Contrails: a science crash course

What we know, what we don't, and why we can act

Audran Borella, CTO & Co-founder, Klima

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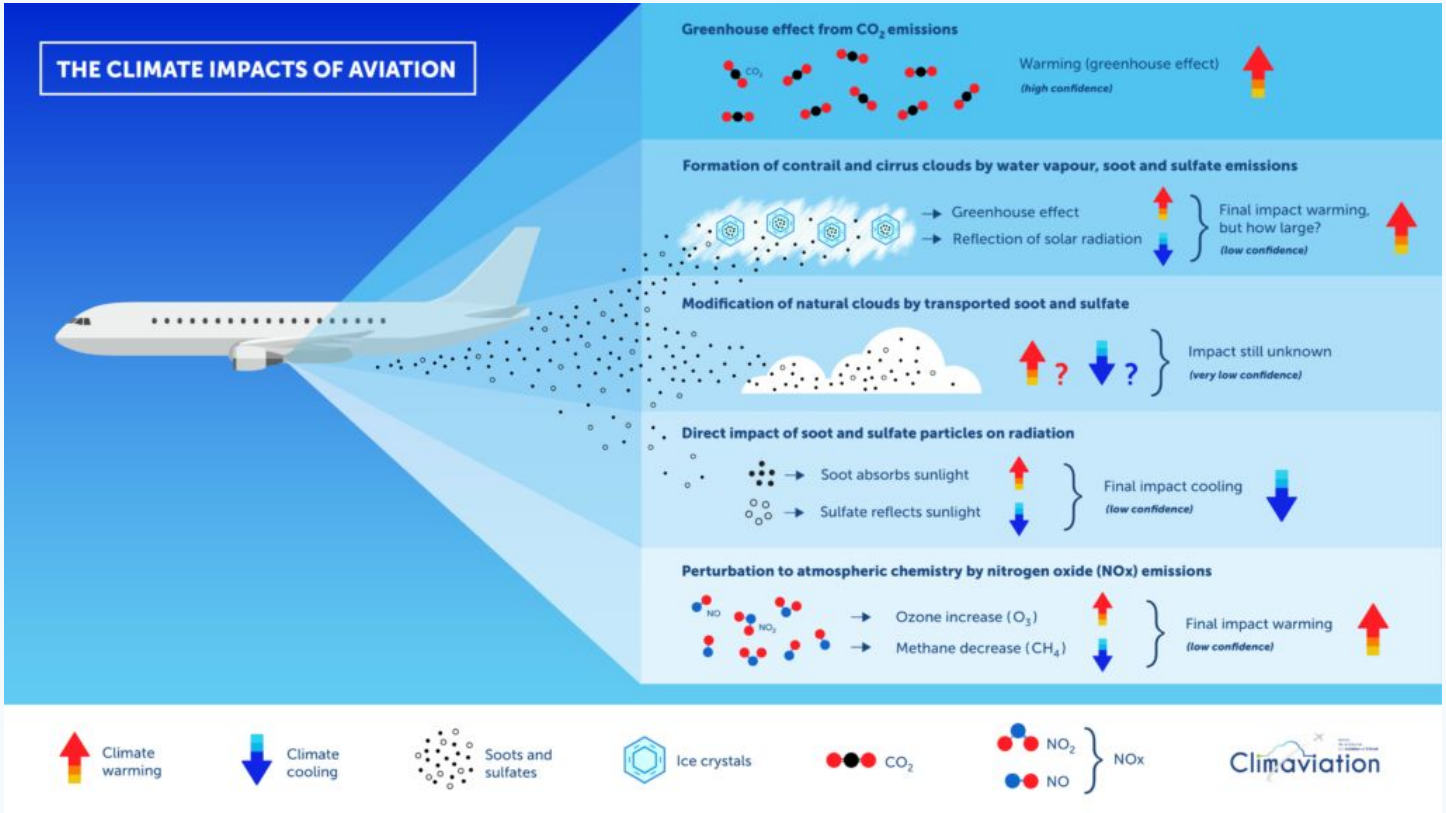
Aviation warms the climate beyond CO_2

Non-CO_2 effects account for a large share of aviation's warming to date



Source: Climaviation

How contrails form and persist

Cold, humid air turns engine exhaust into ice clouds



SHORT-LIVED CONTRAIL

Dissipates within seconds to minutes in dry air.



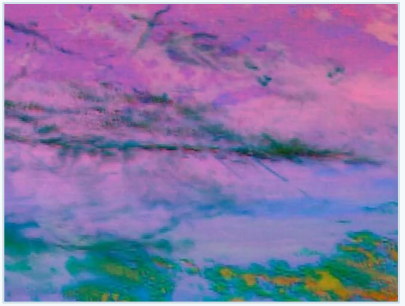
PERSISTENT CONTRAIL

Survives and grows in ice-supersaturated air.



