key optical properties.

Vázquez-Navarro et al. (2015); Gierens & Vázquez-Navarro (2018)

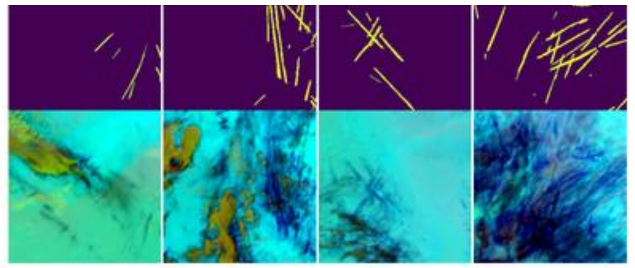
3 Studies on optical properties and forcing



Satellite retrievals estimate contrail cover, optical depth, particle size and radiative effects.

Minnis et al. (2004, 2013); Duda et al. (2019); Spangenberg et al. (2013)

4 Deep learning Algorithms, coverage and forcing studies



Human-labelled geostationary datasets enable large-scale AI detection and benchmarking.

Meijer et al. (2022); Ng et al. (2024); Santos Gabriel et al. (2026), Sonnabed et al. (2026)

Main remaining gaps

Latest AI not yet deployed

Latest tools have not yet been used at large scale for assesing balance between contrail cooling and warming effects.

Net radiative effect still incomplete

Most observational studies primarily constrain outgoing longwave radiation; cooling effects remain unstudied.

Coverage remains limited to certain regions

Observation-based radiative forcing estimates are still largely missing over Europe, one of the busiest aviation regions.

