

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

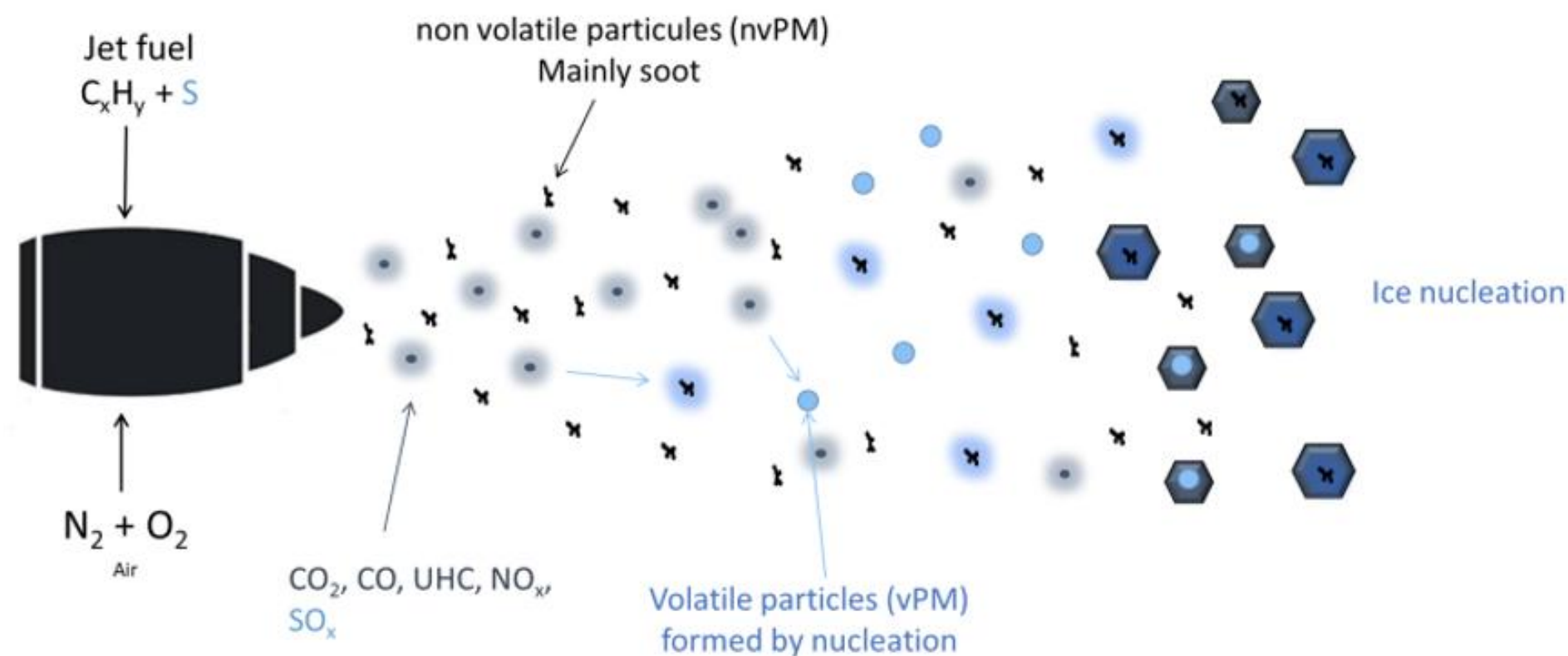
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What are contrails?

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



Combustion products

- Jet fuel + air $\rightarrow$ H₂O, CO₂, 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.

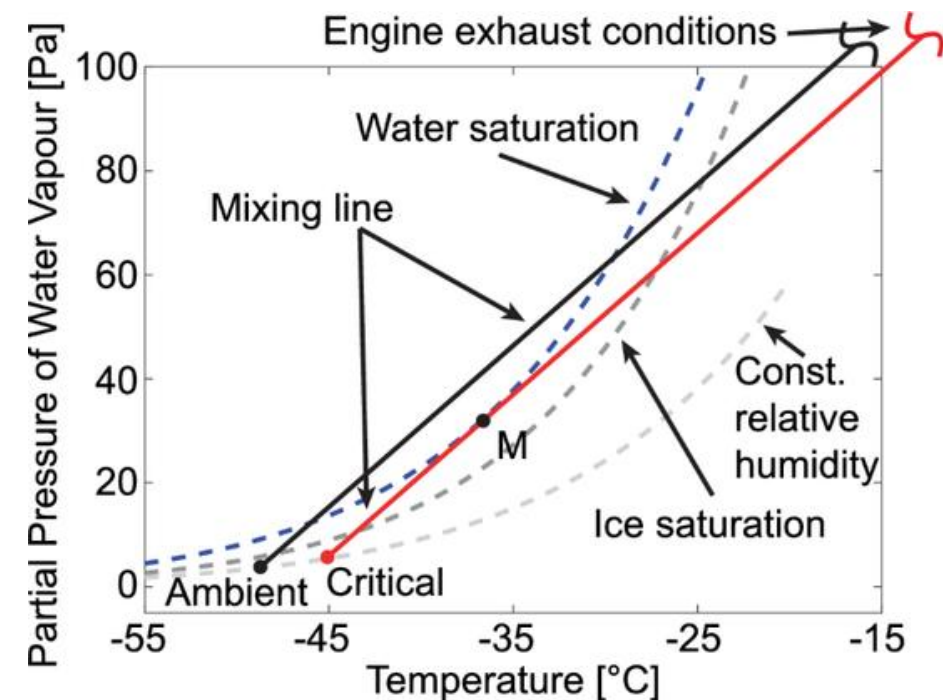
Ice crystals

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

What are contrails?

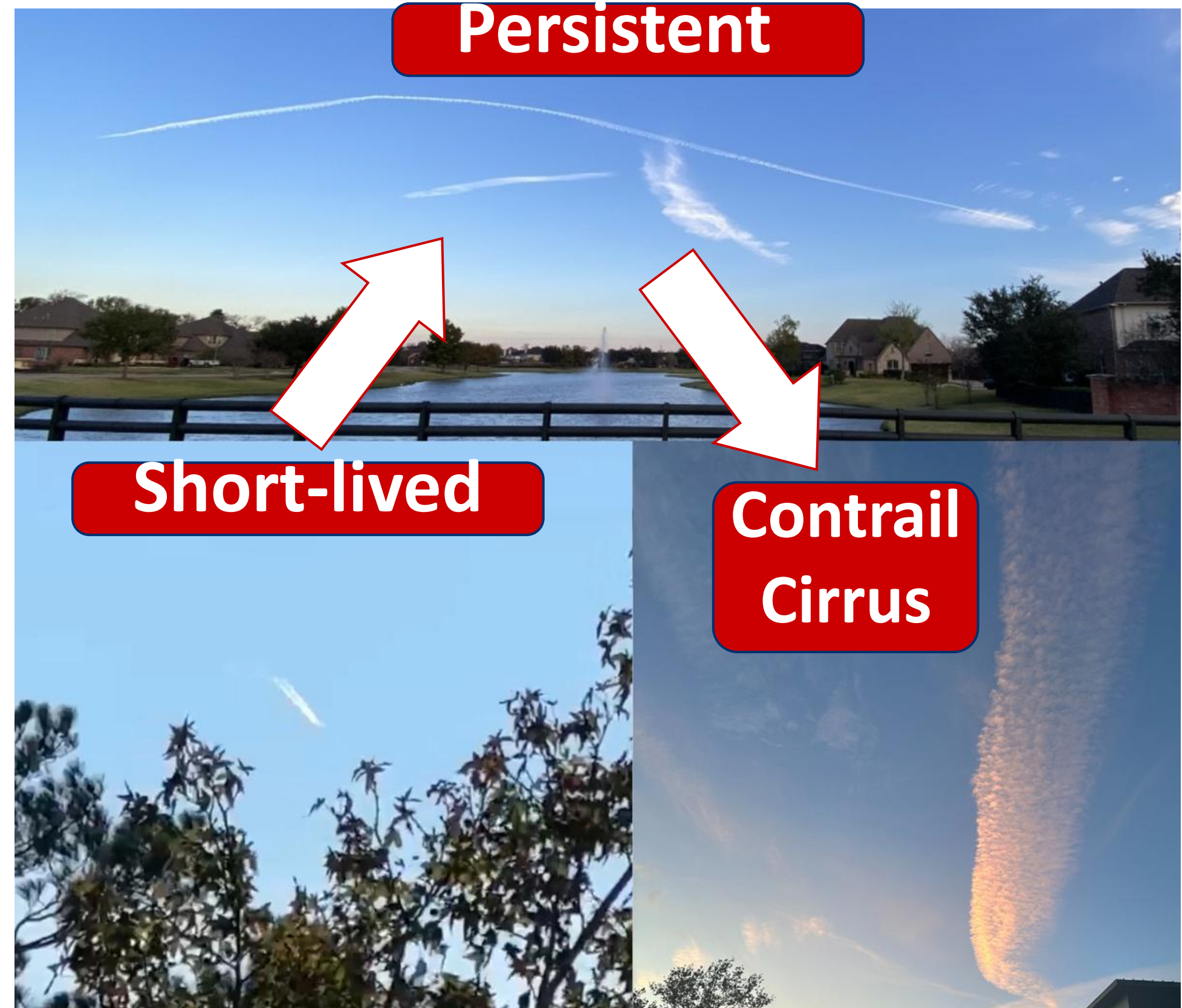
Formation and lifetime depend on atmospheric conditions

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



(Callard et al., 2026)

