A way forward for contrail mitigation

T&E briefing on Klima Consulting's review of the science and technology of contrail mitigation

Alexander Kunkel, Carlos López de la Osa García, Vincent de Haes, Diane Vitry, Erin Vera

September 2026

Executive summary

1. **Contrail mitigation represents a significant lever for reducing the climate impact of aviation.** Contrail mitigation starting in 2030, targeting a 50% reduction of contrail warming by 2040, could reduce global warming by about 0.025°C in 2050 and 0.049°C in 2070.

2. **The science is mature enough to act.** Contrail formation physics is well established. Remaining uncertainties mainly affect how effective avoidance would be, not whether it works.

3. **Future research can support mitigation.** It should focus on the uncertainties that matter for mitigation such as the properties of fresh contrails, contrail radiative impact, contrail-contrail interactions as well as atmospheric adjustments. Additionally, large-scale trials, more flight trials with alternative fuels and humidity sensors on board commercial aircraft as well as a commitment to open-access contrail datasets can boost scientific research.

The briefing sets out **three policy recommendations** towards scaling up contrail avoidance in the early 2030s.

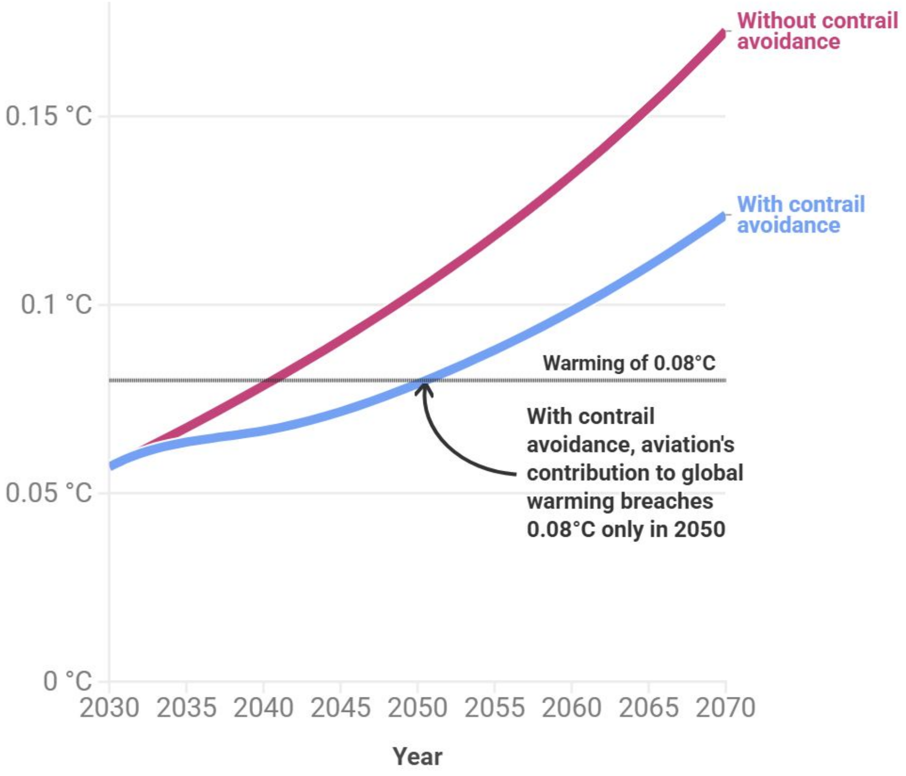
Table of contents

Section 1

Cutting contrail warming could turn back aviation’s climate clock by a decade

If contrail avoidance is scaled up starting in 2030, aviation's contribution to global warming will only reach 0.08°C in 2050 instead of 2040.

Aviation's contribution to global warming



Source: T&E (2026), based on Klima Consulting (2026)

Why should we act on contrails?

Why contrails matter

Aviation's climate impact from contrails is of the same order of magnitude as that of its CO_2 emissions, causing **immediate warming**, but it depends strongly on where and when aircraft fly.

