

Making Contrails Visible: AI-Based Insights into Aviation's Climate Impact using Satellite Imagery

POLICY BRIEF

Manuel Soler, Irene Ortiz, Ermioni Dimitropoulou, Pierre de Buyl, Nicolas Clerbaux, Javier García-Heras, Amin Jafarimoghaddam, Hugues Brenot, Jeroen van Gent, Klaus Sievers, Evelyn Otero, Parthiban Loganathan, Virginia Villaplana, Gracia Pérez.

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E-CONTRAIL

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The E-CONTRAIL project ambition

The Hidden Climate Impact of Contrails

Aviation's impact on global warming is typically measured through its carbon dioxide (CO₂) emissions, estimated at around 2–3% of the total anthropogenic CO₂ emissions. However, this figure overlooks other non-CO₂ contributors—particularly contrails (condensation trails), which form in the upper atmosphere under specific meteorological conditions and may significantly alter the Earth's radiation balance.

Despite their potential climate relevance, contrails remain poorly quantified and difficult to monitor. The European research initiative E-CONTRAIL has addressed this gap by using artificial intelligence and satellite data to systematically detect, classify, and assess the climatic impact of contrails across seasons, times of day, and flight conditions.



By developing more precise tools for observing and understanding contrails, this project seeks to provide a stronger scientific basis for future aviation policy, operational strategies, and climate mitigation efforts in the European skies.

Understanding when, where, and how contrails contribute to warming is a crucial step toward more informed and responsible air travel.

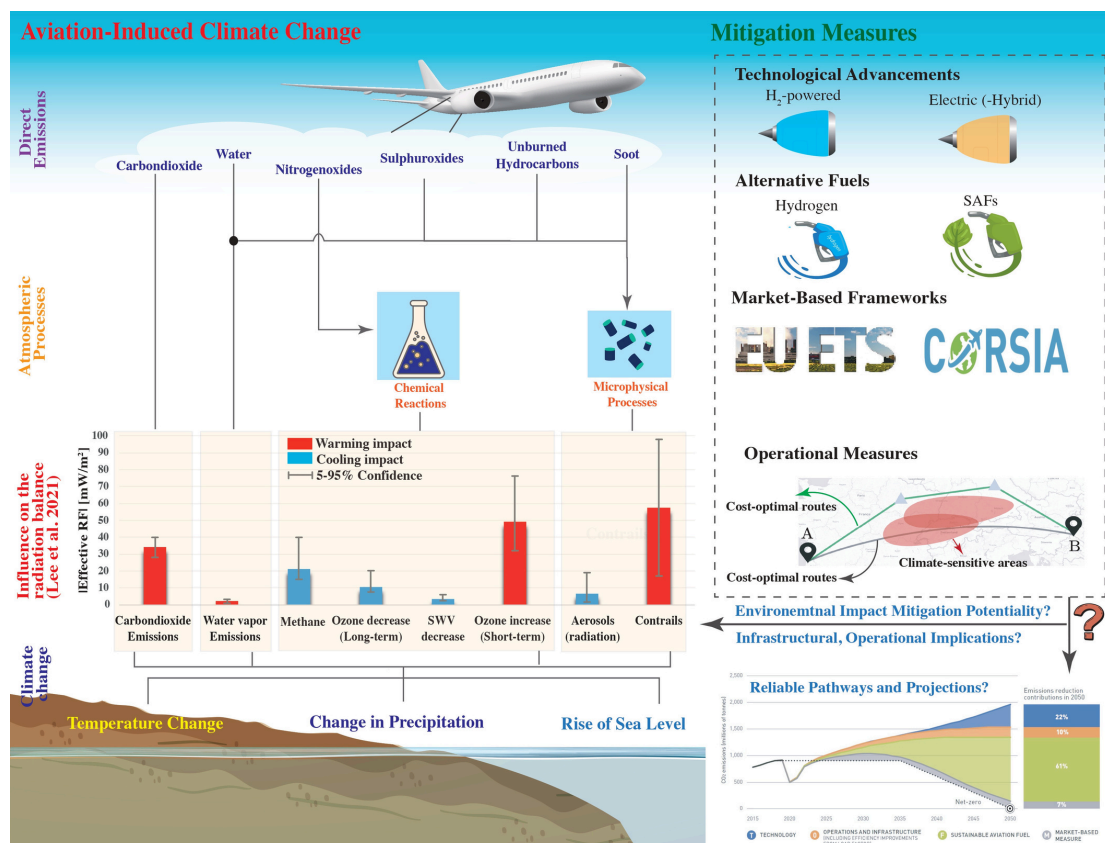
Why Contrails Matter More Than We Think?

As governments and international bodies intensify efforts to reduce global greenhouse gas emissions, aviation remains one of the most difficult sectors to decarbonize. Current policy frameworks—such as the EU Green Deal, ICAO's CORSIA, and national climate plans—largely target CO₂ emissions through improved fuel efficiency, sustainable aviation fuels, and carbon offsetting.

However, a growing body of scientific evidence suggests that this carbon-only approach may significantly underestimate aviation's true climate impact. Non-CO₂ effects, especially those caused by contrails, can lead to substantial atmospheric warming, yet remain largely invisible to policymakers and—despite the recent efforts in Monitoring, Reporting, and Verification—unaccounted for in most emissions inventories.

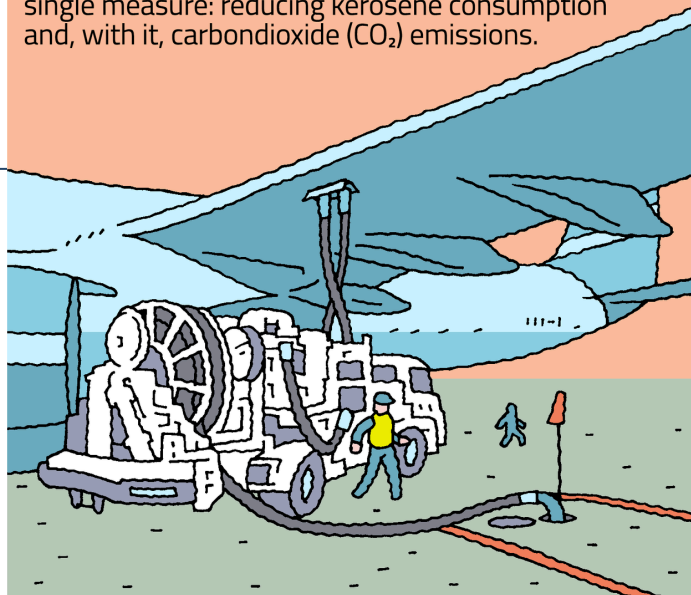
This omission is not just a technical gap, it has political and strategic implications. Without accurate data on the full climatic effects of aviation, it's impossible to monitor the real impact of non-CO₂ agents, nor to evaluate the effectiveness of potential mitigation strategies or to design targeted interventions, such as routing optimization, that could significantly reduce warming.