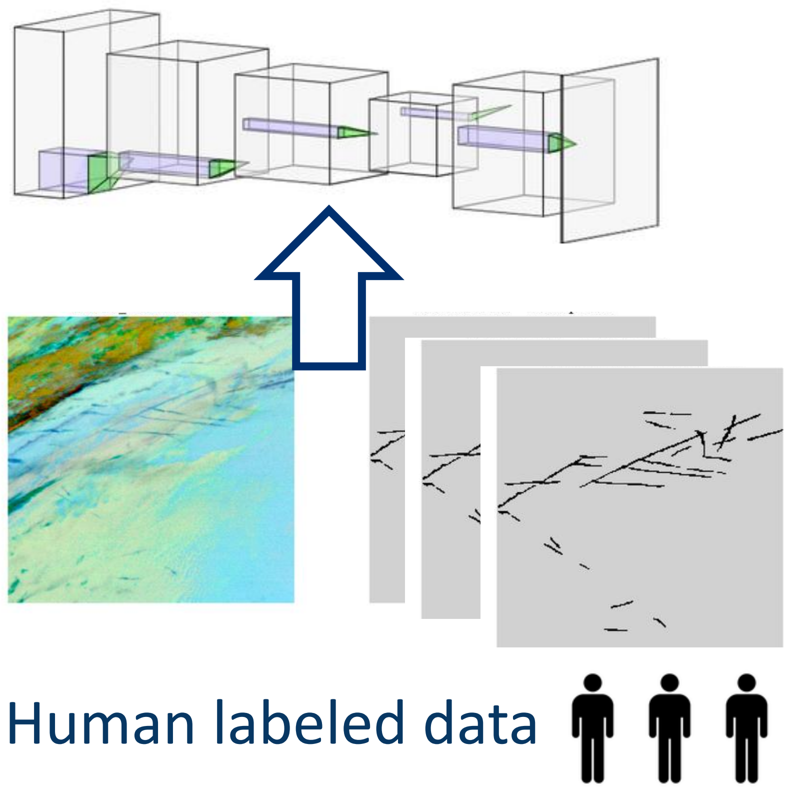
1. Achievements and Research Progress

Contrail Detection Tools

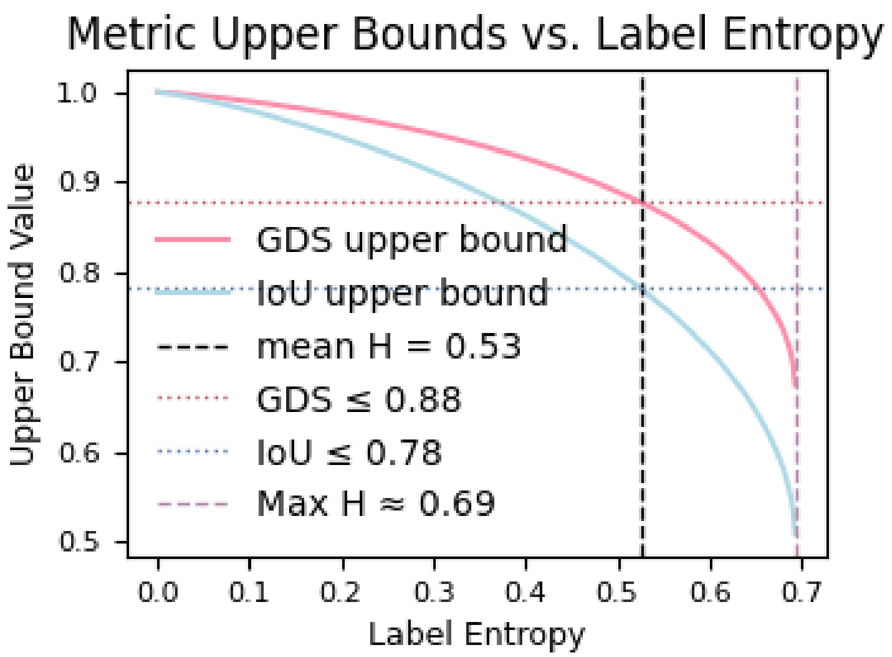
Trained multiple architectures,

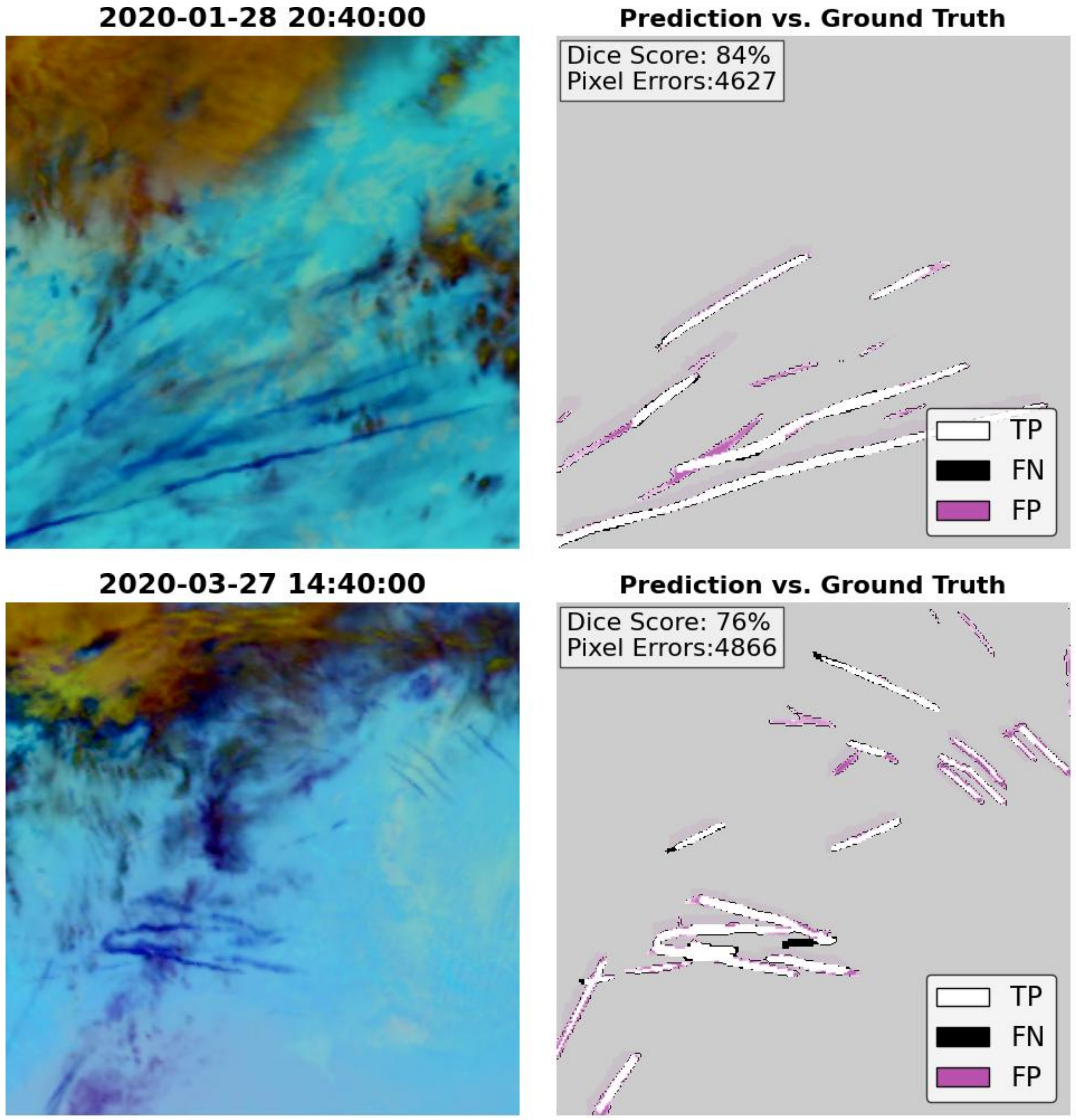
- **Quantitavely:** performace using relaxed metrics is near the theoretical upper bound
- **Qualitavely**: Good detection of main contrail structures, systematic width overestimation