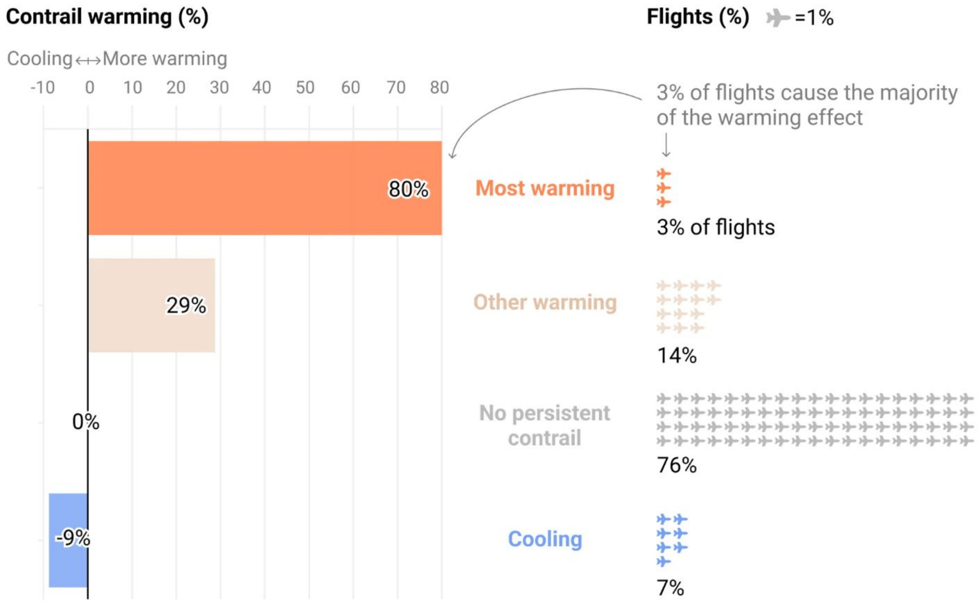
Why action is efficient

Contrail warming is **highly concentrated**, thus targeting a small number of flights can deliver **large climate benefits**.

Why this report

This **report reviews the latest science on contrails, assesses key uncertainties and knowledge gaps**, and examines the potential, remaining challenges and solutions for scaling up contrail mitigation.

3% of flights cause 80% of global contrail warming



Source: T&E (2026), based on Teoh et al. (2024) for 2019 • The distribution of contrail warming varies by region. In Europe, 5% of departing flights account for 80% of contrail warming.

How to reduce contrail warming?

The report considers five contrail mitigation strategies that can be divided into two categories

- Operational contrail mitigation: Avoid flying where and when warming contrails form.
- Fuel-based contrail mitigation: Reduce contrail climate impact even when flying when and where warming contrails form.

The **temperature benefits of contrail avoidance largely outweigh additional CO_2 emissions** for well-designed mitigation strategies. However, the temperature benefits only persist for as long as contrail mitigation is maintained. This underlines the importance of **combining sustained contrail mitigation solutions with effective reductions in CO_2 emissions**. Reducing contrails does not replace the need to reduce emissions from the aviation sector as a whole.

FIVE CONTRAIL MITIGATION STRATEGIES

OPERATIONAL CONTRAIL MITIGATION

1. **Adjustment of flight scheduling**
Reschedule flights to times when contrail warming tends to be lower, e.g. during daytime.

2. **Airline-led pre-tactical avoidance**
Use climate-aware flight planning before departure to avoid high contrail-risk regions.

3. **ATM-led pre-tactical avoidance**
Use airspace closures or restrictions when operationally feasible to steer traffic away from high contrail-risk regions.

4. **Tactical avoidance**
Make in-flight altitude or route adjustments using updated weather data.

FUEL-BASED CONTRAIL MITIGATION

5. **Targeted use of SAF or hydrotreated kerosene**
Use low-sulfur, low-aromatic fuels on flights especially likely to form warming contrails.

Pre-tactical = before departure | Tactical = during flight | ATM = air traffic management | SAF = sustainable aviation fuel

T&E

Contrail mitigation: a fast-acting climate lever

67-225 Mt CO_2e	**Deliver annual emissions savings.** Halving contrail warming would cut between 67 and 225 Mt CO_2e (over 100 years) per year at current traffic levels. That is between 7% and 23% of 2025 global aviation CO_2 emissions, equivalent to the annual emissions of 15 million to 50 million petrol-powered passenger vehicles.
0.025 °C	**Contribute to reducing global warming.** Contrail mitigation starting in 2030, targeting 50% effectiveness by 2040, results in an avoided temperature increase of about 0.025°C in 2050 and 0.049°C in 2070.
3-5%	**Free up more of the climate budget.** Implementing contrail avoidance frees up 3–5 percentage points of the global 2025–2050 temperature budget in a 2°C pathway that would otherwise be consumed by aviation.

The way forward

The roadmap sets out a path to reduce critical uncertainties for contrail mitigation. It connects scientific priorities and policy actions to reduce and manage uncertainties.

T&E

How to reduce uncertainties?

Why are there uncertainties?

All science comes with uncertainty. Understanding what we do and don't know is part of scientific progress. The key question is **which uncertainties matter for action**.