The E-CONTRAIL project has addressed this blind spot by applying data-driven methods to detect, classify, and evaluate the impact of contrails on a large scale. This effort is not just about scientific precision—it is about ensuring that climate policies are based on a complete picture, enabling aviation stakeholders to make informed decisions in line with the urgency of the climate crisis.

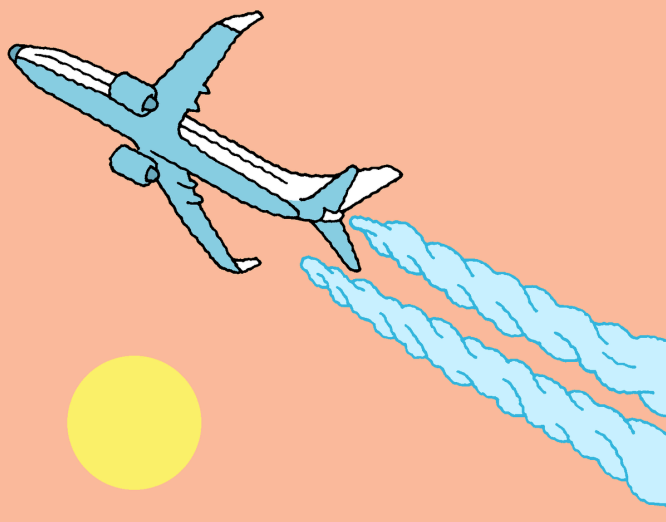


A real contrail story...

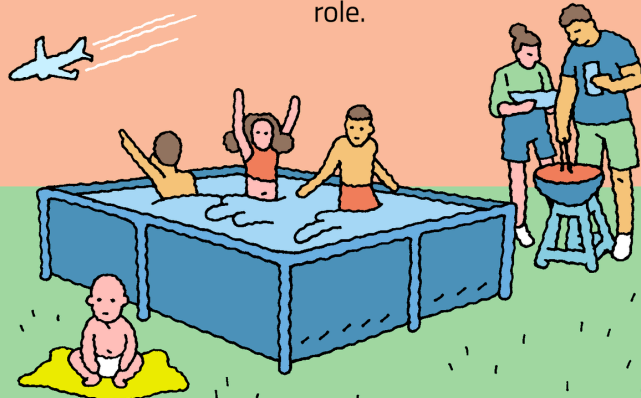
For a long time, the aviation sector has focused the bulk of its efforts to combat climate change on a single measure: reducing kerosene consumption and, with it, carbondioxide (CO₂) emissions.



The problem is that CO₂ is not the only contribution of aircraft to global warming.



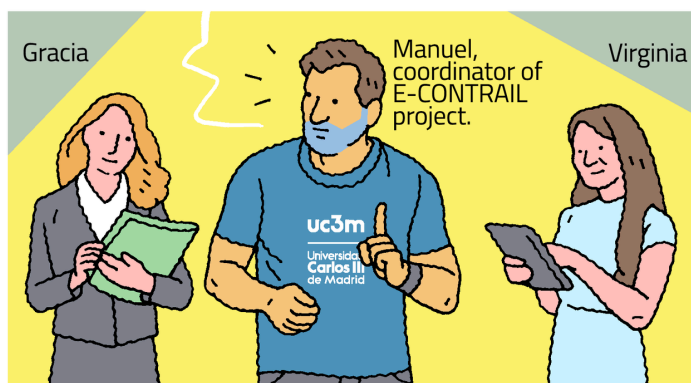
Approximately 25 years ago, it began to be recognized that contrails also play a role.



A role that could be as damaging to the climate as that of CO₂ — or even more so — according to a 2021 article by a group of scientists, some of whom have served as advisors or members of working groups of the Intergovernmental Panel on Climate Change (IPCC).

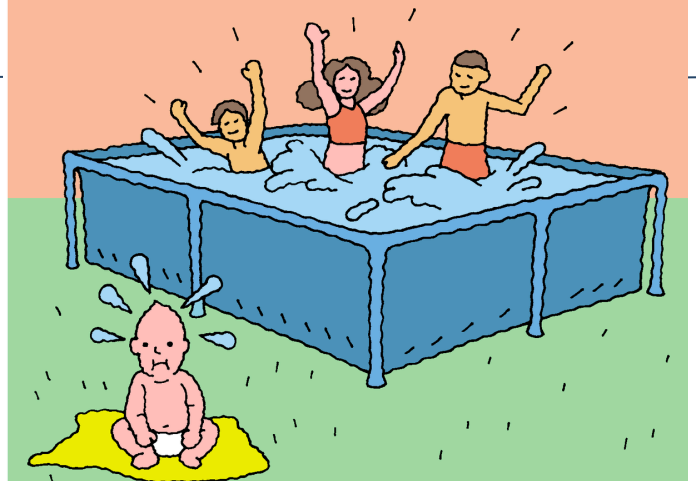
Estimates of the impact of contrails carry too wide a margin of error — and that is a problem. This is largely because, for a long time, insufficient resources were allocated to their study. For economic and political actors, it was easier to focus on reducing CO₂ emissions by burning less fuel — a measure that was beneficial not only for the environment, but also for lowering airline operating costs.

Mitigating the effects of contrail formation does not necessarily lead to lower operational costs. On the contrary, it could result in higher ones.



E-CONTRAIL

Neither the aviation industry as a whole nor the people living on this planet can afford to ignore how, when, and why contrails form — or their contribution to climate change.



That is why the E-CONTRAIL project team, coordinated by Universidad Carlos III de Madrid, began studying them in 2023.



Contrails form because burning a hydrocarbon — a process that requires mixing it with oxygen — produces carbon dioxide, water vapor, nitrogen oxides, soot, and particles from lubricants, among other byproducts.



