https://doi.org/10.1038/s41467-025-66724-6

Tracing contrails within cirrus clouds and their climate effect

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Aircraft contrails are not just streaks in clear blue skies - they represent a significant source of warming from the aviation sector. Two new studies reveal that their climate impact is more complex than previously thought, as many contrails may form within existing cirrus clouds – a factor often overlooked in past assessments. Drawing on aircraft, satellite and meteorological data, Petzold et al. and Seelig et al. provide fresh insights into the occurrence frequency and the radiative properties of these often "hidden" contrails.

White lines are often seen crisscrossing the sky—so-called condensation trails or contrails. They form when hot, humid aircraft exhaust mixes with the cold air at cruising altitudes, and water vapour condenses onto particles emitted by the engines, producing small ice crystals at temperatures below −45 °C. Under favourable meteorological conditions, these line-shaped contrails can spread and evolve into contrail cirrus, a type of high-altitude ice clouds that exerts a measurable influence on the atmospheric radiation budget. The ice crystals reduce the amount of outgoing longwave radiation at the top of the atmosphere and thereby contribute to global warming, that rivals the warming by aviation's carbon dioxide emissions.

However, contrails do not always form in clear blue skies, as often assumed in climate estimates. Instead, they are also produced within existing veils of cirrus clouds[1], where they are difficult to separate from natural cirrus clouds. This intermingling complicates efforts to isolate their specific radiative effects[2] (how they change the radiation budget) and may explain why those embedded contrails have often been neglected in evaluations of the aviation's climate impact.

Contrails, similar to natural cirrus clouds, can influence the Earth's radiation balance by modulating both outgoing and incoming radiation. Their ice crystals can prevent terrestrial radiation from escaping to space and thereby contribute to global warming[3]. During daytime, however, contrails can also reflect incoming solar radiation, reducing the amount that reaches the surface and thereby exerting a cooling effect[4]. On a global average, the net effect of contrails remains warming, comparable in magnitude to that from aviation's carbon dioxide emissions—despite the much shorter contrail lifetimes (hours) versus CO_2 (centuries)[5,6].

When contrails form within pre-existing cirrus clouds, their climate impact becomes even more complex. Contrails developing in thin cirrus may amplify cirrus induced warming, whereas those embedded in optically thick cirrus, such as outflow from convection, may obscure warming or even modulate cirrus-driven daytime cooling[7,8]. These 'hidden' contrails have not been adequately represented in current contrail climate models.

A further challenge lies in distinguishing contrail-induced cirrus from natural cirrus in observational data sets, given the substantial variability in cirrus cloud properties[9]. To effectively isolate anthropogenic contrail cirrus, additional data, such as measurements of aircraft-emitted particles or trace gases, are essential[10,11]. Due to their sensitivity to optically thin ice clouds, lidar observations can be adjusted for this task, especially when criteria such as a typically larger extinction of contrails compared with natural cirrus are met[12] or when complemented with aircraft flight trajectory information[13].

Two new studies address this long-overlooked aspect of contrails forming within cirrus through complementary observational approaches, see Fig. 1 for schematic representations. Petzold et al.[1] use in-situ water-vapour measurements from passenger aircraft to quantify how frequently contrails can form in clear-sky or under more humid cirrus conditions. Seelig et al.[2] focus on the radiative characteristics of the embedded contrails, applying high-resolution lidar observations from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, to derive the radiative forcing of contrails forming after the passage of an aircraft relative to neighbouring less perturbed cirrus regions. Their findings indicate that these embedded contrails can add a measurable contribution to the overall contrail cirrus climate impact.

Drawing on 7 years of in-situ aircraft humidity measurements alongside meteorological cirrus cloud data from the fifth-generation ERA5 reanalysis, Petzold et al.[1] find contrail-forming conditions often within existing cirrus clouds. Over the Northern mid-latitudes, about half of the contrail-favouring conditions occur within subvisible cirrus and clear-sky environments—those conditions that most likely trigger additional warming. The remainder are embedded within thicker cirrus, where their climate impact may be more variable and uncertain. The authors highlight the importance of considering ambient cirrus characteristics, not just ice-supersaturation, in the development of effective contrail mitigation strategies.

The study by Petzold et al.[1] provides a thorough assessment of contrail occurrence conditions based on a wealth of in-situ observations from passenger aircraft. Still, as for all new work, some caveats remain. In particular, the inference of contrail persistence from relative humidity data along the flight track alone is subject to variability. Atmospheric conditions can change rapidly, and contrails may dissipate within minutes to hours. Thus, determining which fraction of those contrail-prone regions truly represent climatically relevant, persistent contrails requires complementary information on contrail lifetime, for instance from satellite retrievals, or model simulations.