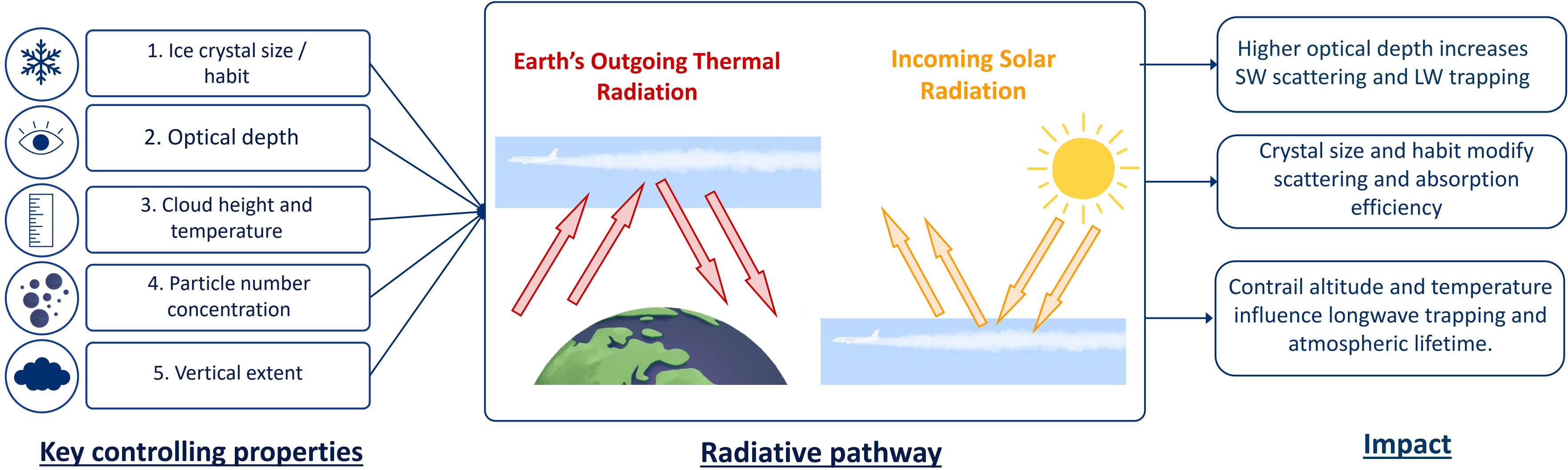
- In **ice-subsaturated air**, crystals quickly sublimate, producing short-lived contrails.
- In **ice-supersaturated air**, they persist, grow, and spread into contrail cirrus.



Contrails have a Climate Impact



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





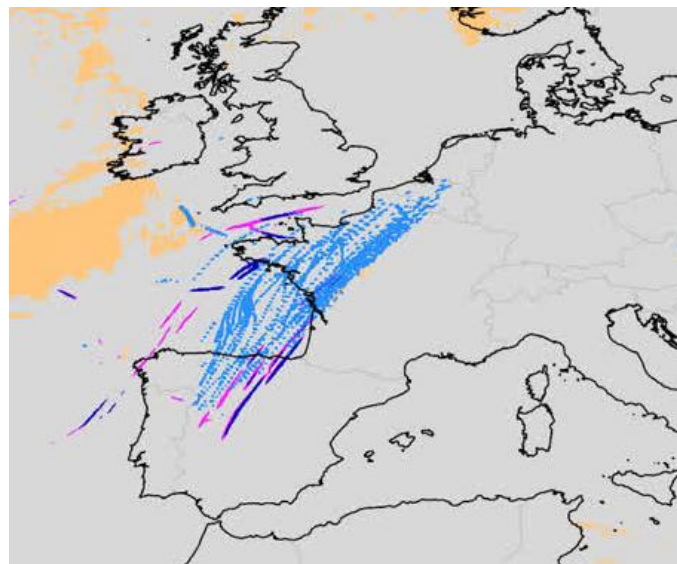
Presentation Outline

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

1. Research Objectives

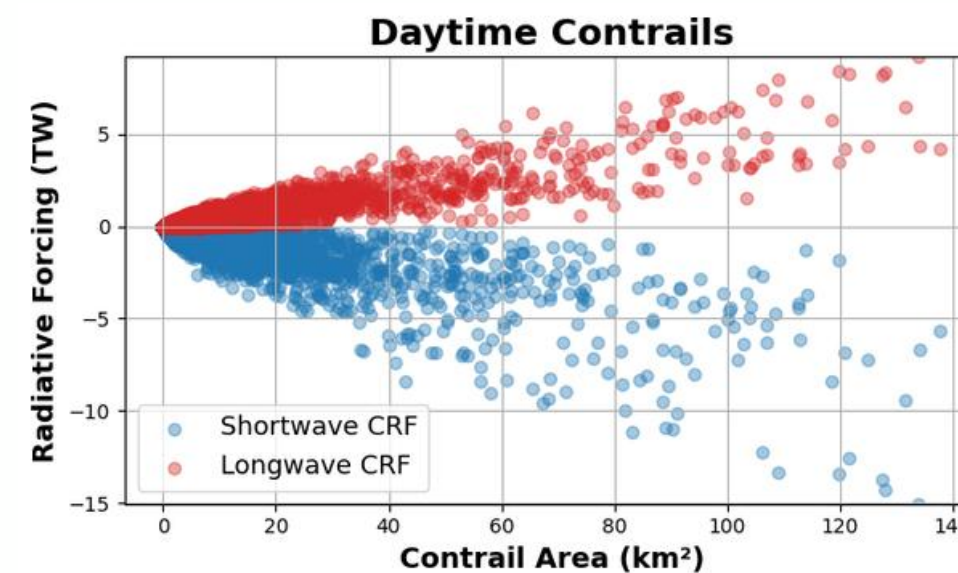
1

Develop advanced tools for contrail detection and monitoring



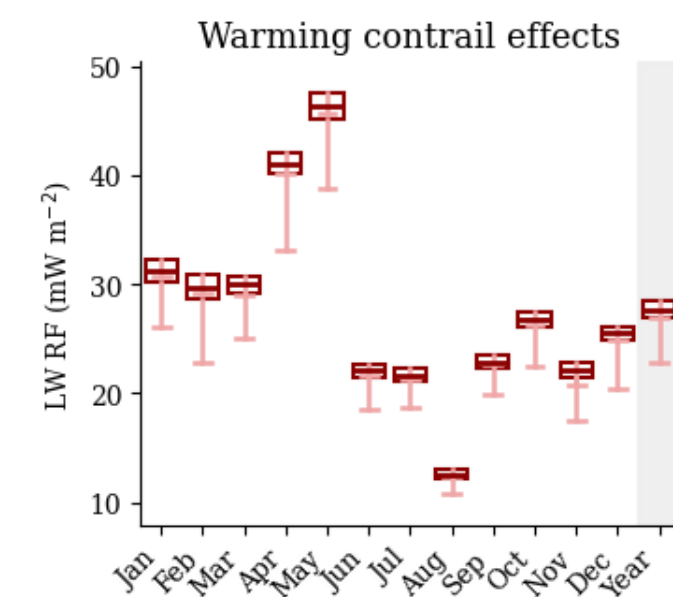
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Investigate contrail formation, persistence, and radiative forcing



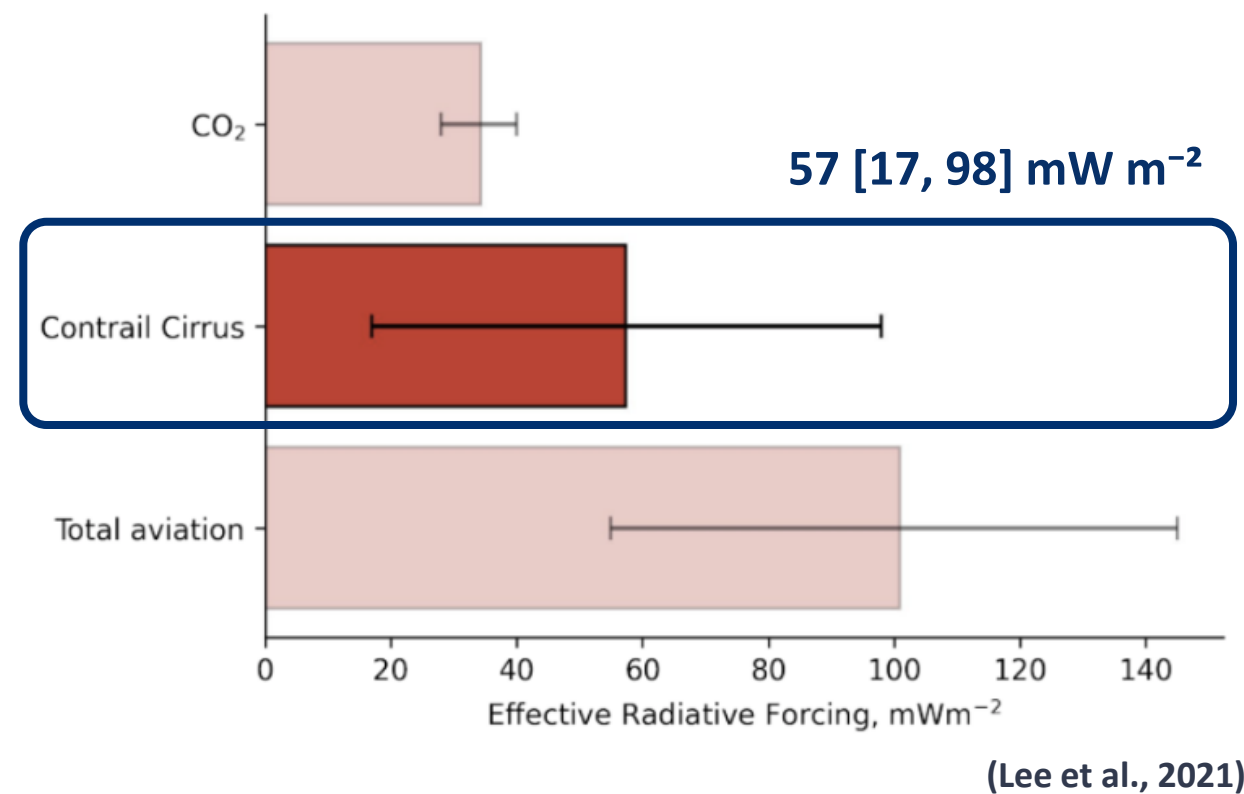
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Constrain uncertainties in contrail climate forcing estimates



