PREDICTING AND OBSERVING CONTRAILS AND THEIR IMPACTS

SUMMARY: Contrails contribute to global warming. Mitigation is possible but requires improved prediction and observation, with ground-based cameras offering new opportunities.






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Aviation contributes to climate change through both carbon dioxide emissions and shorter-lived atmospheric phenomena such as condensation trails (contrails). A cost-effective strategy to reduce aviation's climate impact is avoiding contrail formation through relatively small adjustments to aircraft flight altitude, a method already proven feasible for commercial flights [1]. However, implementing such strategies requires reliable prediction and observation of contrails, which is still a grand challenge.

Contrails are line-shaped ice clouds that form behind aircraft. Early observations of contrails date back to the beginning of the 20th century as aircraft began reaching sufficiently high altitudes. Depending on the atmospheric conditions, contrails may be short-lived and dissipate within minutes (Fig. 1a), or persistent, lasting for more than 10 minutes up to several hours and spreading into extended cirrus-like cloud structures (Fig. 1b). Persistent contrails are particularly important because they can modify the Earth's radiation budget (Fig. 1c). The climate impact of contrails is assumed to be significant, but large uncertainties still exist. Estimates suggest that contrails contribute approximately 1–2% of total anthropogenic warming and account for roughly half of aviation's climate impact [2]. According to the International Air Transport Association, global air traffic demand is projected to more than double by 2050. As a result, the importance of understanding and mitigating contrail effects will only grow, given their significant contribution to aviation-related climate impacts.

Contrail persistence is governed by the presence of ice supersaturated regions (ISSRs), where the relative humidity with respect to ice exceeds 100%. Avoiding these relatively thin layers of air could

substantially reduce persistent contrail formation. However, predicting the occurrence and distribution of ISSRs remains challenging due to limitations in atmospheric models and observations.

To improve predictions of ISSRs, increased observational capabilities are required. High-resolution observations that allow contrails to be associated with individual flights are particularly valuable for validating prediction models. While satellite observations have significantly advanced the field, they exhibit important limitations due to their coarse resolution. This motivates the development of complementary techniques such as ground-based camera systems, which provide continuous, high-temporal-resolution observations.