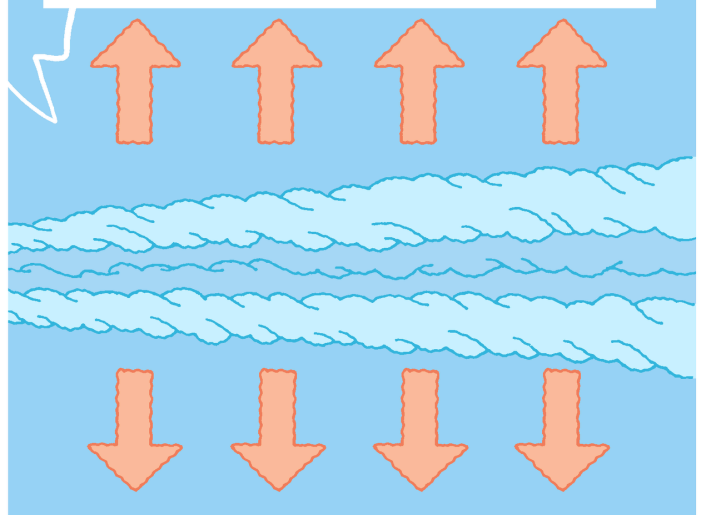
If atmospheric conditions allow, suspended particles already present in the atmosphere — together with those emitted by the aircraft — act as nuclei, attracting water vapor to form bead-like droplets that then freeze into tiny ice crystals.

Approximate temperature: $[-40^{\circ}\text{C}, -50^{\circ}\text{C}]$

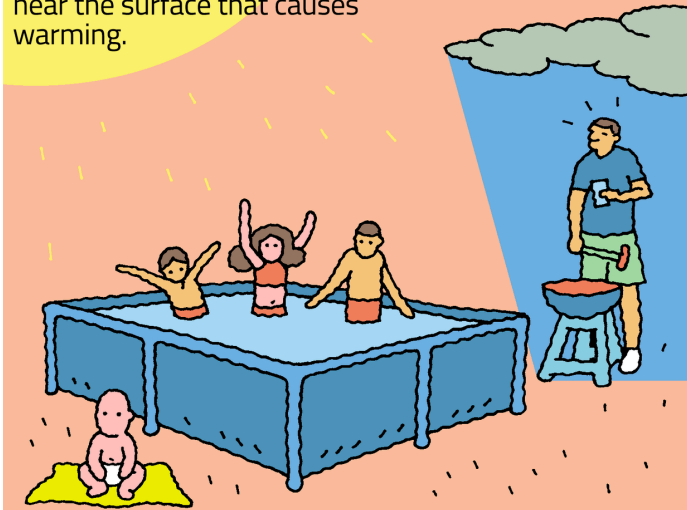


Relative humidity: close to 100%

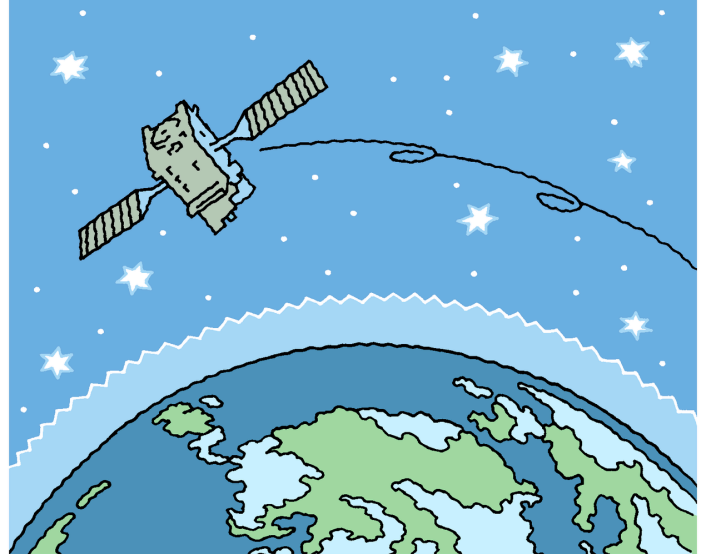
These ice crystals are what form contrails — artificial clouds induced by aircraft that block incoming shortwave radiation from the sun, but also trap outgoing infrared longwave radiation emitted by the Earth.



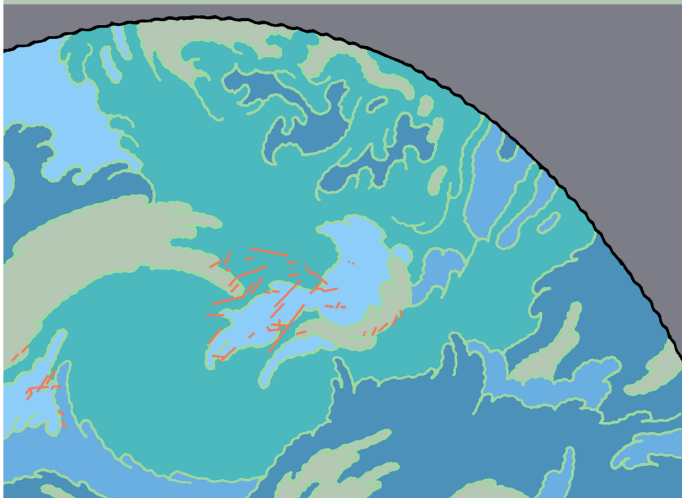
The first effect is cooling, and it's easy to understand because it's similar to how clouds provide shade as they pass. But the infrared radiation emitted by the Earth is also blocked by these aviation-induced clouds — and it's this trapped radiation near the surface that causes warming.



In E-CONTRAIL, an image recognition algorithm has been trained to identify contrails using imagery from the Meteosat satellite.



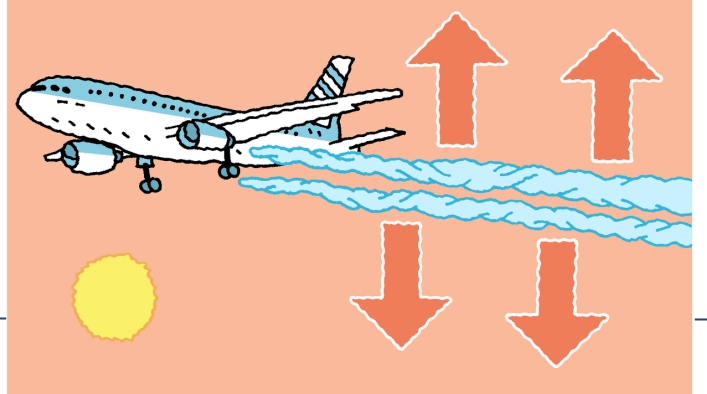
Using an atmospheric radiation transfer model, the team has been able to determine the extent to which the contrails identified by artificial intelligence contributed to surface warming or cooling of the Earth.