1. SoTA: Contrail Impacts

Main Aviation Climate Impact Contributions



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

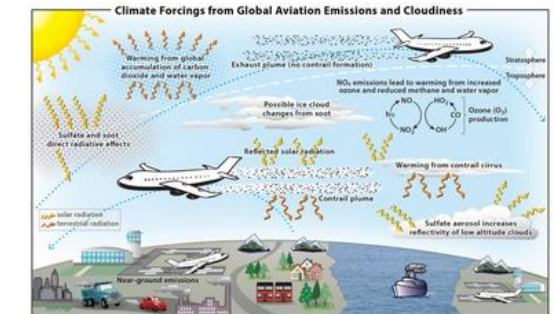


How contrail climate impact is currently estimated

1 Global climate models

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

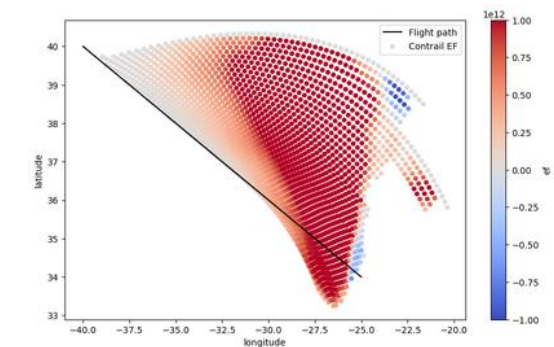
Burkhardt & Kärcher (2011); Chen & Gettelman (2013); Lee et al. (2021)



2 Plume-based contrail models

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

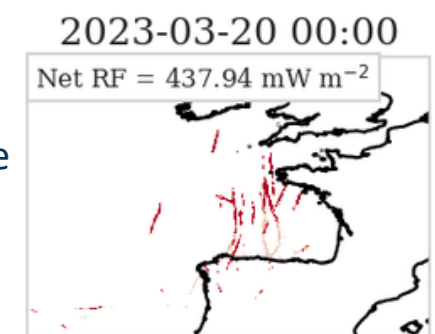
Schumann (2012); Teoh et al. (2020, 2024)



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); Sonnabend et al. (2026)

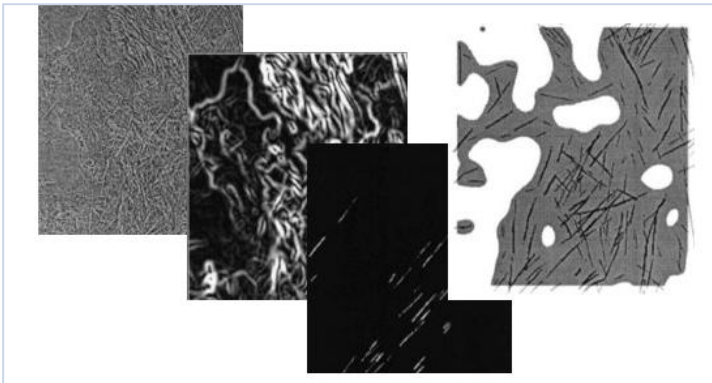


Implication: stronger observation-based constraints are needed to reduce uncertainty in contrail occurrence, microphysical properties and radiative forcing.

1. SoTA: Observational studies

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

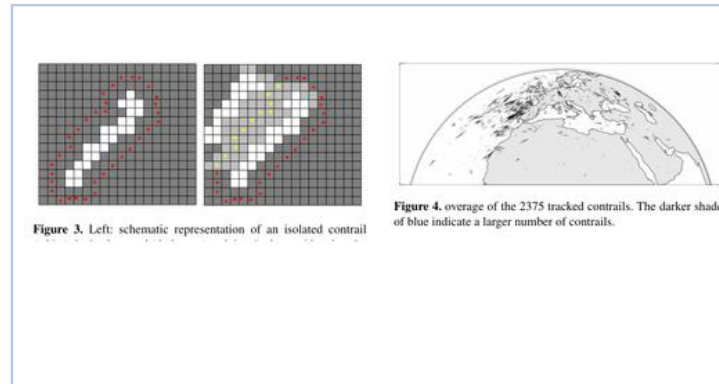
1 Early satellite studies



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)

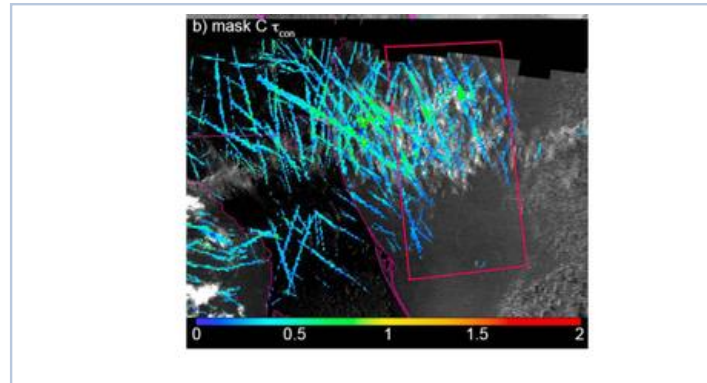
2 Detection and tracking of linear contrails



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)

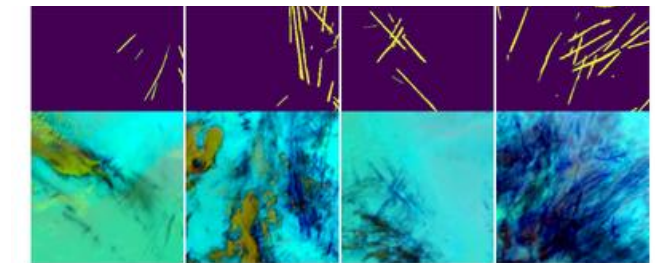
3 Studies on optical properties and forcing



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 assessing 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.

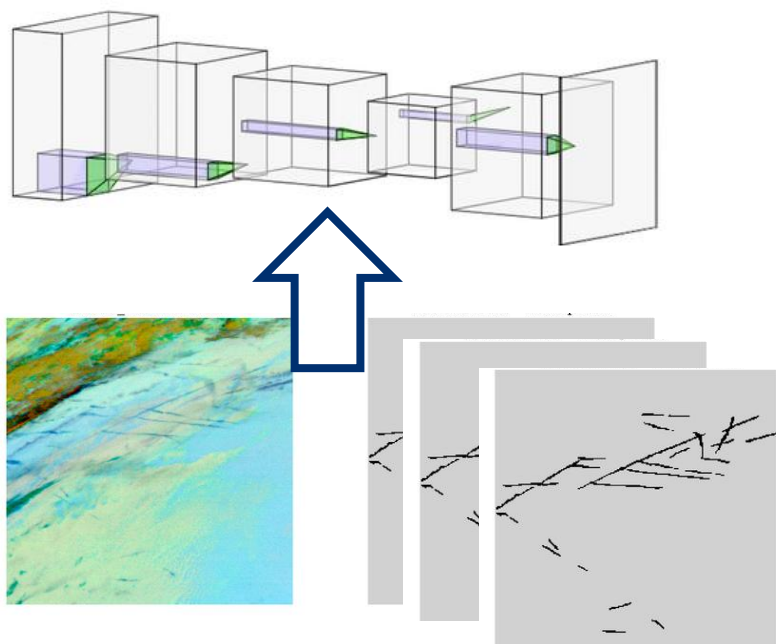
1. Achievements and Research Progress

Contrail Detection Tools

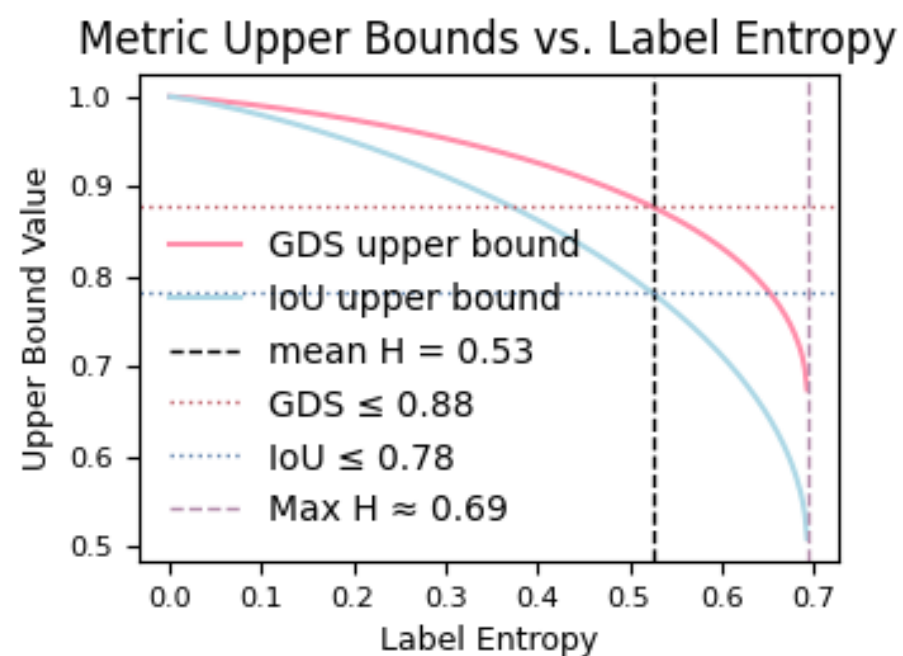
Trained multiple architectures,

- **Quantitatively:** performance using relaxed metrics is near the theoretical upper bound
- **Qualitatively:** Good detection of main contrail structures, systematic width overestimation