Convolutional Neural Network



Human labeled data



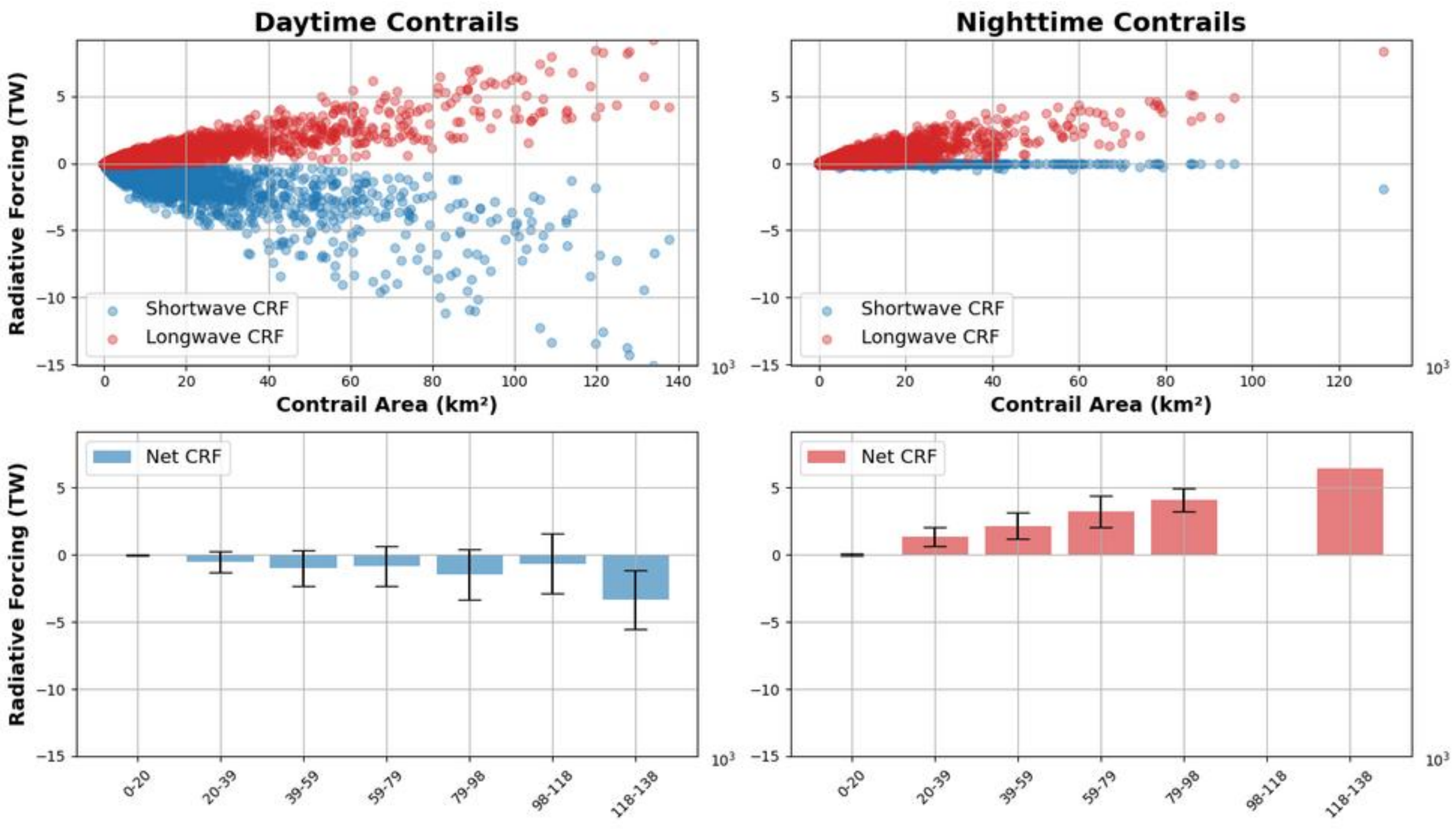


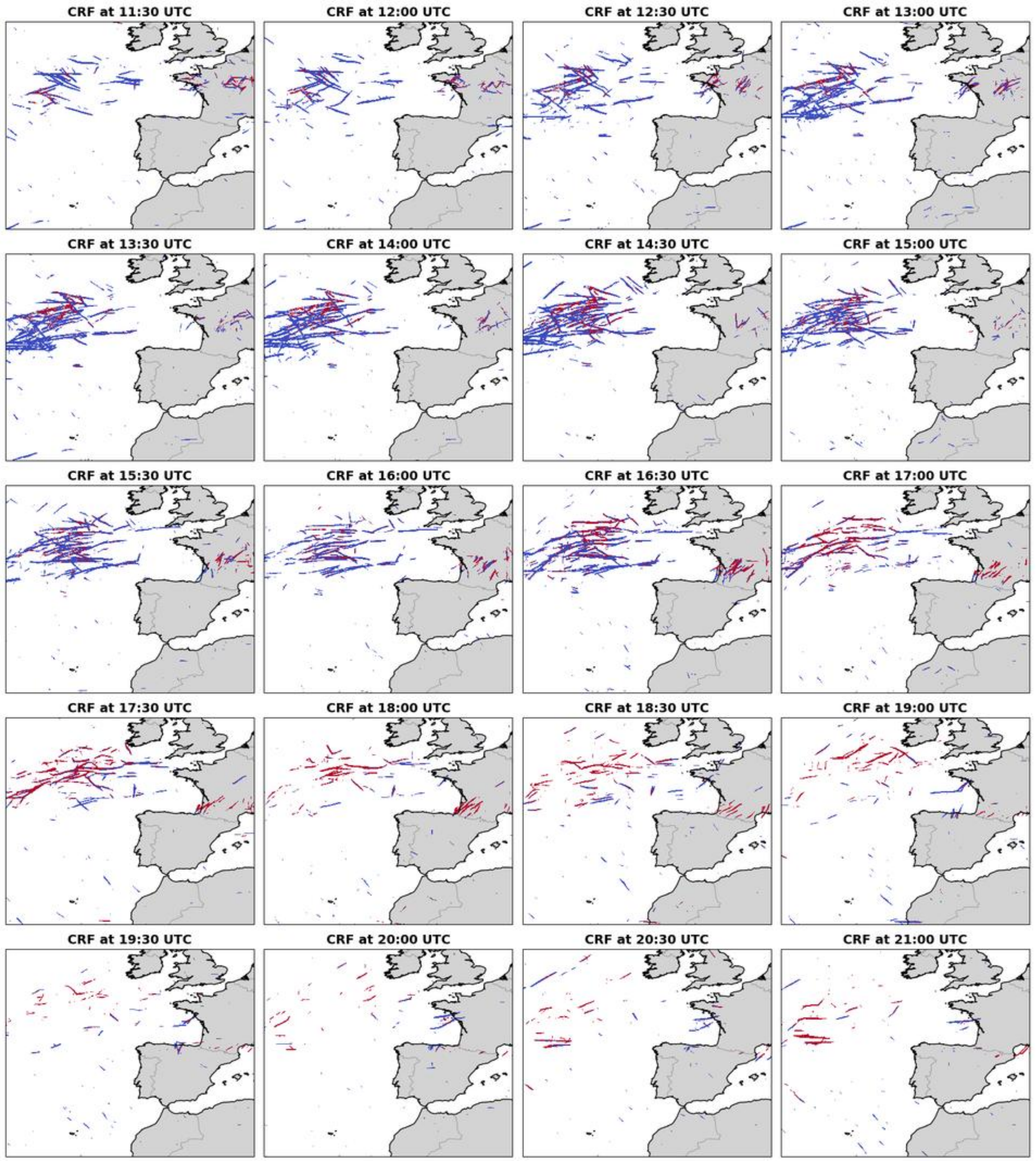
1. Achievements and Research Progress

First experiment

MSG-SEVIRI geostationary satellite imagery for two winter study periods: 24–30 January 2023 and 24–30 January 2024.

- Methods successfully quantify contrail radiative impacts
- Strong warming at night, net cooling during daylight.
- **Net warming, consistent with winter conditions**: shorter daylight hours reduce the compensating shortwave cooling.