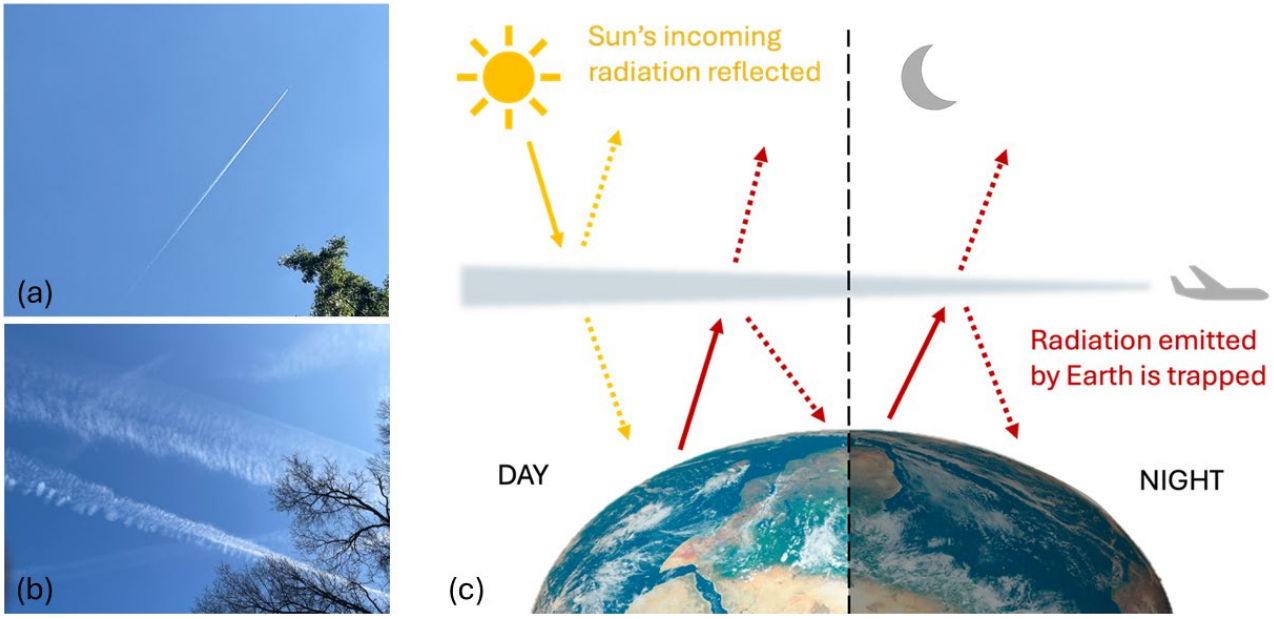


Figure 1. Examples of: (a) a short-lived contrail that dissipates in a short distance behind the aircraft and (b) persistent contrails that grow and remain in the sky for longer periods of time after the aircraft's passage (10 min to several hours). (c) Illustration depicting the interaction of contrails with the Sun's incoming shortwave radiation and Earth's outgoing longwave radiation. The net effect of contrails is warming. Photos taken by Emily Tracey.

CONTRAIL FORMATION

The formation and evolution of contrails are governed by a combination of thermodynamic, microphysical, and dynamical processes. Aircraft engines emit hot, humid exhaust containing water vapor, heat, and soot particles. As this exhaust mixes rapidly with the cold ambient air at cruising altitude, the temperature decreases while the relative humidity increases. If saturation is reached,

water droplets form on available condensation nuclei and quickly freeze into ice crystals, producing a visible contrail. Emitted soot particles provide the surface for water vapour to condense onto.

The thermodynamic conditions required for contrail formation are described by the Schmidt–Appleman criterion, which depends on ambient temperature, pressure, and humidity, as well as engine-specific parameters such as propulsion efficiency and water vapor emissions [3-5]. Together, these variables determine a critical temperature threshold below which the mixing of exhaust gases with ambient air leads to saturation and contrail formation. While the Schmidt-Appleman criterion predicts the formation of contrails, it does not predict their persistence. Contrails persist only when they form within ISSRs. These regions are relatively common in the upper troposphere because the ice nuclei required for ice formation are rare, allowing air to remain supersaturated with respect to ice for extended periods. ISSRs typically occur in ascending air, where cooling reduces the saturation vapor pressure faster than the water vapor concentration decreases. The upward motion of humid air is a relatively small-scale phenomena that occurs commonly near fronts and warm conveyor belts around storm systems. The vertical extent of ISSRs is often small, typically on the order of 500–1000 m [6] due to the strong temperature gradient in the upper tropopause and local variations in atmospheric water vapour. ISSR occurrence varies seasonally with minimum occurrence in the summer and maximum in late winter.

Beyond initial formation, contrail evolution is strongly influenced by aircraft wake dynamics. Four phases are usually distinguished: the jet, vortex, vortex dissipation, and diffusion phases [7,8]. During the jet phase, immediately after emission, exhaust gases mix with ambient air and initial ice crystals form. In the vortex phase, counter-rotating wingtip vortices transport the contrail downward by tens of meters. The primary vortex pair may descend into warmer air, causing ice crystals to sublimate, while secondary vortices may lift some ice crystals back toward altitudes more favorable for persistence. During the vortex dissipation phase, the wake breaks down and ice crystals are released into the surrounding atmosphere. In the final diffusion phase, the contrail spreads both horizontally and vertically due to atmospheric turbulence, wind shear, particle sedimentation, and radiative processes. Persistent contrails can evolve into cirrus-like clouds that last for several hours with significant impact on Earth's radiation balance.

CONTRAIL MODELS AND PREDICTION

Predicting contrail formation and evolution is essential for implementing mitigation strategies such as altitude adjustments. The Schmidt–Appleman criterion provides a first-order estimate of whether contrails will form under given atmospheric conditions. However, it does not determine whether they will persist. Persistence depends primarily on the distribution of ISSRs, but numerical weather prediction models often struggle to accurately resolve humidity at higher altitudes, where ISSRs occur [9].