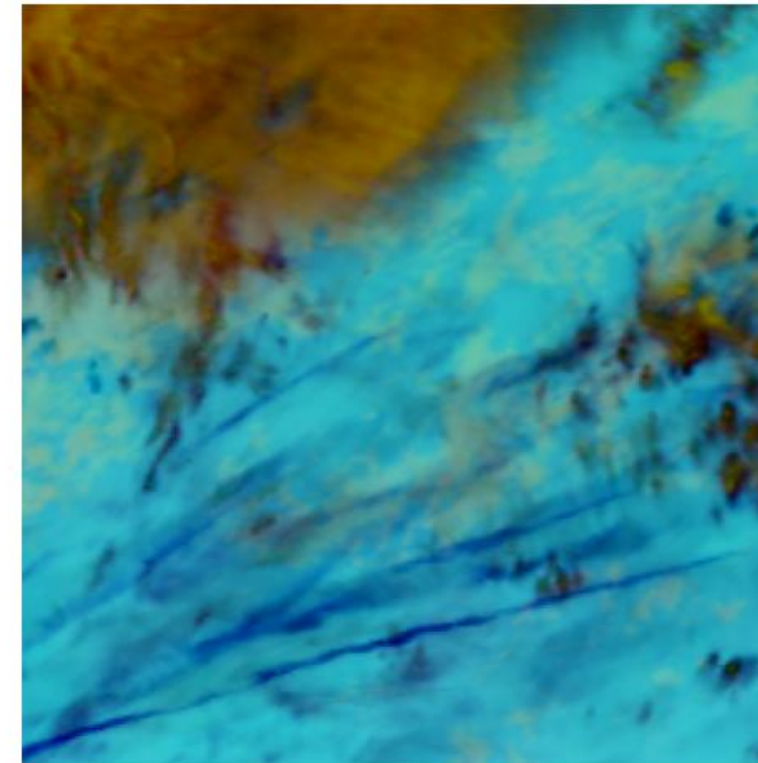
Convolutional Neural Network



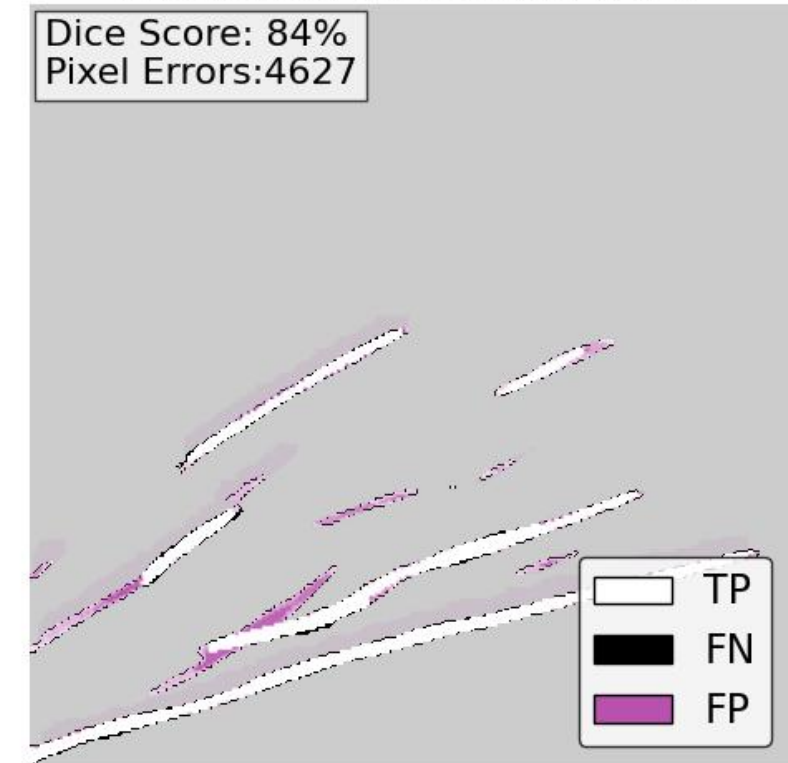
Human labeled data 



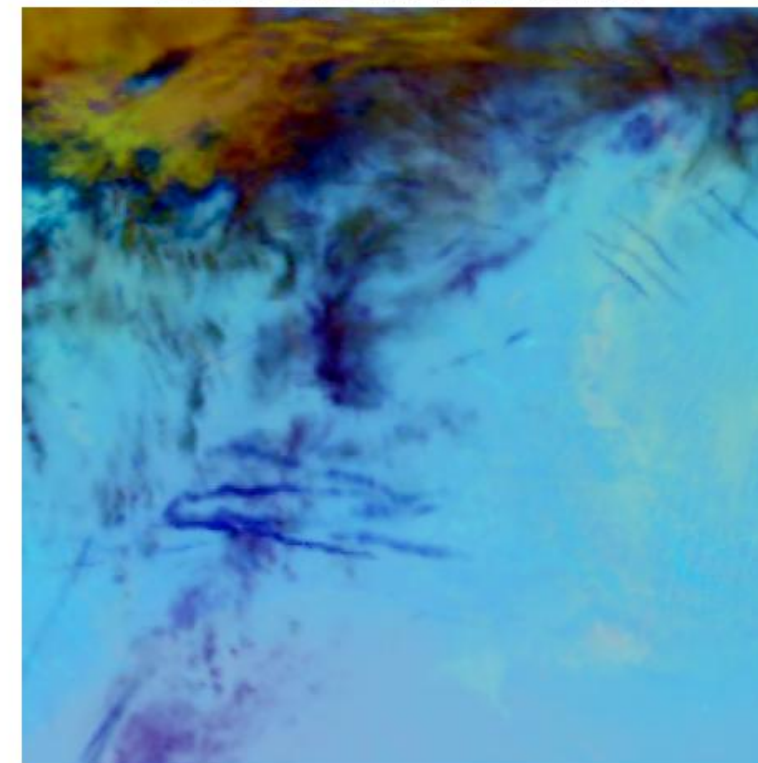
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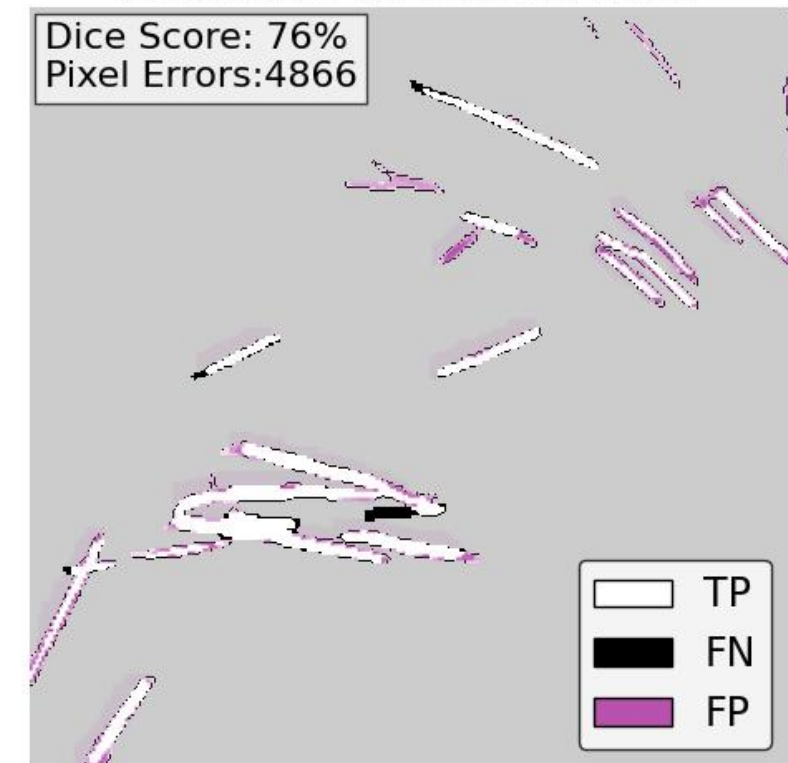
Prediction vs. Ground Truth