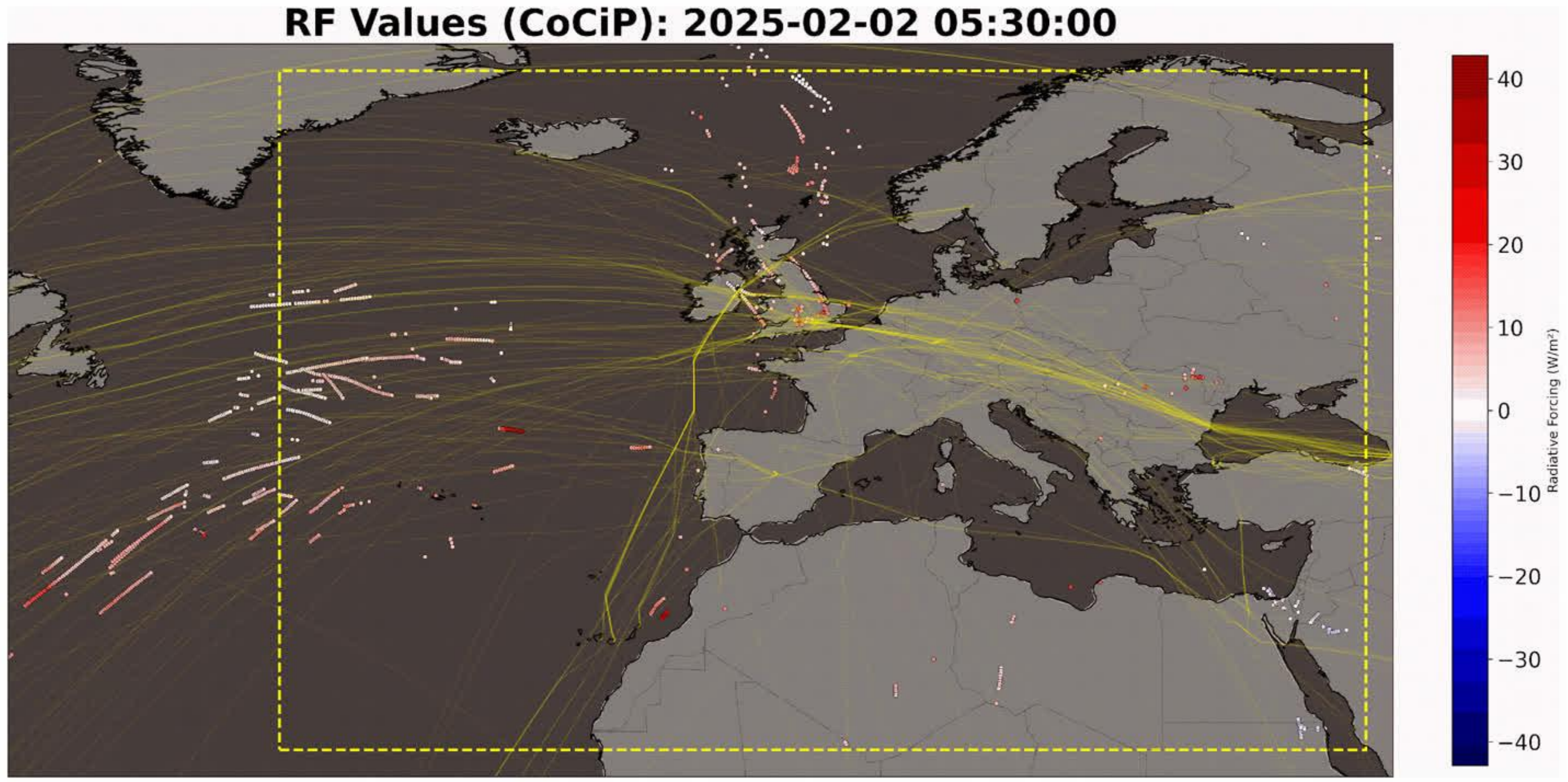




1. Achievements and Research Progress

Second Experiment

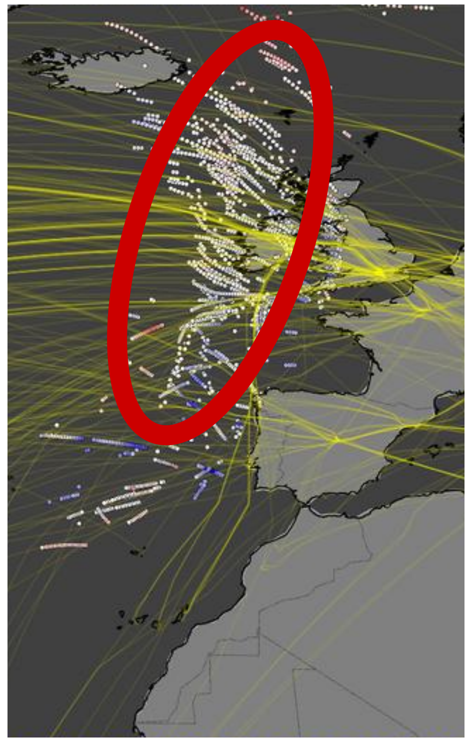
One week of data comparing satellite observations with modeled contrails (01-08 February 2025)



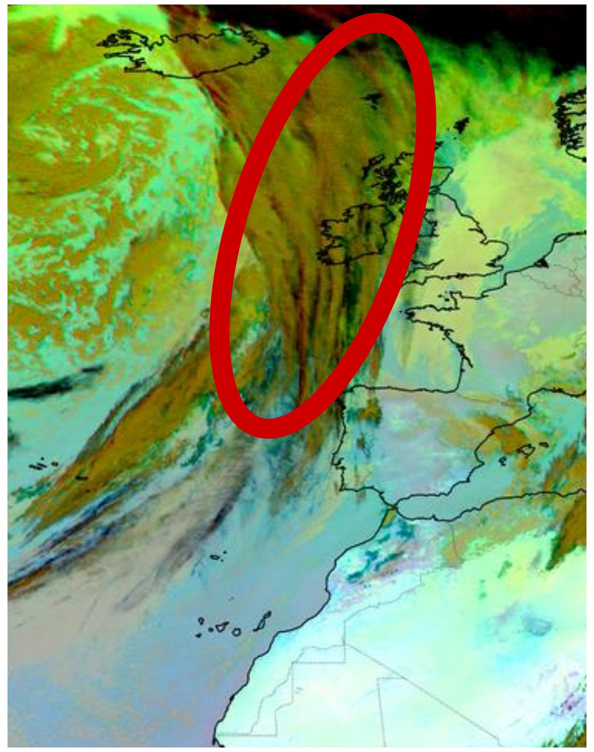
Benchmark contrail simulations

Lagrangian Contrail Model CoCiP (Schumann et al., 2012)