Moreover, direct observational contrail evidence, the optical depth thresholds distinguishing subvisible cirrus from other cloud

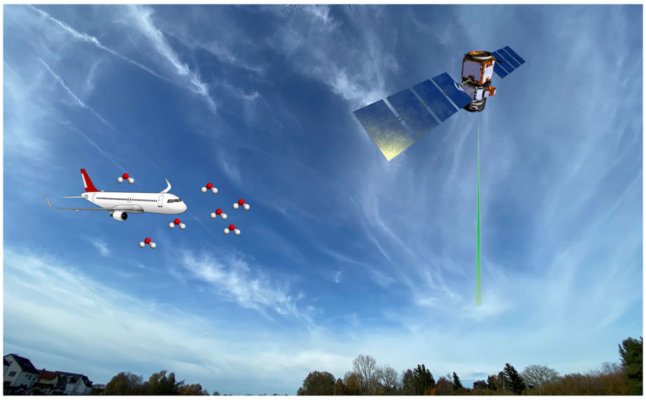

Fig. 1 | Contrails frequently form within existing veils of cirrus, making them difficult to separate from natural clouds and therefore these masked contrails are often neglected in aviation climate impact studies. Two new studies examine those contrails embedded in cirrus clouds. Petzold et al.[1] quantify the occurrence of contrails in humid cirrus-forming conditions using aircraft measurements (aircraft and water vapour molecules on the left side of Fig. 1). Seelig et al.[2] employ lidar observations from the CALIPSO satellite (right side in Fig. 1) to evaluate the radiative properties of those embedded contrails. Visualisation and photo, credit: Christiane Voigt, graphic elements: aircraft: clipground (CC by 4.0) and satellite: NASA/CNES (public domain).

classes, as well as the differentiation between day and night radiative effects over the contrails' lifetime, supporting the proposed conceptual distinction between contrail-induced warming or cooling within visible and thick cirrus may need additional considerations, underscoring the need for targeted analyses using satellite observations.

Such observational constraints are provided by Seelig et al.[2], who advance this line of enquiry by combining satellite-based cloud observations with aircraft trajectory data along drifted flight tracks. Analysing the radiative fluxes of 40,000 embedded contrails, the authors quantify their climate impact. They find that young embedded contrails exert a measurable local net radiative forcing, dominated by the night-time contrails. When scaled globally, this signal would add around 10% to current estimates of the radiative forcing from visible, line-shaped contrails. These findings highlight that embedded contrails may constitute a non-negligible, slightly larger component to aviation's overall climate impact than previously recognised.

While the radiative flux characterisation of contrails within cirrus clouds marks an important step toward a more robust estimate of their climate influence, future studies could extend the analyses to longer contrail lifetimes beyond the 30 min intentionally considered by Seelig et al.[2]. Despite being experimentally challenging, such efforts would help to capture longer-lived and hence climatically more relevant contrail cirrus. In addition, sorting contrails by their own, and the surrounding cirrus' optical properties, as proposed by Petzold et al.[1] could provide quantitative evidence to assess warming or cooling mechanisms. Moreover, combining existing and upcoming polar-orbiting with geostationary satellite observations, and high-resolution aircraft measurements, potentially augmented by artificial intelligence methods—could improve the contrail detection frequency, prolong their tracking duration and better constrain both, the radiative forcing and the climate impact from contrails embedded in cirrus clouds. In light of global warming reaching +1.42 °C in August 2025[14], mitigating aircraft shorter lived non-CO_2 effects, such as contrails and NO_x emissions, remains critical to achieve the 2 °C goal of the Paris agreement[15]. Advances in contrail prediction, such as including the integration of natural cloud effects and satellite-based evaluations support the development of operational contrail avoidance strategies[16]. While sustainable aviation fuels hold a long-term promise, flight altitude adjustments to avoid specifically those contrail-prone regions, that effectively lead to warming contrails, may offer a faster, cost-effective mitigation pathway. Latest risk analyses[17] accounting for current uncertainties in aviation's non-CO_2 climate impact, further emphasise that both additional scientific investigations and immediate climate action to reduce contrails are urgently required to progress towards a climate neutral and competitive aviation sector.

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Received: 9 November 2025; Accepted: 13 November 2025;
Published online: 28 November 2025

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Acknowledgements

We thank Silke Groß, Tina Jurkat-Witschas and Markus Rapp for helpful comments on the manuscript.

Author contributions

C.V. and Z.W. wrote the manuscript.

Competing interests
The authors declare no competing interests.

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