More advanced models, such as the Contrail Cirrus Prediction model (CoCiP), simulate the full lifecycle of contrails. These models combine flight trajectory data with meteorological inputs to predict contrail formation, evolution, and radiative forcing. They incorporate processes such as ice crystal growth,

sedimentation, contrail spreading, and interactions with radiation. However, uncertainties due to the meteorological input data and parametrized microphysical processes remain. Improving observational data is therefore critical for validating and refining contrail prediction models [9].

CONTRAIL OBSERVATION

Satellite observations are currently the primary tool for large-scale contrail detection. Two main types of satellites are used: low Earth orbit (LEO) and geostationary (GEO) systems. LEO satellites provide high spatial resolution, allowing contrails to be resolved in detail. However, they revisit the same location relatively infrequently, typically every 12 hours to several days. This limits their ability to track contrail evolution and makes it difficult to observe all events. Additionally, attributing observed contrails to specific flights is challenging due to the limited temporal coverage. GEO satellites, in contrast, provide high temporal resolution, often delivering imagery every 5–30 minutes. However, their spatial resolution is coarser, typically on the order of 1–2 km. As a result, newly formed contrails, which are initially very thin, may not be detectable for the first 20–30 minutes. This again complicates flight attribution and limits the study of early contrail evolution. These complementary limitations highlight the need for additional observational approaches that can bridge the gap between spatial and temporal resolution. ***Lidar systems*** provide detailed vertical profiles of atmospheric properties and are highly sensitive to thin clouds, including contrails. They are particularly useful for determining contrail altitude, optical depth, and microphysical structure. However, lidar measurements are typically limited to narrow fields of view. Furthermore, only a small number of lidars are operated globally. Hence, lidar observation cannot provide continuous large-scale coverage.

Ground-based camera systems provide a promising complement to satellite and lidar observations. All-sky or wide-field cameras can continuously monitor large portions of the sky with high temporal resolution, capturing the full lifecycle of contrails. A key advantage of these systems is the ability to associate contrails with individual flights. By combining camera observations with flight tracking data, it is possible to match observed contrails to specific aircraft (Fig. 2). This enables direct validation of contrail prediction models and allows observed contrail properties such as lifetime, width, and spreading rate to be linked to aircraft characteristics and atmospheric conditions. Ground-based camera observations can also help quantify biases in satellite detection by identifying contrails that are missed due to spatial or temporal limitations. With appropriate calibration or multi-camera configurations, it is possible to reconstruct contrail geometry and estimate altitude, further increasing their scientific value. Single ground-based camera systems are limited by a lack of global coverage, however, a network of cameras like the Global Meteor Network [10] can provide both high-resolution observations and increased coverage.

FUTURE WORK

Future research should focus on integrating observational and modeling approaches to reduce uncertainties in contrail prediction and climate impact. Ground-based camera networks, similar in concept to existing meteor observation networks, offer a scalable and cost-effective means of continuously monitoring the sky at high temporal resolution. Combining these observations with

satellite images, lidar measurements, and flight trajectory information would enable more comprehensive validation of contrail models. Improved characterization of ISSRs, particularly their small-scale variability, remains a key challenge that requires both enhanced modeling and targeted observation campaigns. Finally, improving prediction accuracy is essential for implementing