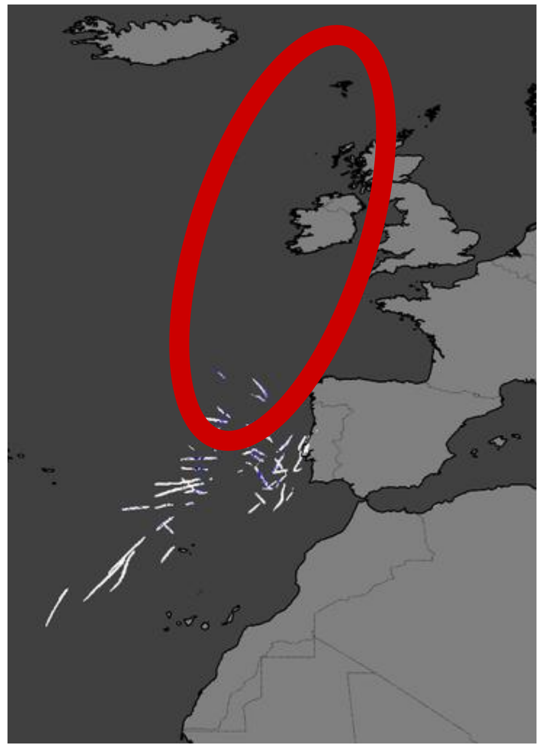
Simulations vs Observations



Simulated



Observed



Detected

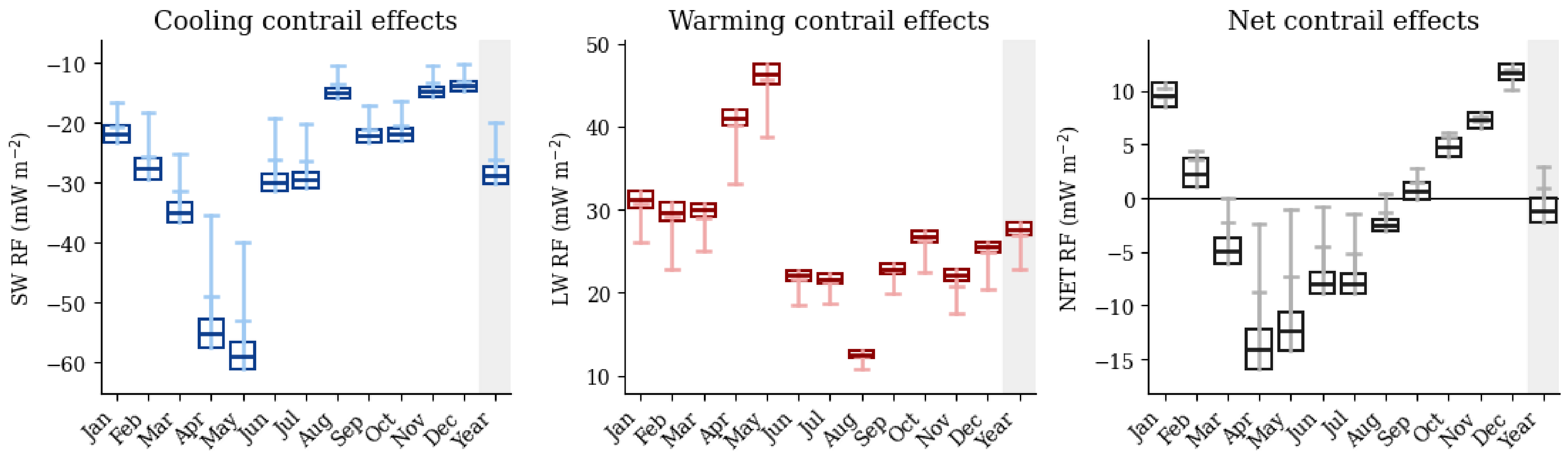
Simulations predict a larger contrail population than can be directly observed. This creates a **validation gap**, where many modelled contrails remain unverifiable because **satellite detections are limited** by cloud background, resolution, and viewing conditions.