Finally, they have also developed a predictive algorithm based on deep learning techniques that links weather forecasts with the potential formation of contrails when aircraft fly through a given area.

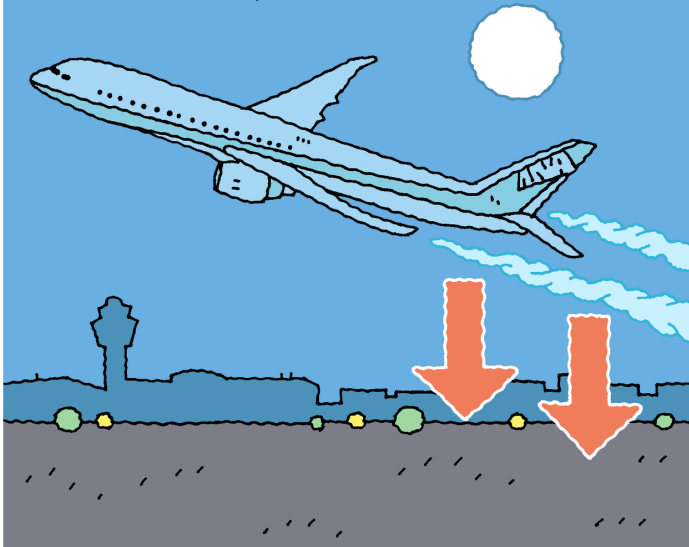


During the day, contrails can either cool or warm the Earth's atmosphere. They cool it when the amount of solar radiation they reflect exceeds the terrestrial radiation they absorb. But when they trap more outgoing radiation from the Earth than they reflect from the Sun, the net effect is warming.



E-CONTRAIL

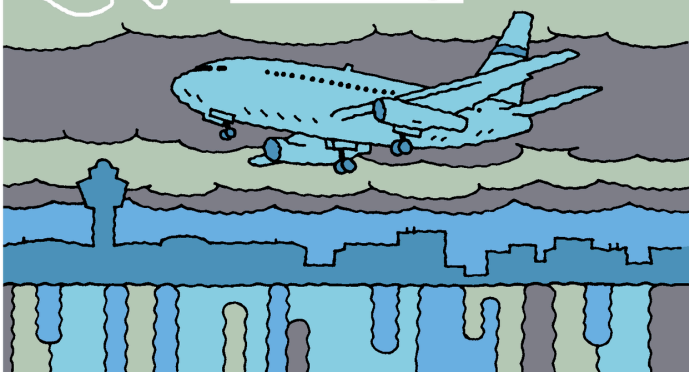
Contrails formed at night, however, always have a warming effect, since there is no solar infrared radiation to reflect — they only trap the radiation emitted by the Earth.



We are working to reduce the margin of error in quantifying the impact of contrails. If aviation-related CO₂ alone accounts for between 2% and 3% of global warming, contrails and other non-CO₂ agents could increase the industry's total contribution to between 4% and 6%. With a more than sufficient level of certainty, our results show that contrails generated during night flights have a warming effect on the climate.



This effect is more pronounced in autumn, spring, and especially in winter, when nights are longer. In summer, however, the impact of contrails is more benign — even for night flights. The impact of contrails generated during the day is more uncertain and requires further research. However, our results suggest that the net contribution of daytime contrails — particularly during midday hours — could be cooling.

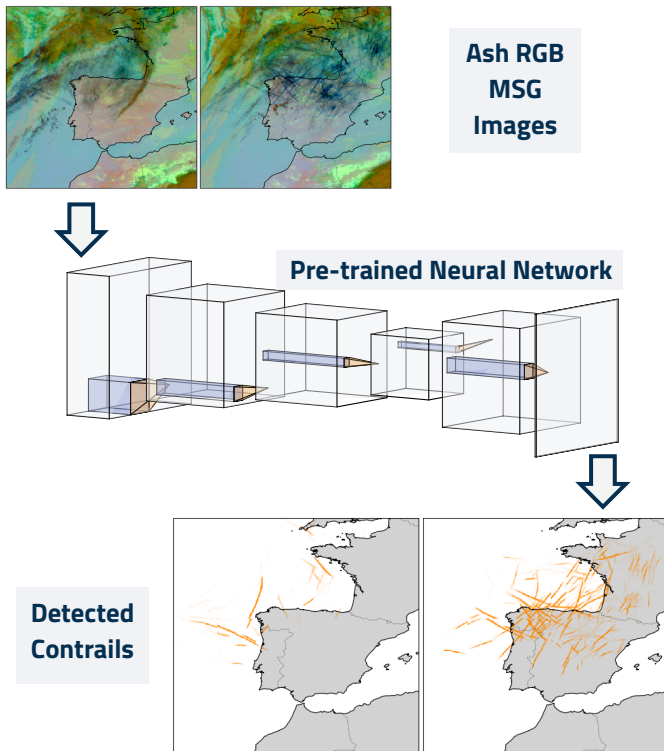


On 18 June 2025, the members of the international E-CONTRAIL team met at the headquarters of SESAR JU, the project's funding body, to present their findings and make them available to policymakers willing to take action to mitigate the climate impact of these flights with an unequivocal warming effect.