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Prediction vs. Ground Truth

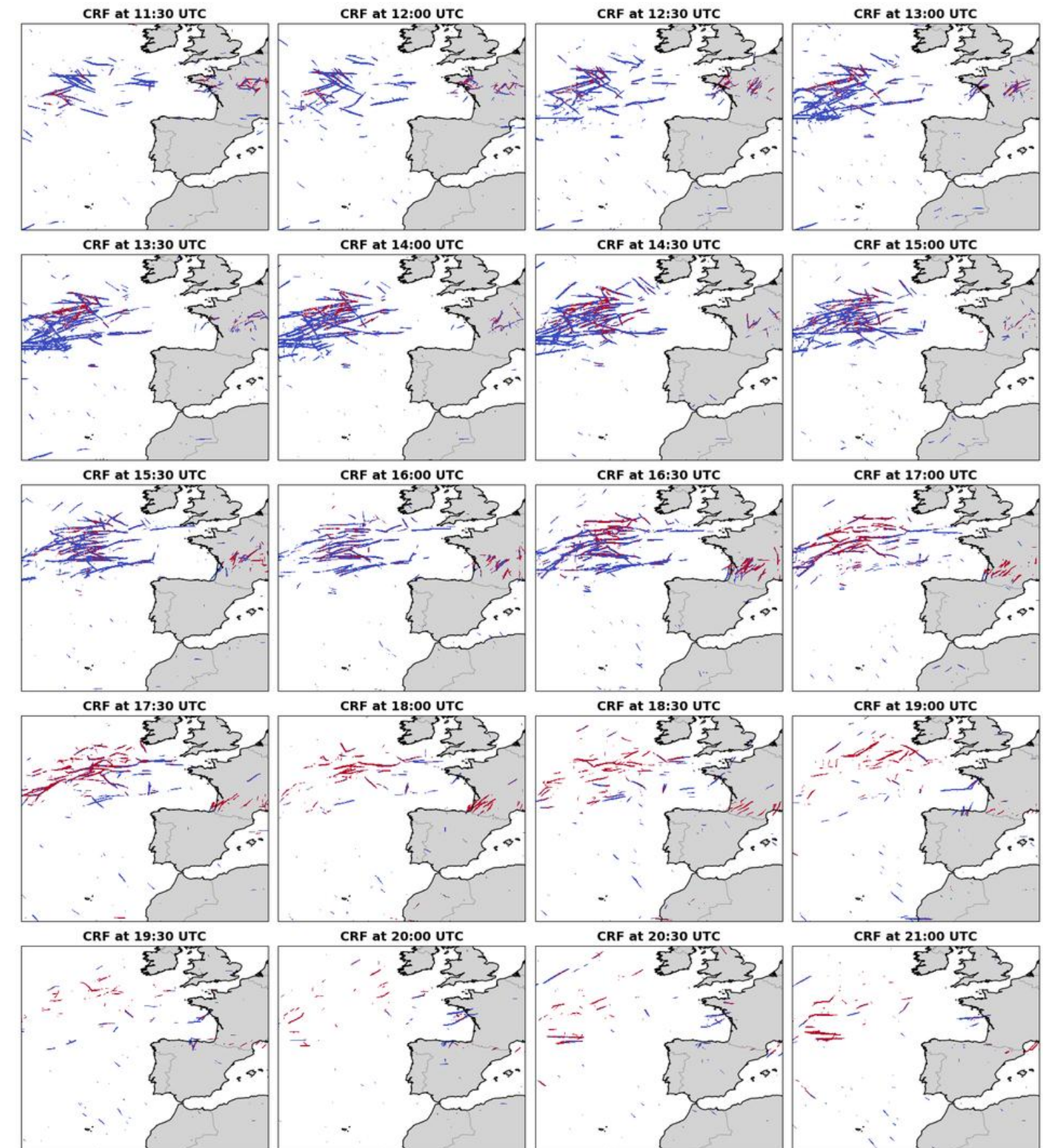
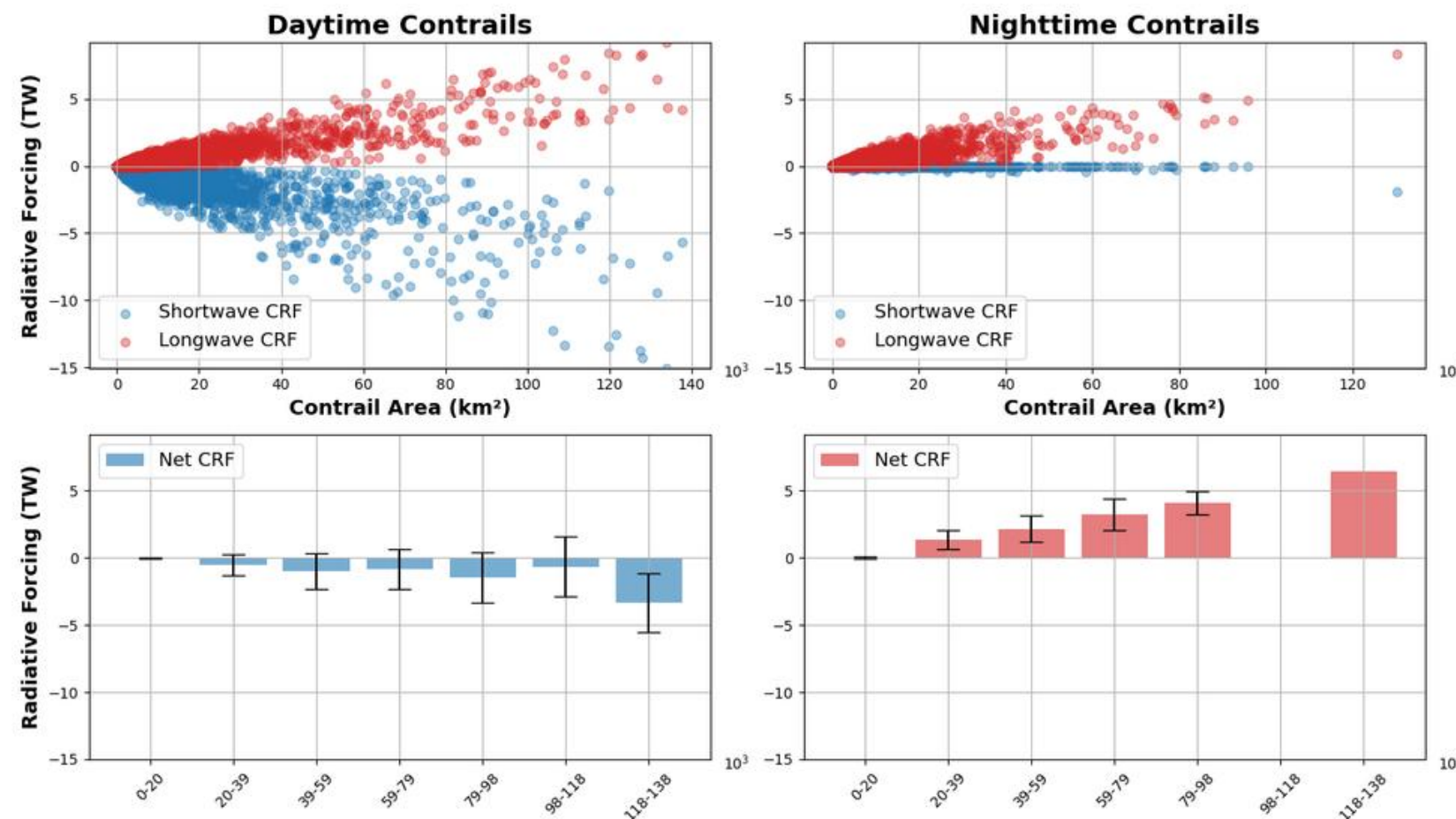


1. Achievements and Research Progress

First experiment

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

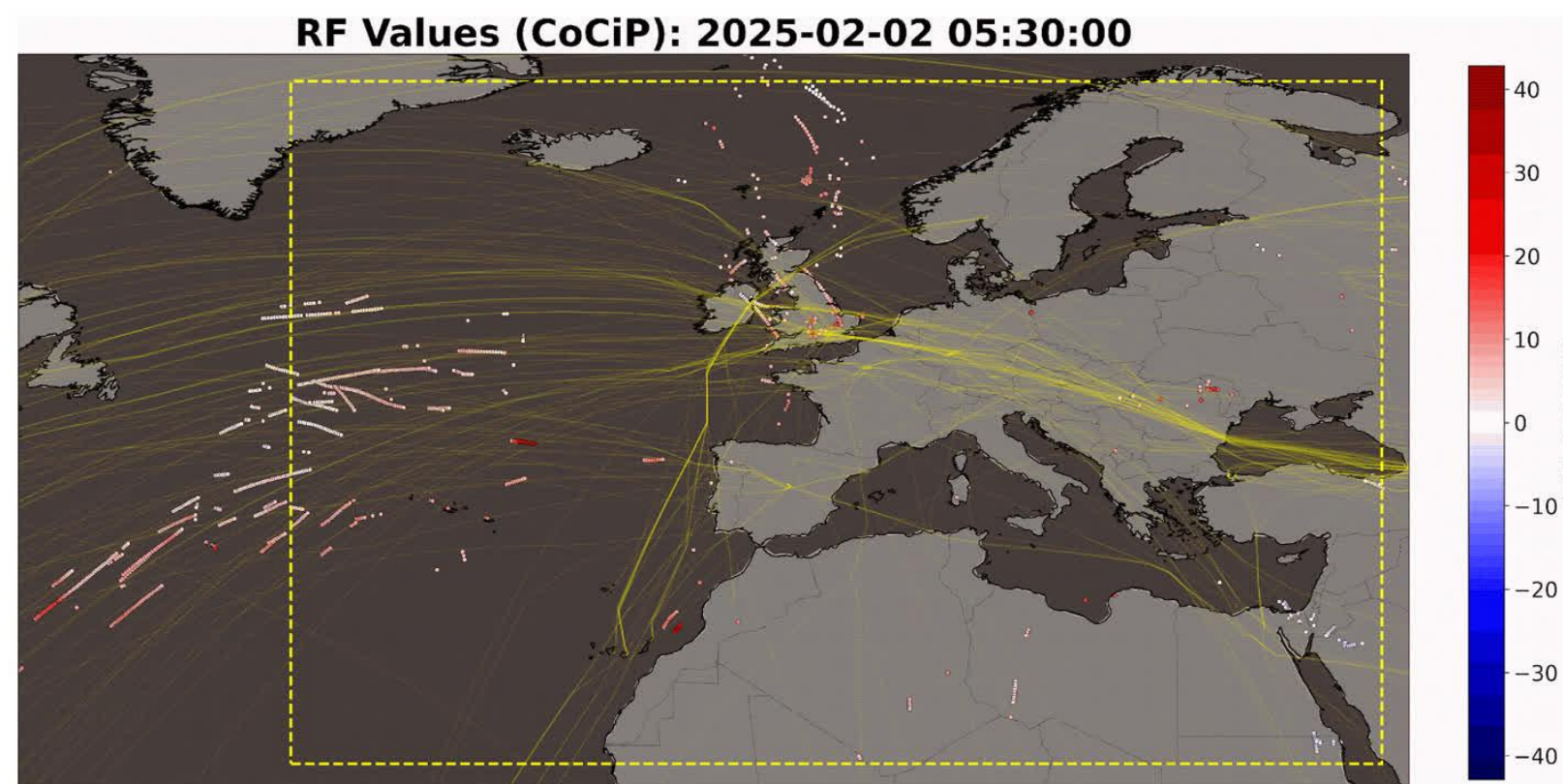
- Methods successfully quantify contrail radiative impacts
- Strong warming at night, net cooling during daylight.
- **Net warming, consistent with winter conditions:** shorter daylight hours reduce the compensating shortwave cooling.