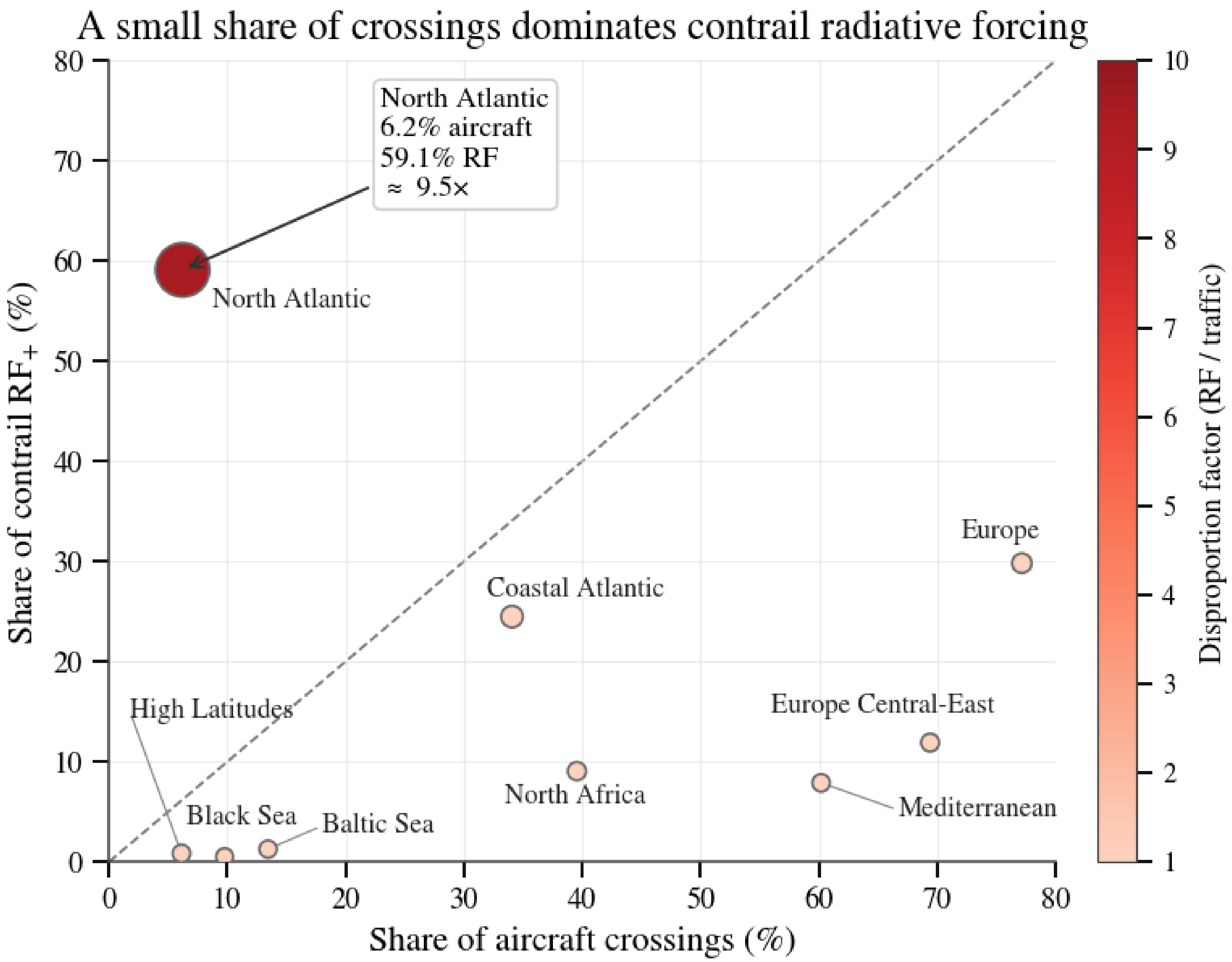
1. Achievements and Research Progress

Third Experiment

MSG-SEVIRI geostationary satellite imagery for the entire year 2023 to capture seasonality effects and annual overall net effects.

- **Strongest cooling**: April and May, but with highest uncertainty.
- **Seasonality**: winter and autumn show net warming.
- **Regional effect**: stronger radiative forcing over the North Atlantic due to higher detection rates.
- **Europe**: fewer detections likely despite congested airspace.
- **Main uncertainty**: contrail microphysical and optical properties.





1. Achievements and Research Progress

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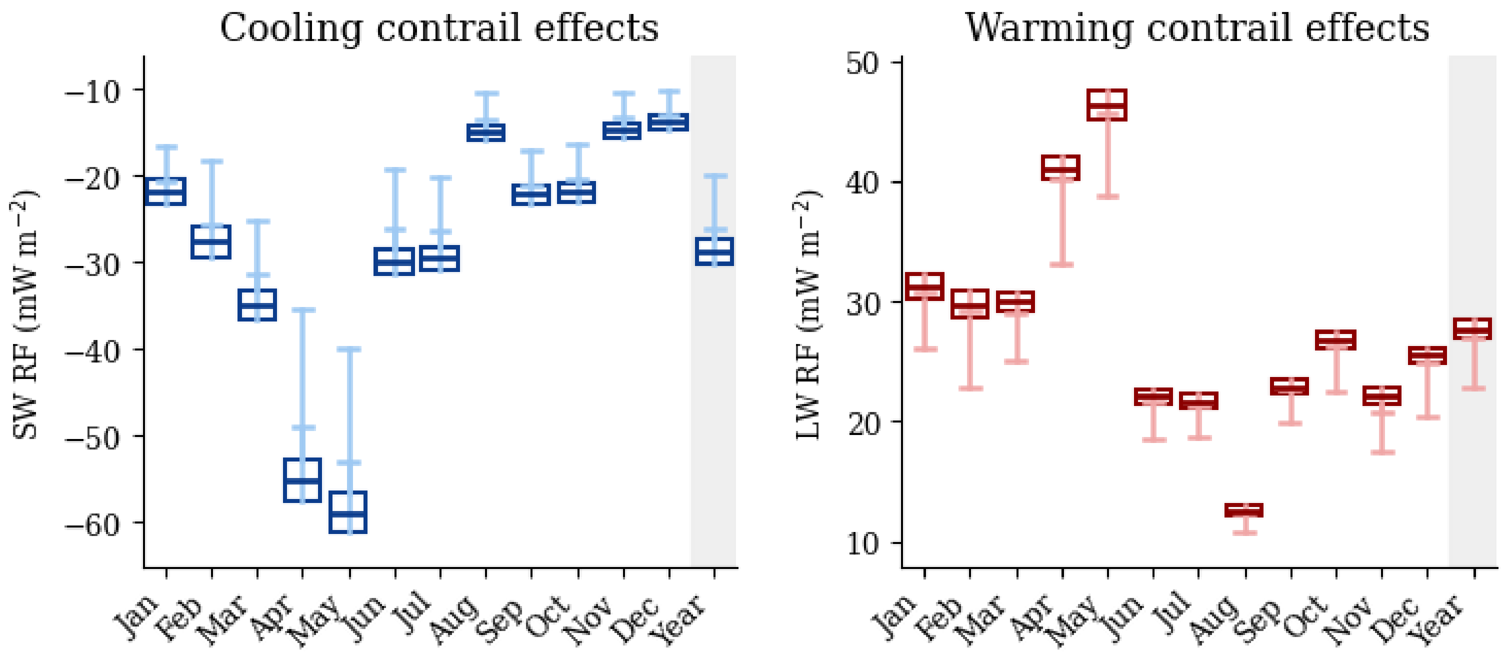