The end

The E-CONTRAIL models and algorithms

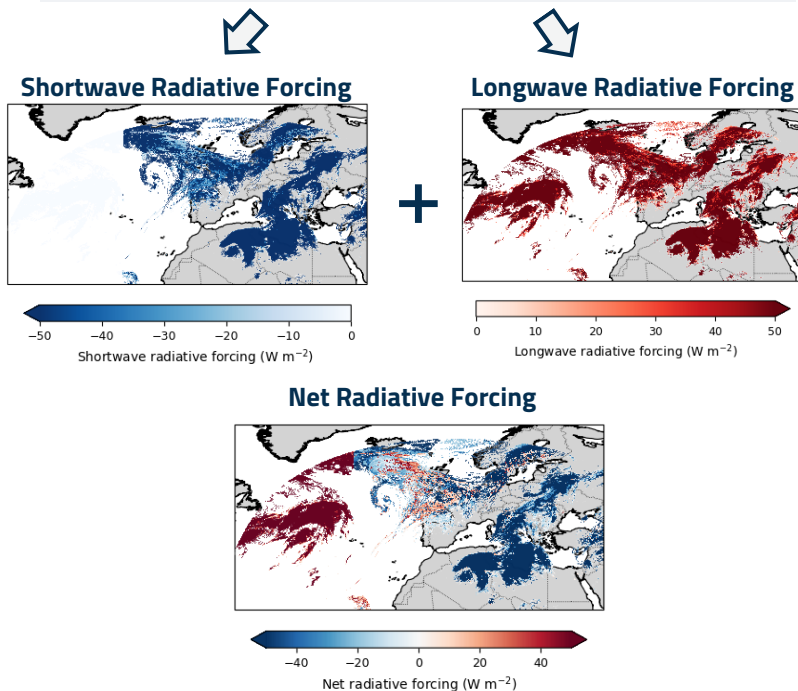


Contrail detection

AI-based algorithm trained with satellite images in Europe

I. Ortiz, J. García-Heras, A. Jafarimoghaddam and M. Soler. **Robust Evaluation of OpenContrails dataset using Neural Networks with Temporal Corrections via Optical Flow.** *IEEE Transactions on Geoscience and Remote Sensing*, 2025. DOI: [10.1109/TGRS.2025.3629628](https://doi.org/10.1109/TGRS.2025.3629628)

Characterization of Ice Cloud Microphysics: Optical Depth, Top Pressure & Effective Radius



Radiative forcing Estimation

Attribution of climate impact to contrails

E. Dimitropoulou, P. de Buyl, and N. Clerbaux. **Satellite-based estimation of contrail cirrus cloud radiative forcing derived through a Rapid Contrail-RF Estimation Approach**, *EGUsphere* [preprint], <https://doi.org/10.5194/egusphere-2025-697>, 2025.

I. Ortiz, E. Dimitropoulou, P. de Buyl, N. Clerbaux, J. García-Heras, A. Jafarimoghaddam, H. Brenot, J. van Gent, K. Sievers, E. Otero, P. Loganathan, M. Soler. **Satellite-Based Quantification of Contrail Radiative Forcing over Europe: A Two-Week Analysis of Aviation-Induced Climate Effects.** *SESAR Innovation Days 2024*.

The E-CONTRAIL models and algorithms

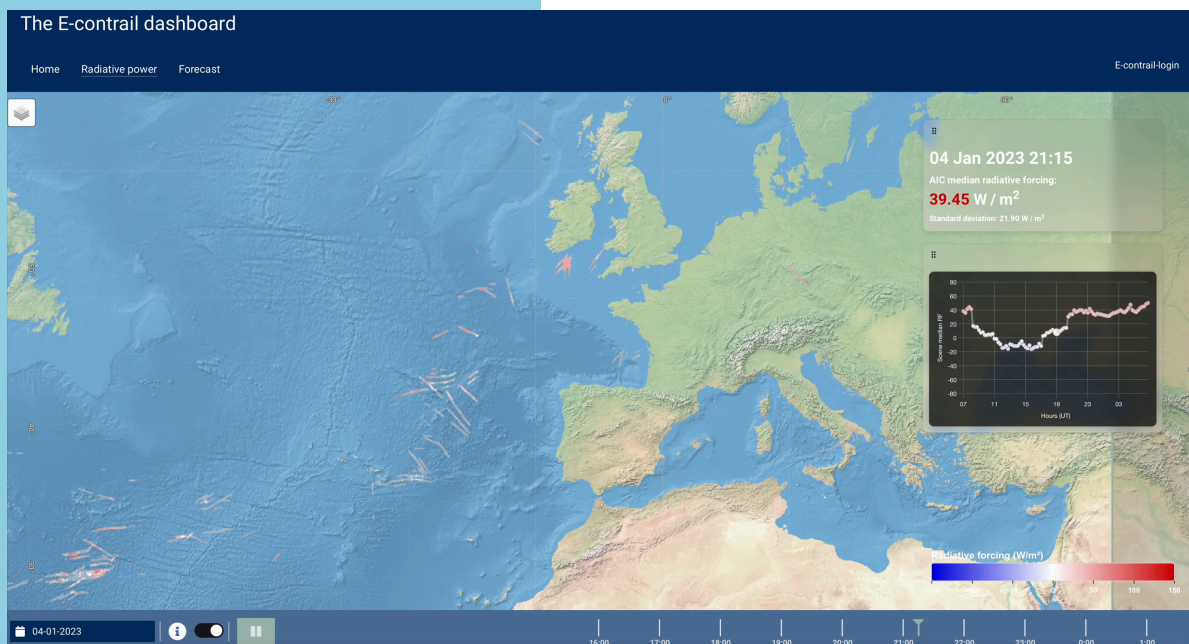
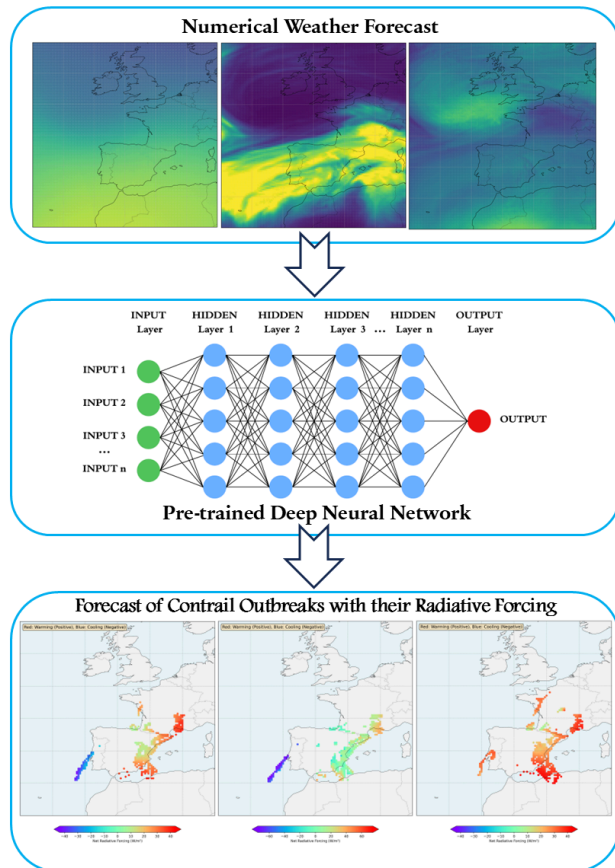
Forecast of Contrail Outbreaks and its radiative forcing

AI-based algorithm trained with contrail observations, radiative forcing estimation, and weather forecasts

Akbari et al., (2025). Contrail Outbreak and Radiative Forcing forecasting. In preparation.