1. Achievements and Research Progress

Second Experiment

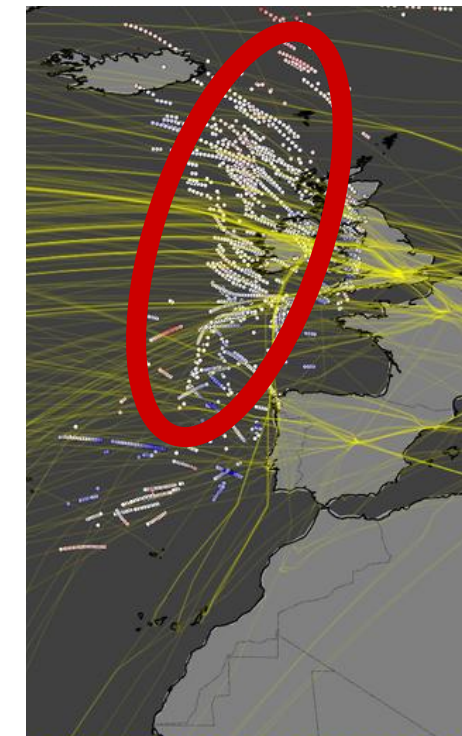
One week of data comparing satellite observations with modeled contrails (01-08 February 2025)



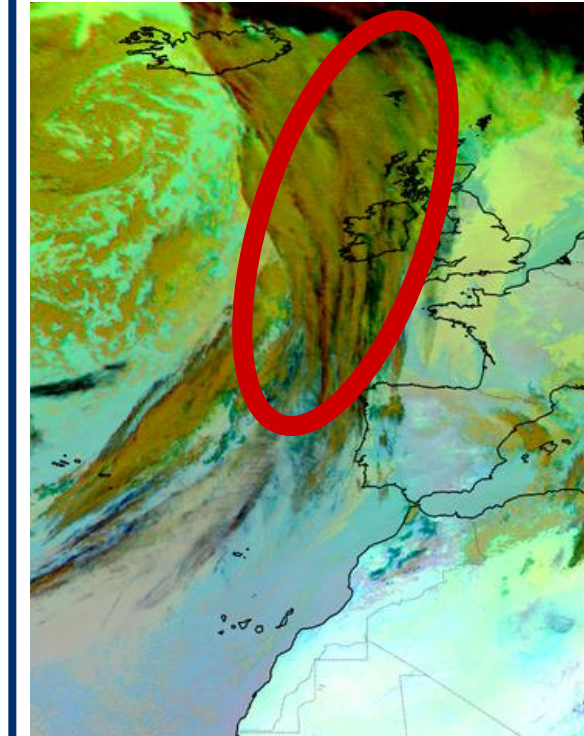
Benchmark contrail simulations

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

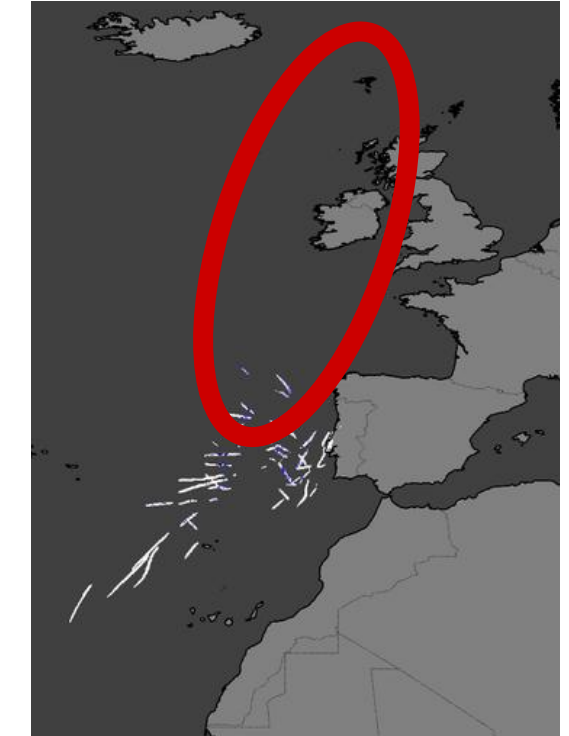
Simulations vs Observations



Simulated



Observed



Detected

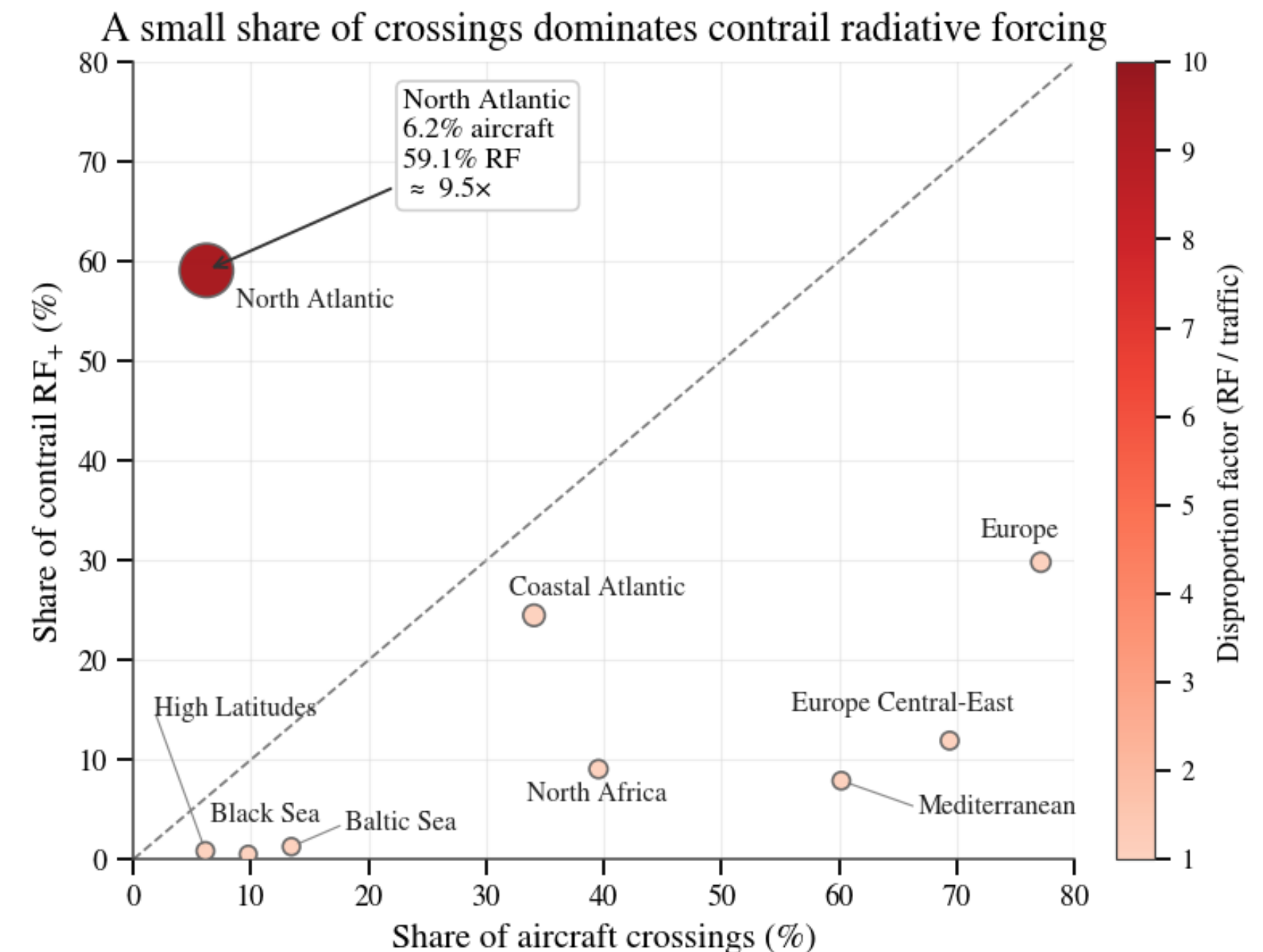
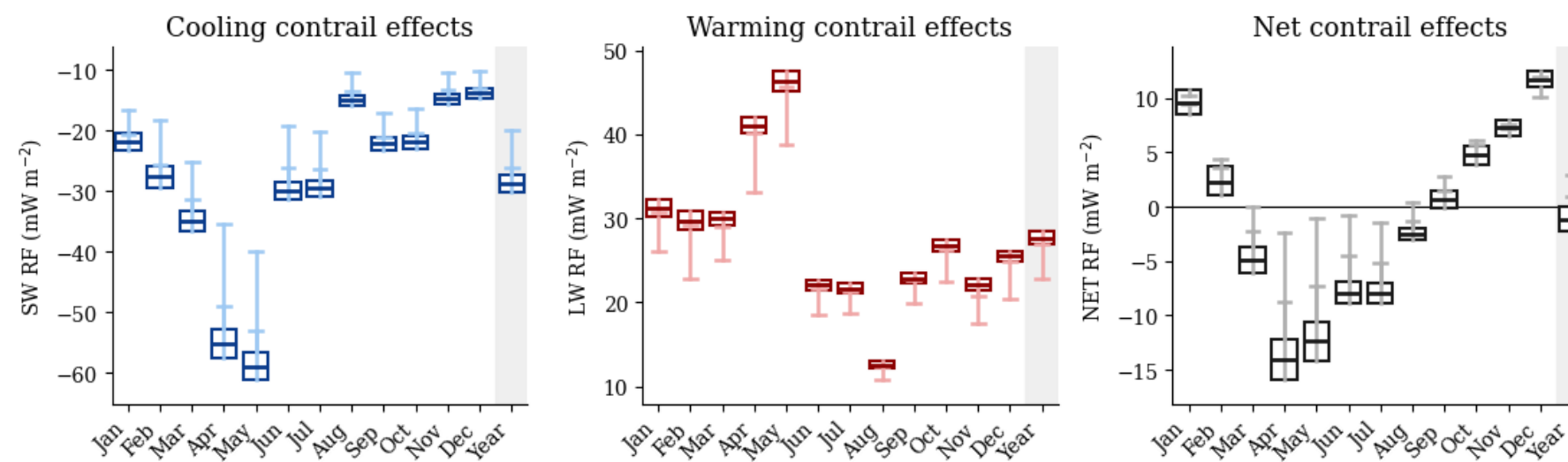
Simulations predict a larger contrail population than can be directly observed. This creates a **validation gap**, where many modelled contrails remain unverifiable because **satellite detections are limited** by cloud background, resolution, and viewing conditions.