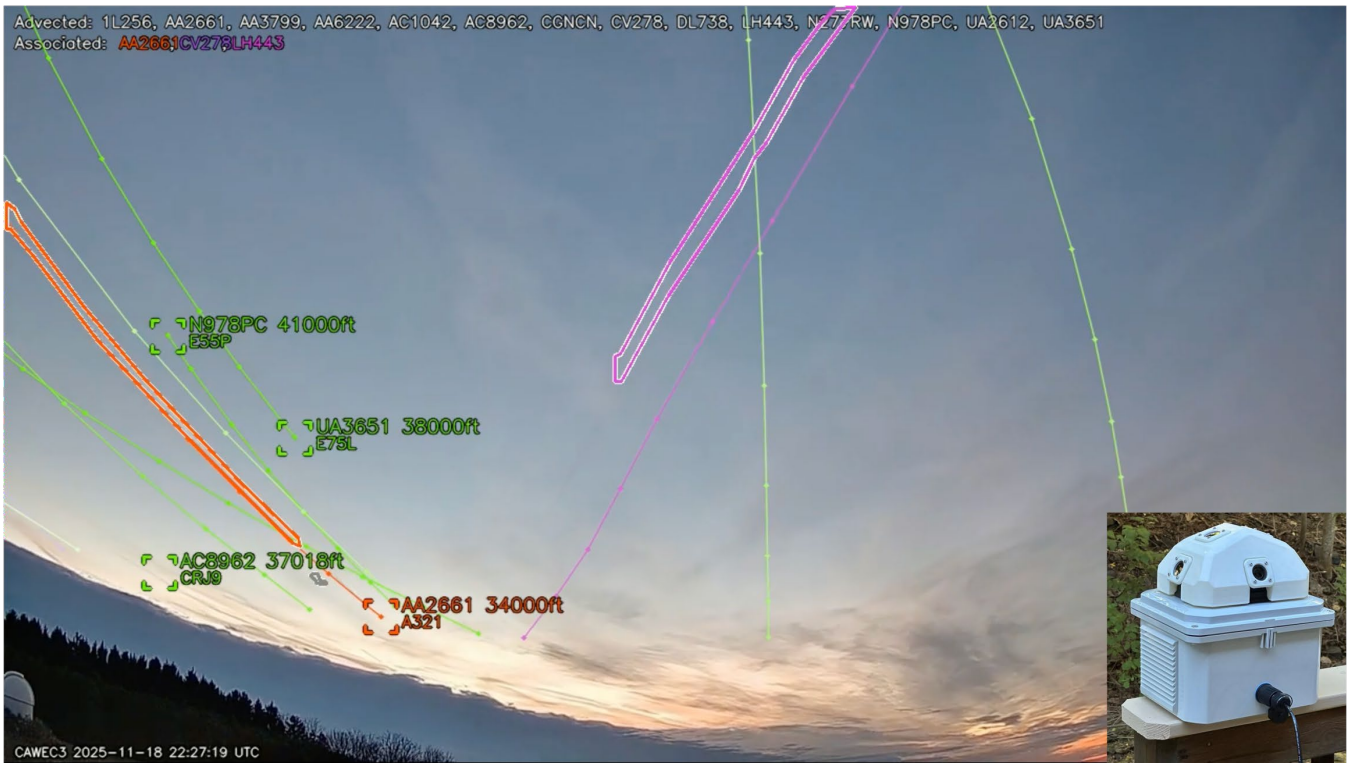


Figure 2. Contrails observed by a global Meteor Network (GMN) camera on November 11th, 2025 in London, Ontario. The flight tracks from Automatic Dependent Surveillance–Broadcast (ADS-B) data are overlayed on the image. Green flight tracks were not associated with a contrail. The pink and orange flight tracks were automatically associated with a contrail segmented by the same colour. The inset shows the GMN all-sky camera used to capture the image.

operational contrail avoidance strategies. By identifying flights most likely to produce persistent contrails, it may be possible to achieve substantial reductions in aviation climate impact with only minor changes to flight operations.

CONCLUSIONS

Contrails are a significant but uncertain contributor to aviation-induced climate change. While the physical mechanisms governing contrail formation are relatively well understood, predicting their occurrence and long-term evolution remain challenging due to limitations in atmospheric data and modeling. Current observational tools, particularly satellites, provide valuable insight but are

constrained by trade-offs between spatial and temporal resolution. Ground-based camera systems offer a promising complementary approach, especially for enabling direct association between contrails and individual flights. Reducing uncertainties in both prediction models and observations will be essential for developing effective mitigation strategies. As aviation demand continues to grow, improving our understanding of contrails represents an important opportunity to reduce the climate impact of air travel.

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