Dashboard visualization econtrail.aeronomie.be

SESAR Solution with the 2023 climate impact quantification (detected contrails, RF estimation) and the contrail outbreak forecasting



Contrail impact quantification in Europe (2023)

Contrail detection

Ortiz et al. (2026). Observation-Based Assessment of Contrail Climate Impacts across the Euro-Atlantic Region. In prep..

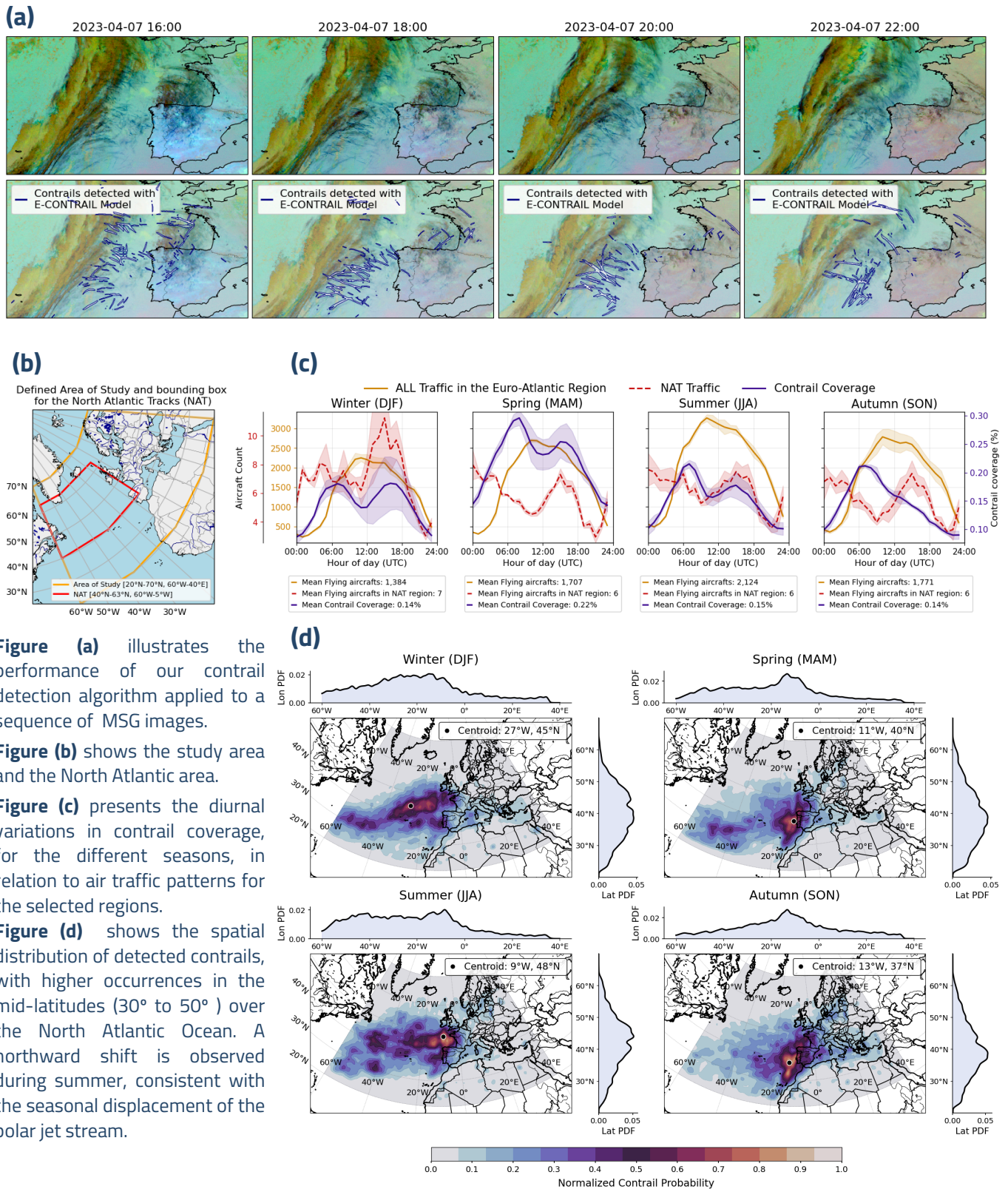


Figure (a) illustrates the performance of our contrail detection algorithm applied to a sequence of MSG images.

Figure (b) shows the study area and the North Atlantic area.

Figure (c) presents the diurnal variations in contrail coverage, for the different seasons, in relation to air traffic patterns for the selected regions.

Figure (d) shows the spatial distribution of detected contrails, with higher occurrences in the mid-latitudes (30° to 50°) over the North Atlantic Ocean. A northward shift is observed during summer, consistent with the seasonal displacement of the polar jet stream.

Contrail impact quantification in Europe (2023)

Contrail detection – key conclusions

Ortiz et al. (2026). Observation-Based Assessment of Contrail Climate Impacts across the Euro-Atlantic Region. In prep..

As part of the E-CONTRAIL project, we have successfully applied our novel contrail detection algorithm for the first time to a comprehensive dataset covering the Euro-Atlantic region. The following conclusions are derived from the analysis of MSG geostationary imagery spanning the full year of 2023. This analysis has provided unprecedented insight into contrail properties and distribution in this high-traffic area.

- **High-Fidelity Performance and Key Limitations:** The E-CONTRAIL contrail detection algorithm has been benchmarked using labeled GOES-16 imagery, demonstrating a very low false-positive rate while effectively detecting the majority of targeted contrail features. Missed contrails are generally attributed to cloud occlusion in the satellite scene rather than inherent model deficiencies. A critical limitation impacting model applicability and validation, particularly for this project, is the lack of labeled imagery outside the U.S., especially in Europe, which prevents proper regional validation and generalization.
- **Peak Seasonal Occurrence:** The 2023 analysis for the Euro-Atlantic region confirms a distinct seasonal variation. The highest frequency of contrail coverage occurred in April and May, which both registered a peak mean coverage of 0.25%.
- **Bimodal Diurnal Peaks:** Contrail detection frequency follows a bimodal diurnal pattern. A primary peak occurs in the morning (typically 07:00–09:00 UTC), driven by early departures and favorable atmospheric conditions. A secondary mid-afternoon peak (15:00–17:00 UTC) is also prominent, especially over the North Atlantic, corresponding to peak transatlantic flight activity.
- **Key Geographic Concentration:** Spatially, contrail detections are not uniformly distributed. They are concentrated in the mid-latitudes (30° to 50° North), closely following the seasonal movements of the polar jet stream. Longitudinally, analysis shows a higher density of contrails over the Atlantic Ocean compared to continental Europe.