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.

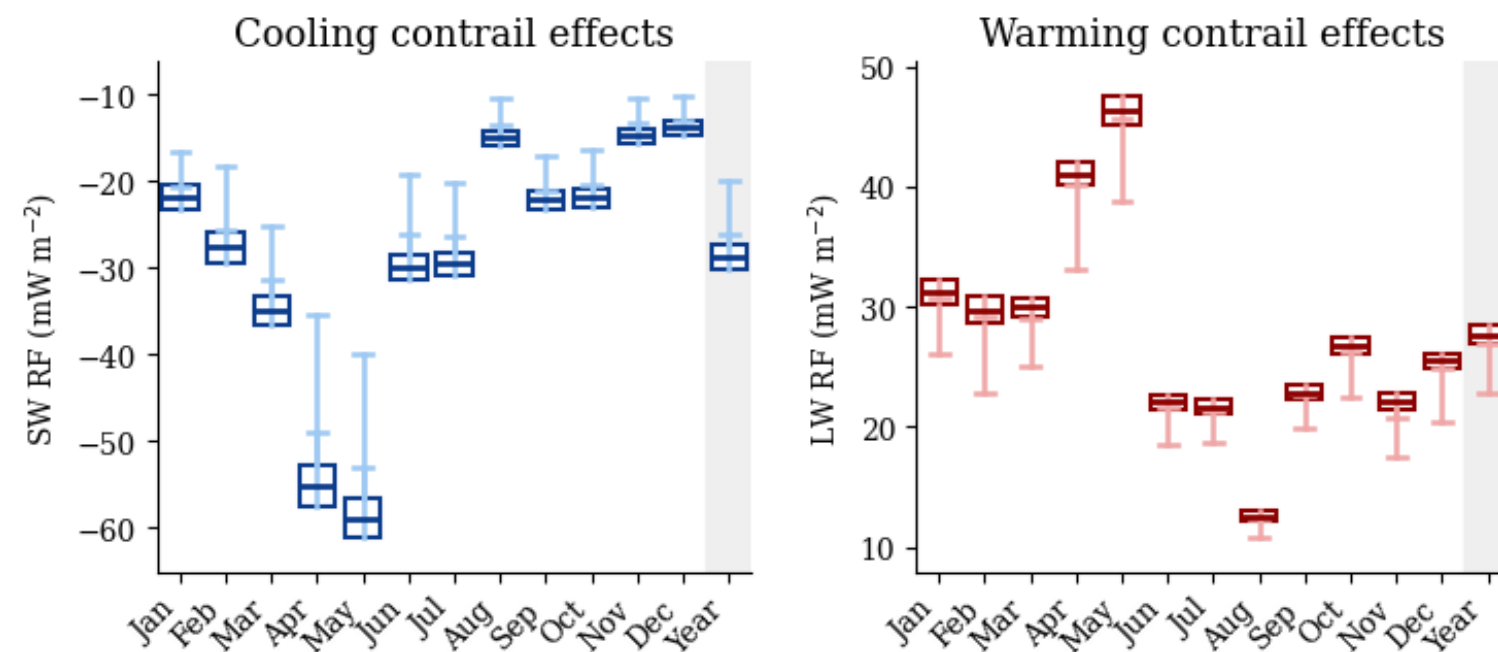
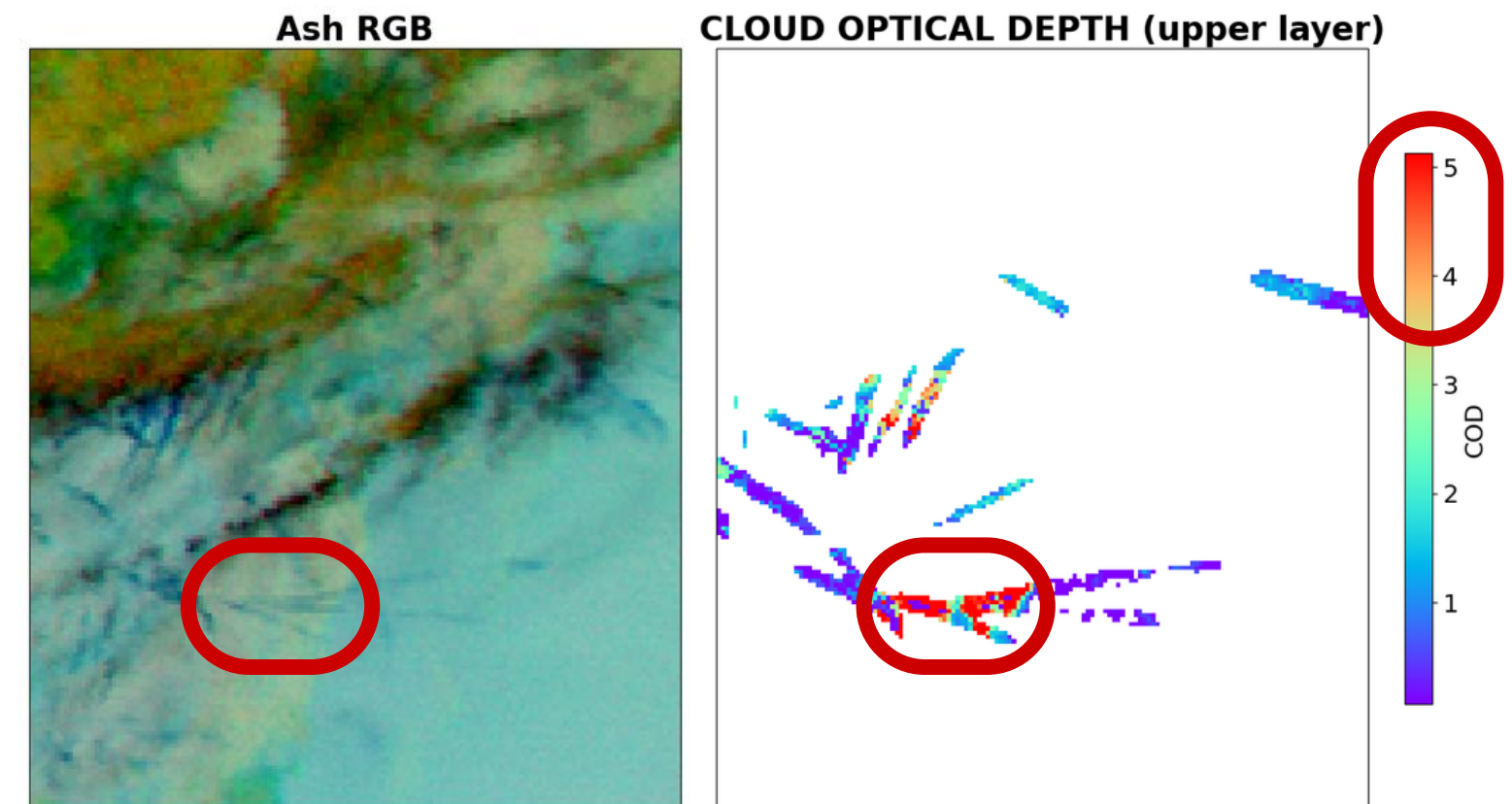


1. Achievements and Research Progress

Third Experiment

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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