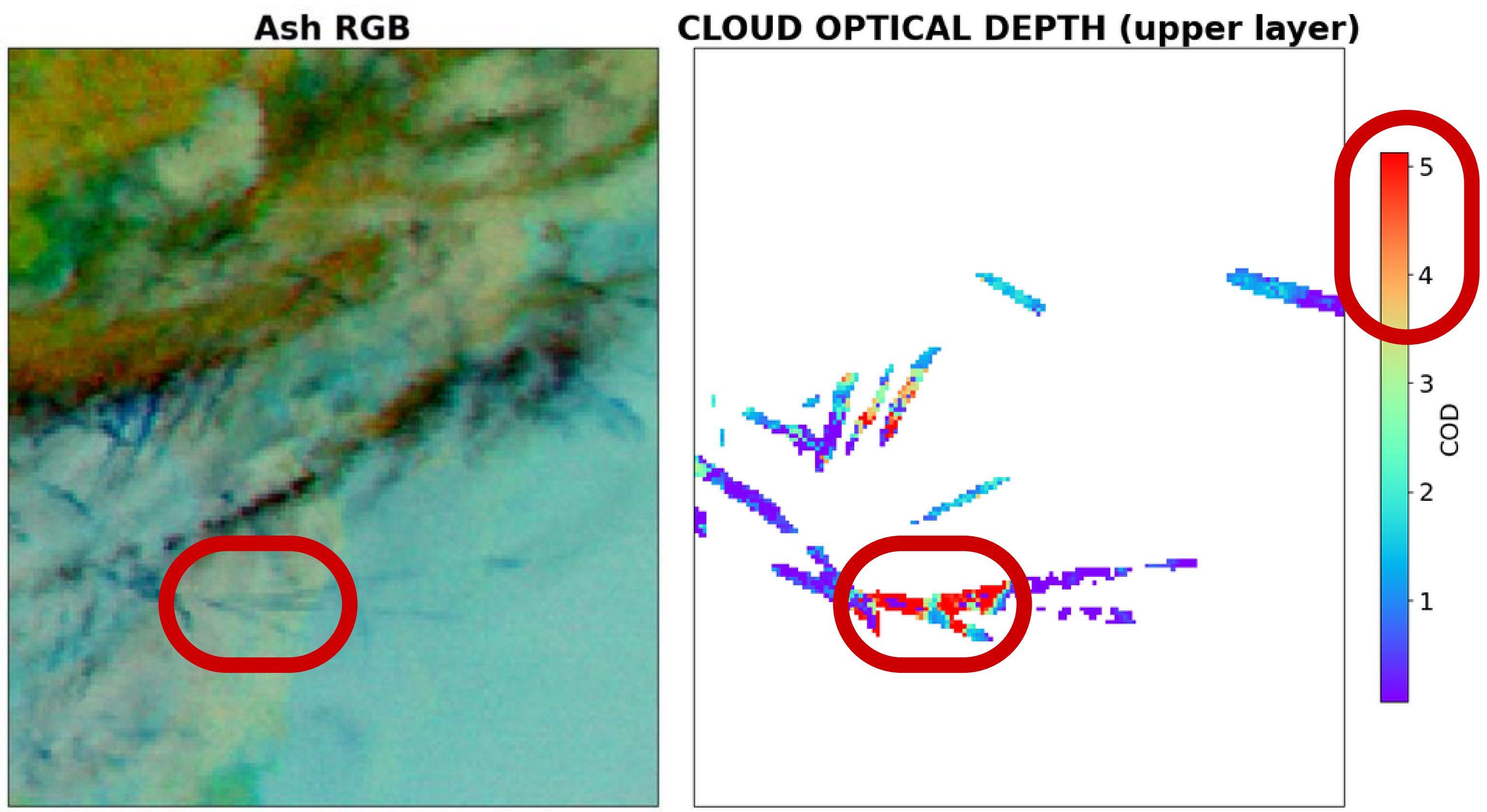

Limitation

- **Optical depth > 3**: typically indicates optically opaque cloud conditions.
- **Contrails are optically thin**: such high values are not physically representative.
- **Literature upper limit**: maximum reported contrail optical depth is around 2.3.

1. Next Steps

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Research stay

Sandia National Laboratories

Investigate contrail microphysics

Generate laboratory data

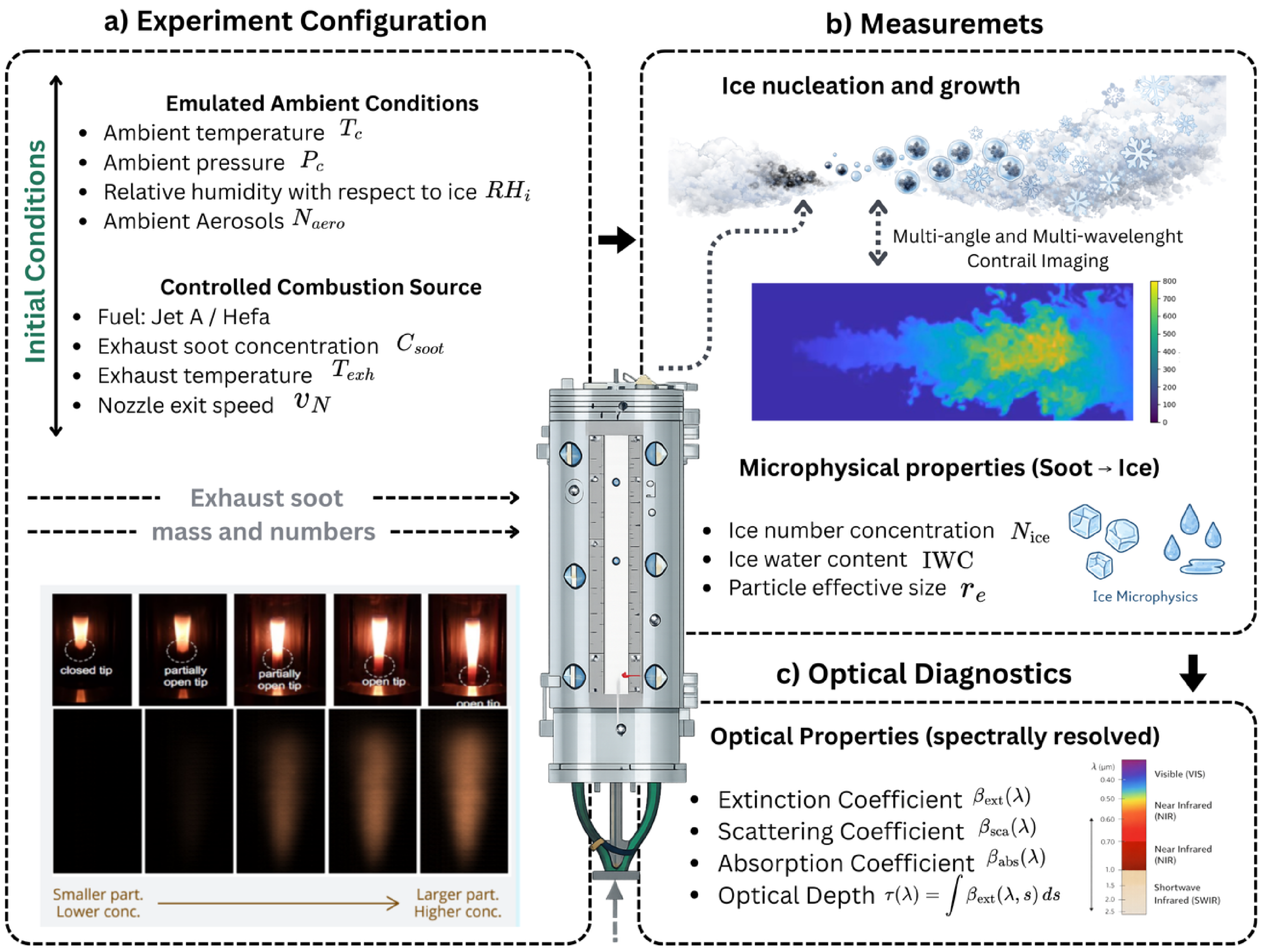
- Controlled measurements of contrail formation, optical properties, and microphysical evolution.