Contrail impact quantification in Europe (2023)

Radiative forcing estimation

Ortiz et al. (2026). Observation-Based Assessment of Contrail Climate Impacts across the Euro-Atlantic Region. In prep..

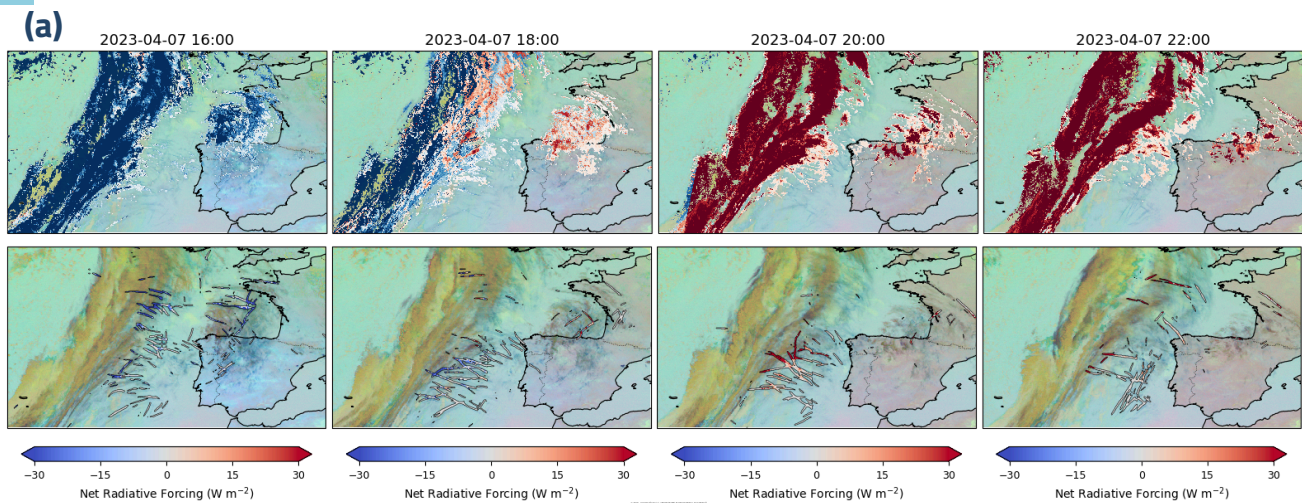
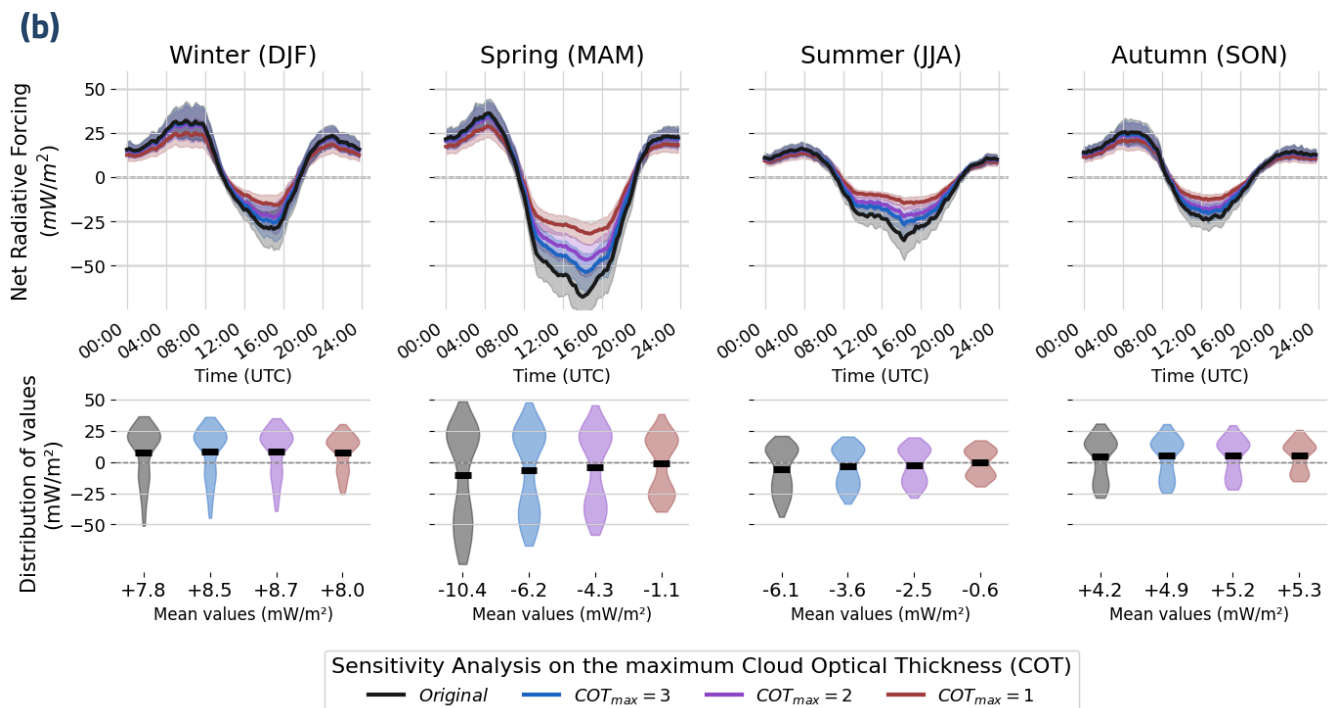


Figure (a) illustrates the radiative forcing (RF) characterization of ice clouds using our RF lookup tables (LUTs)

Figure (b) presents the diurnal trends of all detected and characterized contrails, which are analyzed across seasons using our RF Look Up Tables (LUT). Several curves are plotted alongside the original dataset to examine the sensitivity to the upper limit of Cloud Optical Thickness (COT), which occasionally exceeds the expected range for thin cirrus clouds (typically below 3). Radiative forcing is computed both from the original SEVIRI-derived COTs and by applying alternative upper thresholds. The results indicate a robust warming effect during winter and autumn, while in summer and spring, potential characterization uncertainties may lead to an underestimation of the actual warming contribution.