Investigate contrail microphysics

Generate laboratory data

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

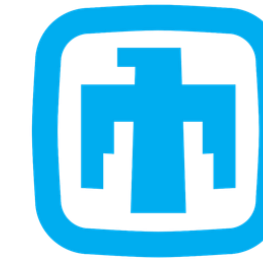
Refine process understanding

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

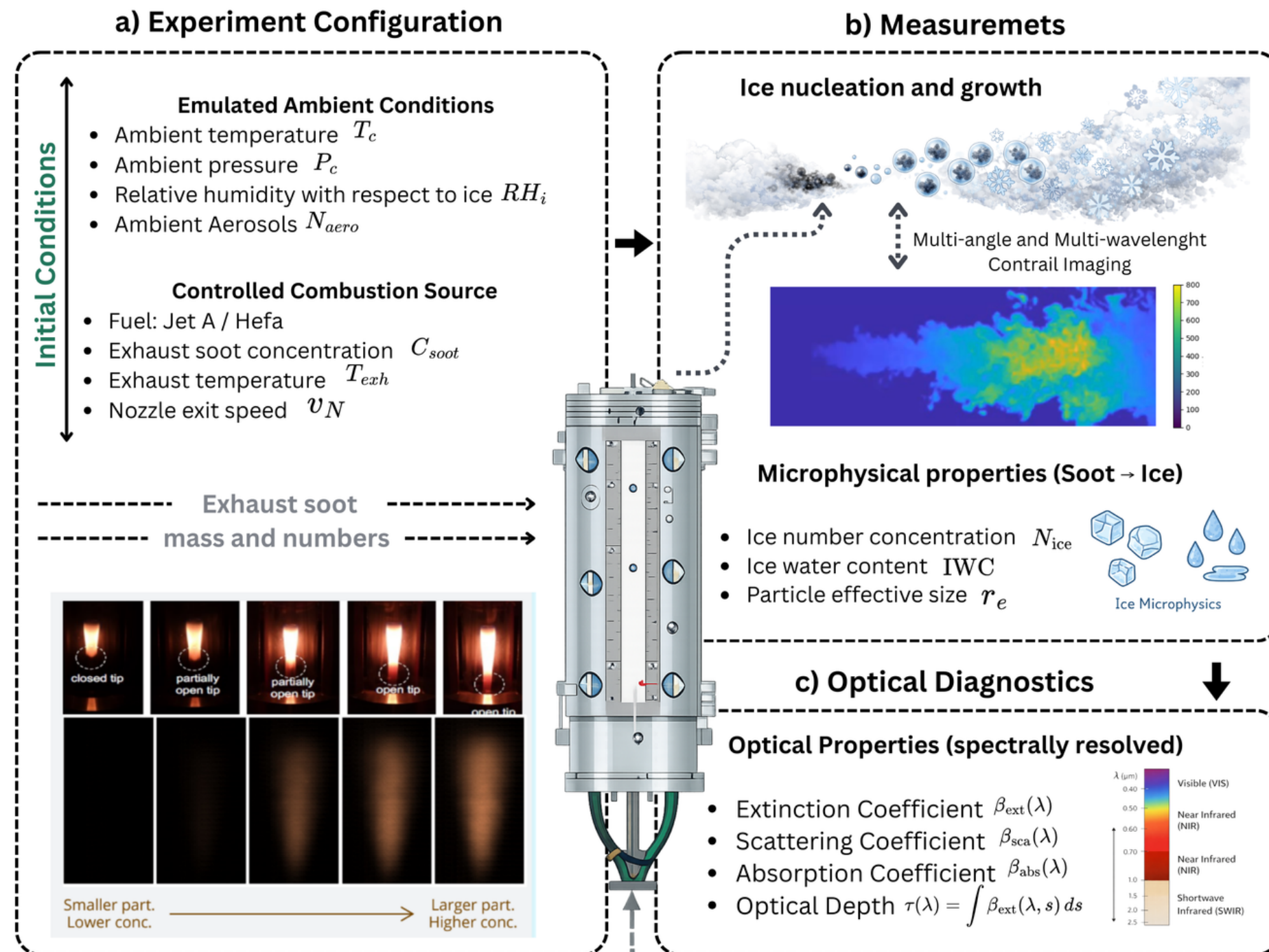
Constrain impact estimates

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

Research stay



Sandia
National
Laboratories

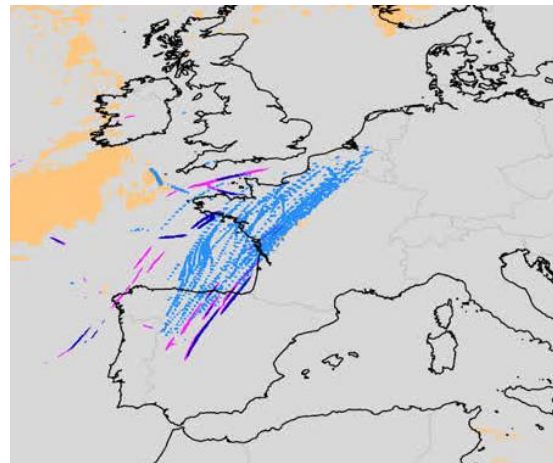


1. Summary

Research Objectives

1

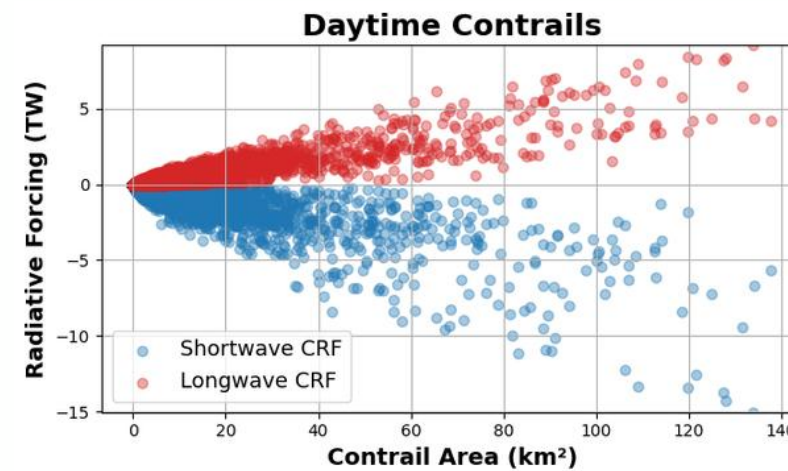
Develop advanced tools for contrail detection and monitoring



Done

2

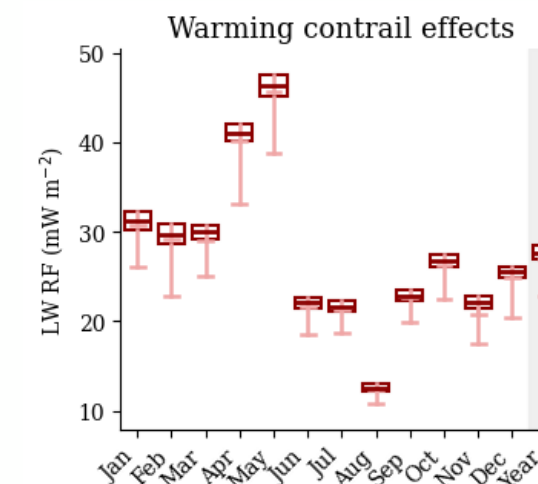
Investigate contrail formation, persistence, and radiative forcing



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
Aviation's climate impact is dominated by non-CO₂ effects—primarily contrails—but their magnitude remains poorly constrained due to reliance on model-based estimates. Here, we present a year-long assessment across the Euro-Atlantic region using a novel, observation-based framework that combines geostationary satellite data, neural-network detection, and rapid radiative forcing estimation. We find that contrail occurrence is highly concentrated over the North Atlantic and adjacent routes (75% of detections), where transatlantic flight corridors intersect the jet stream. This spatial concentration translates into a strong imbalance in climate impact: North Atlantic traffic accounts for only ~45% of flights but contributes ~60% (potentially up to 85%) of annual contrail-induced warming in this region. This extreme concentration highlights a high-leverage mitigation opportunity: targeting the most influential subset of flights—particularly transatlantic routes, focusing on nocturnal and low-altitude operations, with stronger constraints in autumn and winter—could deliver substantial near-term reductions in aviation climate forcing.

Keywords: Aviation, Contrails, Satellite Observations, Climate Mitigation

Global mean surface temperature reached a record high in 2024, approximately 1.25°C (±0.12°C) above 1850–1900 levels, marking the first calendar year in which warming exceeded the 1.5°C threshold relative to pre-industrial levels [1] and breaking the limit established under the Paris Agreement [2]. This milestone represents a critical escalation of climate risk, increasing the likelihood of longer-term, potentially irreversible impacts, including accelerated sea-level rise and permanent vegetation change [3, 4]. Despite mitigation efforts, global temperatures are projected to rise by approximately 2.2–2.5°C by 2100 [5]. Identifying and targeting key anthropogenic climate drivers is therefore essential for limiting this expected warming. One such driver is aviation, a hard-to-abate sector that accounts for approximately 3% of total global anthropogenic radiative forcing [6], with this contribution expected to increase given the projected twofold rise in global passenger and cargo traffic growth rates by 2050, according to the International Civil Aviation Organization (ICAO) [7]. The sector has a technical mitigation roadmap in place, which includes the adoption of sustainable aviation fuels (SAFs) [8], the development of advanced engine technologies [9], and the design of hybrid-electric or hydrogen-powered aircraft [10]. However, these measures and regulatory frameworks, such as the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) [11], are primarily CO₂-focused and require medium to long-term developments. Also, while such initiatives address the carbon component, they overlook non-CO₂ effects, which have been recognized to contribute approximately two-thirds of aviation's total anthropogenic radiative forcing [6], albeit with large uncertainties. These non-CO₂ forcing agents include nitrogen oxides (NO_x), aviation-induced ozone (O₃) formation, methane (CH₄) reduction, water vapour emissions (H₂O) at cruise altitudes, and aviation-induced contrails and contrail cirrus clouds.

1

Thank you!