Refine process understanding

- Assess how laboratory measurements improve our current understanding of contrail formation and persistence.

Constrain impact estimates

- Connect laboratory findings to existing estimates of contrail radiative forcing and climate impact.



1. Summary

Research Objectives

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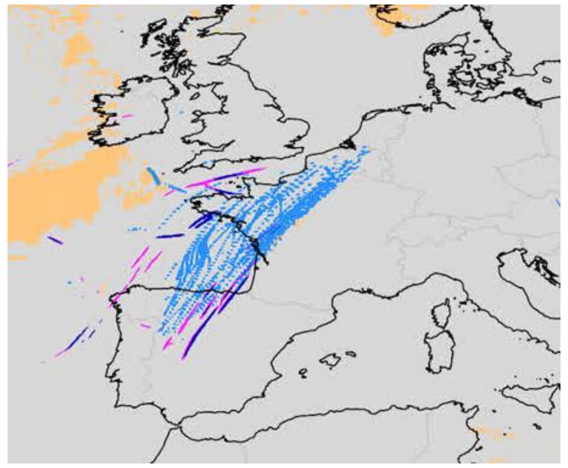
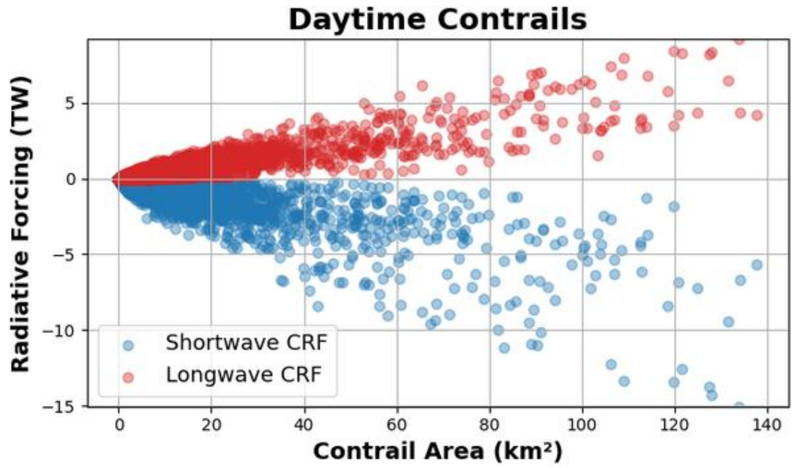
Develop advanced tools for contrail detection and monitoring



Done

2

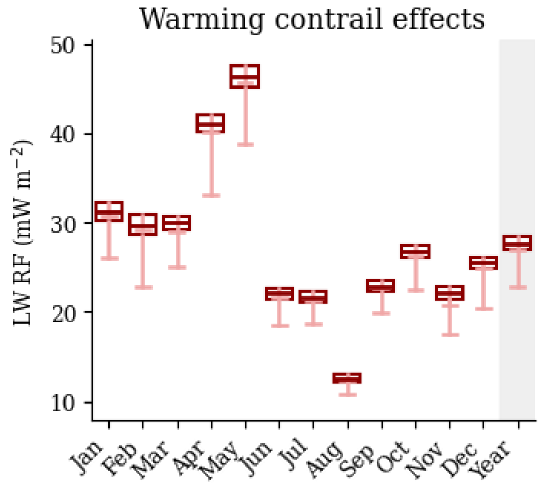
Investigate contrail formation, persistence, and radiative forcing



In progress

3

Constrain uncertainties in contrail climate forcing estimates



Next Step

1. Summary

Conferences:

- Ortiz, I., Soler, M., García-Heras, J., Brenot, H., Clerbaux, N., and de Buyl, P.: **Advancing Contrail Detection Methods over European Skies,** EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024.

- Ortiz, I., Dimitropoulou, E., de Buyl, P., Clerbaux, N., García-Heras, J., Jafarimoghaddam, A., ... & Soler, M. . **Satellite-Based Quantification of Contrail Radiative Forcing over Europe: A Two-Week Analysis of Aviation-Induced Climate Effects.** Submitted to SESAR Innovation Days 2024, Rome, Italy.

- Ortiz, I., Simorgh, A., García-Heras, J., Dimitropoulou, E., De Buyl, P., Clerbaux, N., and Soler, M.: **Assessing Contrail Radiative Effects: A Comparison of MTG Satellite Detections and Physics-Based Simulations,** EGU General Assembly 2025, Vienna, Austria, 27 Apr–2 May 2025.

- Ortiz, I., Dimitropoulou, E., de Buyl, P. ... & Soler, M. **AI-Based Insights into Aviation's Climate Impact using Satellite Imagery in E-CONTRAIL Project**, 3rd Contrail London Workshop. September 2025, London.

- Ortiz, I.,Brenot, H., Dimitropoulou, E., de Buyl, P. ... & Soler, M. **A Novel Ice RGB Composite to Improve Satellite-Based Contrail Detection over Complex Atmospheric and Surface Backgrounds**, ECATS 2026 Conference. January 2026, Brussels.

Journal Publications:

- Ortiz, I., García-Heras, J., Jafarimoghaddam A. and Soler M., "**Robust Evaluation of Neural Networks Trained on the OpenContrails Dataset**," in IEEE Transactions on Geoscience and Remote Sensing, vol. 63, pp. 1-17, 2025, Art no. 4112717,
- Ortiz, I., Dimitropoulou, E., de Buyl, P. ... & Soler, M. **Observation-Based Assessment of Contrail Climate Effects across the Euro-Atlantic Region in 2023**, 03 May 2026, PREPRINT (Version 1) available at Research Square.


Observation-Based Assessment of Contrail Climate Effects across the Euro-Atlantic Region in 2023

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Abstract

Thank you!