Contrail impact quantification in Europe (2023)

Radiative forcing estimation – key conclusions

Ortiz et al. (2026). Observation-Based Assessment of Contrail Climate Impacts across the Euro-Atlantic Region. In prep..

In parallel with detection, the E-CONTRAIL project has estimated the radiative forcing of the contrails identified in the 2023 MSG geostationary imagery dataset. This estimation, applied for the first time over the Euro-Atlantic region for a full year, has led to the following key conclusions:

- **Algorithm Benchmarking and Microphysical Limitations:** The E-CONTRAIL radiative forcing algorithm benchmarks effectively against the fluxes measured by radiometers on board the CERES LEO satellite (with accuracies above 80%). However, a key limitation is its strong dependency on the cloud microphysical retrieval algorithm, which can misattribute contrail properties, particularly assigning contrails with very low heights or very high cloud optical thicknesses, potentially leading to inaccuracies in the radiative forcing estimates. This limitation has been analyzed and mitigated by a cloud optical thickness sensitivity analysis.
- **Diurnal Net Cooling and Spring Uncertainty:** The contrail net radiative forcing is dominated by the shortwave (SW) cooling effect during central daylight hours. This results in an overall net cooling effect at the daily peak of solar insolation, as the reflection of solar radiation outweighs the longwave (LW) warming. This cooling effect during the day is, however, more uncertain, especially during the spring (March, April, May, June) months.
- **Seasonal Net Warming:** A clear seasonal dependency exists, with a net warming effect observed from August to April. This warming is most intense during the winter months (November to February), when reduced solar insolation minimizes the SW cooling effect, allowing the LW greenhouse effect to dominate.
- **High Sensitivity to Surface Albedo:** The SW cooling component of contrail RF is sensitive to the underlying surface, and this sensitivity increases as the contrail optical thickness grows. The cooling effect is strongest over dark surfaces (e.g., forests, oceans), and weaker over bright, reflective surfaces or existing cloud layers. Contrails forming above existing water clouds still have a notable radiative effect, but this influence diminishes as the underlying cloud layer becomes optically thicker. During daytime, contrails over thick liquid water clouds, produce a net warming effect.

Policy Recommendations

The E-CONTRAIL project demonstrates with high confidence that night-flight contrails significantly contribute to climate warming, an effect most pronounced in winter, while summer contrails are often neutral or cooling. This warming impact is geographically concentrated, with a high occurrence over the Atlantic Ocean. These complex findings provide a clear basis for targeted mitigation but also underscore the urgent need for further investment in fundamental research to refine predictive models. In light of these results, we propose the following policy actions:

- 1 Prioritize mitigation actions for flights occurring at dark (or mostly at dark):**

The project confirms that contrails formed at night, or on flights that take place mostly at night, exert a net warming effect by trapping longwave radiation without an offsetting shortwave cooling component. Therefore, mitigation strategies should be prioritized for nighttime operations to selectively avoid the formation of these consistently warming contrails.
- 2 Prioritize contrail mitigation actions during winter months.**

The radiative forcing of contrails shows a strong seasonal dependency. A significant net warming impact is observed during the autumn and, most markedly, the winter months. Mitigation efforts should be strategically focused on flights during these periods. Conversely, mitigation appears less critical in summer when both contrail frequency and impact are lower. Due to significant uncertainties in the net forcing effect during spring, imposing mitigation measures in these months is not recommended without further research.
- 3 Focus Special Attention on Oceanic Flights:**

Contrails are more common over the oceanic regions, where aircraft typically cruise at higher altitudes for longer durations, and the upper atmosphere is both colder and more humid. A large share of contrails occurs over the southern North Atlantic oceanic regions, where dense transatlantic flight routes favor their formation. In contrast, central Europe's drier upper atmosphere and shorter flight paths lead to fewer or less persistent contrails.
- 4 Invest in Fundamental Contrail Research to Close Knowledge Gaps:**

An accurate, trustworthy Monitoring, Verification, and Reporting (MVR) scheme for aviation's non-CO₂ impacts is essential for effective climate policy. Achieving this requires continued and significant investment in fundamental research. Priority areas related to contrail research should include, among others, novel contrail models, advancing satellite-based detection and radiative forcing estimation algorithms, expanding observation means, constructing and sharing labelled datasets, identifying flight attribution techniques to link specific contrails to their originating flights, developing robust contrail avoidance schemes in flight planning.

To align aviation policy with climate reality, we must act on this knowledge. By leveraging AI-powered detection, adjusting flight scheduling practices, and incorporating non-CO₂ impacts into regulatory frameworks, we can take immediate, practical steps toward reducing aviation's warming effect.



Universidad Carlos III de Madrid

Project Coordinator (Spain)

The UC3M Aerospace Engineering group brings together expertise in several areas, including the Aircraft Operations Lab, led by Project Coordinator Manuel Soler. UC3M has supported the project by developing remote sensing algorithms to detect contrails and aviation-related cloudiness, linking them to the responsible flights. The university also leads efforts in dissemination, communication, and exploitation of the project's results.



Royal Belgian Institute for Space Aeronomy (Belgium)

This scientific institute has its main research and public services in space aeronomy, including the physics and chemistry of the atmosphere of Earth and other planets and outer space. BIRA has contributed to E-CONTRAIL by developing the climate impact assessment and visualization tool panel, showing the climate impact of condensation trails that were assessed by tracking the prediction of aviation condensation trails using deep learning models.



KTH Royal Institute of Technology (Sweden)

Sweden's largest technical university. Based in Stockholm, this public university focuses on research and education in engineering and technology. The Engineering Mechanics department has contributed by developing deep-learning models to predict the radiative forcing of contrails based on data-archive numerical weather forecasts and historical traffic. This models helped develop the climate impact assessment presented in the visualization tool dashboard.



Royal Meteorological Institute of Belgium (Belgium)

The institute focuses on multiple scientific research fields related to meteorology such as climate projections, Hydrometeorology, and atmospheric modeling, among others. Within the Remote Sensing from Space Department, RMI has a unique competence at the European level for the measurement of the Earth radiation budget, expertise that will bring into the E-CONTRAIL project. The remote sensing methods and radiative transfer models enable the measurement of contrails in the radiative forcing of the atmosphere.

More about the project

www.econtrail.com



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