This report reviews the key **uncertainties** for predicting the contrail climate impact of a flight one by one, relying on the latest science as of July 2026. It goes on to show how the uncertainties most important for contrail mitigation can be reduced - either through smart mitigation strategies or future research, supported by the right policy.

The conclusion of the study

Overall, **the science is mature enough to act** - if mitigation is designed carefully.

FOUR KEY UNCERTAINTIES FOR CONTRAIL MITIGATION

1. **When and how do contrails form?**
   Low risk for operational contrail avoidance. High uncertainty for SAF & lean-burn engines.

2. **How much heat do contrails absorb?**
   Nighttime flights are the safest target for navigational contrail avoidance (eliminates cooling uncertainty to a large extent).

3. **How do contrails interact with one another?**
   Prioritise navigational contrail avoidance in less dense traffic corridors.

4. **How do contrails interact with the atmosphere?**
   Only mitigate contrails when there is a high expected net climate benefit to err on the side of caution.

1. When and how do contrails form?

What the science says

- Contrails are made of tiny ice crystals that form in the aircraft exhaust. Soot particles, produced when fuel does not burn completely, helps these ice crystals form.
- Reducing soot emissions generally reduces contrail warming. However, when soot emissions become very low, for example with SAF, hydrogen, or some newer engine designs, other particles emitted or already present in the air can help contrails form instead. This means that there can be substantial contrail formation even when soot emissions are close to zero.
- Other factors, such as fuel sulphur content and engine age, also affect contrail formation, but their influence is not yet well understood.
- There is also uncertainty about what happens when contrails form in existing natural clouds. Although they are expected to add warming locally, accounting for them could decrease previous estimates of total contrail warming. Scientists do not yet know whether this is significant.

Do uncertainties block action?

- Low risk for navigational contrail avoidance: Reduces effectiveness but does not invalidate the mitigation strategy.
- High risk for contrail management via fuel properties: We cannot yet confidently predict whether different fuels will reduce contrail warming, especially in newer jet engines.

2. How much heat do contrails absorb?

What the science says

- Contrails can warm the climate by trapping heat that would otherwise escape to space, but they can also cool it by reflecting sunlight back into space. Because these two effects partly cancel each other out, even relatively small errors in estimating either one can lead to larger errors in the overall climate impact.
- The shape of a contrail also matters. Estimating the warming impact of contrails is complex. For instance, their shape influences their cooling effect. Most models simplify these details.
- Scientists do not yet have a standard set of data that combines realistic weather conditions, accurate physics, and realistic contrail shapes. As a result, it is difficult to properly test and compare different models.

Do uncertainties block action?

- Low risk for nighttime contrails: Without sunlight, only the warming term remains, eliminating the uncertainty around cooling contrails to a large extent.
- Medium risk for daytime contrails: Whether a contrail is cooling or warming can vary with time of day and cloud shape, making daytime mitigation decisions less reliable.

3. How do contrails interact with one another?

What the science says

- Contrails need water in the air to grow. In busy flight corridors, many contrails can form in the same area and compete for the available water. Once much of that water has been used, any new contrails are likely to be smaller or disappear more quickly. They may also form in contrail clouds left by earlier flights.
- This means that if one airline reroutes a flight to avoid creating a contrail, the climate benefit may be smaller than expected if several other aircraft are already creating contrails in the same patch of air.
- Most models currently treat contrails as if they form independently, rather than accounting for how they affect each other.

Do uncertainties block action?

- No risk for airspace restrictions: They are an all-or-nothing policy by design.
- Low risk in low-traffic regions: When there are few nearby contrails, there is less competition for the available water. Avoiding a contrail in these areas is therefore more likely to deliver the expected climate benefit.
- Medium risk in dense-traffic regions: Even when one airline avoids forming a contrail, nearby flights may still create contrails in the same patch of air, potentially reducing the overall benefit of that avoidance.

4. How do contrails interact with the atmosphere?

What the science says

- Contrails can make the air where they form drier. As the ice crystals in a contrail fall, they take some water with them. This may reduce the formation of natural high clouds that also warm the climate, partly offsetting contrail warming. The size of this effect depends on the weather and remains uncertain because it can only be estimated using computer models, which give different results.
- Even when this effect is taken into account, contrails that form high above the ground appear to warm the Earth's surface less than an equivalent amount of CO_2, which is spread throughout the atmosphere. Current contrail warming estimates account for this difference, but they remain uncertain.

Do uncertainties block action?

- Medium risk for shifting departure times: Contrail interactions with the atmosphere could decrease the effectiveness of this strategy.
- High risk for interventions with a fuel burn penalty: This uncertainty affects the net climate benefit of contrail mitigation. But it **does not invalidate avoidance**: Even if contrail interactions with the atmosphere are large, flights producing strong contrail warming still justify rerouting. It does mean, however, that current **CO_2-equivalent estimates carry significant model-dependent uncertainty.**

How much do uncertainties impact different mitigation approaches?

Uncertainty	1. Shift departure times	2. Airline-led pre-tactical avoidance	3. Airspace restrictions	4. Tactical avoidance	5. SAF / Hydrotreated fossil jet fuel
How contrails form	No uncertainties blocking this mitigation strategy	Small impact on effectiveness of this mitigation strategy	Small impact on effectiveness of this mitigation strategy	Small impact on effectiveness of this mitigation strategy	Fine for rich-burn; field testing needed for lean-burn
How much heat do contrails absorb	Start with night flights	Start with night flights	Start with night flights	Start with night flights	Targeted use on night flights
Contrail-contrail interactions	No uncertainties blocking this mitigation strategy	Start in low-traffic areas or coordinate at network level	No uncertainties blocking this mitigation strategy	Start in low-traffic areas or coordinate at network level	No uncertainties blocking this mitigation strategy
Contrail-atmosphere interactions	Impact on effectiveness of this mitigation strategy	Ensure strong net benefit threshold	Ensure strong net benefit threshold	Ensure strong net benefit threshold	Ensure strong net benefit threshold

Source: T&E (2026), based on Klima Consulting (2026)

Uncertainty Impact: None Low Medium High

Scientific priorities to reduce key uncertainties for contrail mitigation

01 Target research at key uncertainties

How many ice crystals form, how large they grow, the surrounding atmospheric conditions, and how all of this affects the contrail's warming or cooling impact.

02 Open observational datasets

Make more real-world data from typical flight altitudes openly available, so researchers can improve models.

03 Better weather forecasts

Intercompare and enhance models with better physics and new observational data, for instance from geostationary satellites.

04 Contrail model intercomparison

Compare different contrail models to better understand where they give different results, for instance when contrails interact with one another, and cross-check with observations.

05 Radiative benchmarks

Model how contrails interact with sunlight and heat as realistically as possible in 3D, then compare the model results with what we actually observe in the atmosphere.

06 Climate model intercomparison

Run coordinated climate-model experiments to reduce uncertainty about how strongly contrails affect the climate.

07 Digital twin

Combine contrail models with better observational datasets so that mitigation measures can be verified against agreed benchmarks in the early 2030s.

Three recommendations to support scientific priorities via policy

01

Fund R&D for contrail mitigation

Focus research on the uncertainties that most affect whether contrail avoidance delivers a real climate benefit. Priorities include:

- Contrail formation: Follow up on the ECLIF3 and VOLCAN campaigns to test how SAF and hydrotreated fossil kerosene affect contrail formation in newer engines.
- How much heat do contrails absorb: Build better observational datasets to improve estimates of contrail warming and cooling.
- Contrail-contrail interactions: Improve models of how nearby contrails affect one another when they form in the same area.
- Contrail-atmosphere interactions: Run coordinated comparisons of climate models to assess how contrails affect the atmosphere.

02

Fund large-scale contrail avoidance trials

Medium-scale trials before 2030, followed by a large-scale contrail avoidance trial in the early 2030s would provide a setting in which contrail-contrail interactions can be observed at realistic traffic densities, and in which mitigation measures can be tested against observed outcomes in different weather conditions. A large-scale trial would require thousands to tens of thousands of flights, sustained for at least a year. It must use transparent methods, a common evaluation framework and open data to verify benefits at scale. It should apply conservative net-climate-benefit thresholds that account for the uncertainty in contrail-atmosphere interactions and any additional CO_2 emissions.

03

Require OEMs to develop and install humidity sensors on commercial aircraft

Unlike satellites, low-maintenance humidity sensors can directly map regions where contrails form. The priority should be to support the development certified, low-maintenance humidity sensors by around 2029, followed by installation on new aircraft and retrofitting of existing aircraft from 2031. Sensors should be installed in a sufficient number of aircraft to achieve wide geographic coverage.

Acknowledgements

Briefing published: September 2026

Contributors: Alexander Kunkel, Carlos López de la Osa García, Vincent de Haes, Diane Vitry, Erin Vera

Responsible editor: William Todts, Executive Director

To cite this briefing

T&E (2026). Briefing on Klima Consulting's report "Defining a way forward for the science and technology of contrail mitigation"

Acknowledgements

The findings and views put forward in this publication are the sole responsibility of the authors listed above.

Further information

Alexander Kunkel
Senior Data Analyst
alexander.kunkel@transportenvironment.org

www.transportenvironment.org | Bluesky | LinkedIn