CONTRAIL CIRRUS

Spreads over hours into cirrus-like cloud layers.



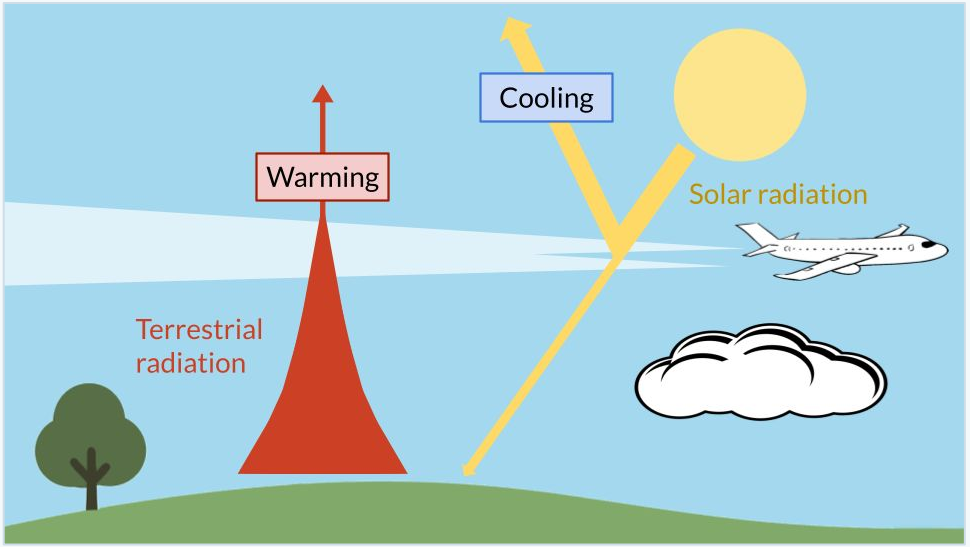
SEEN FROM SPACE

Contrail outbreak over Northern Europe, 27 Dec 2024.

Persistence needs ice-supersaturated air: thin layers (0.5 to 1 km), a few hundred km wide, moving with the weather.

Warming or cooling?

Contrails trap heat day and night, but reflect sunlight only during the day



NIGHT

Greenhouse effect only: always warming.

DAY

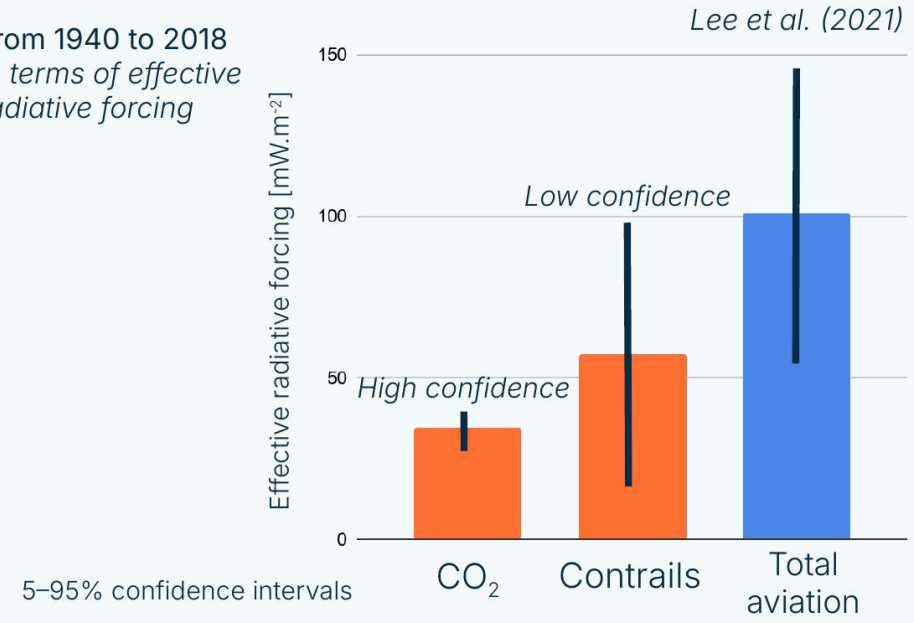
Greenhouse effect minus sunshade effect: partly offset, can even cool.

On average, contrails warm the climate. Night-time contrails are the clearest case.

Contrails: about a third of aviation's climate impact

Comparable to aviation's CO_2, but with a much wider uncertainty range

From 1940 to 2018
In terms of effective radiative forcing



LEE ET AL. (2021)

Largest single term of aviation's climate impact, **but with low confidence.**

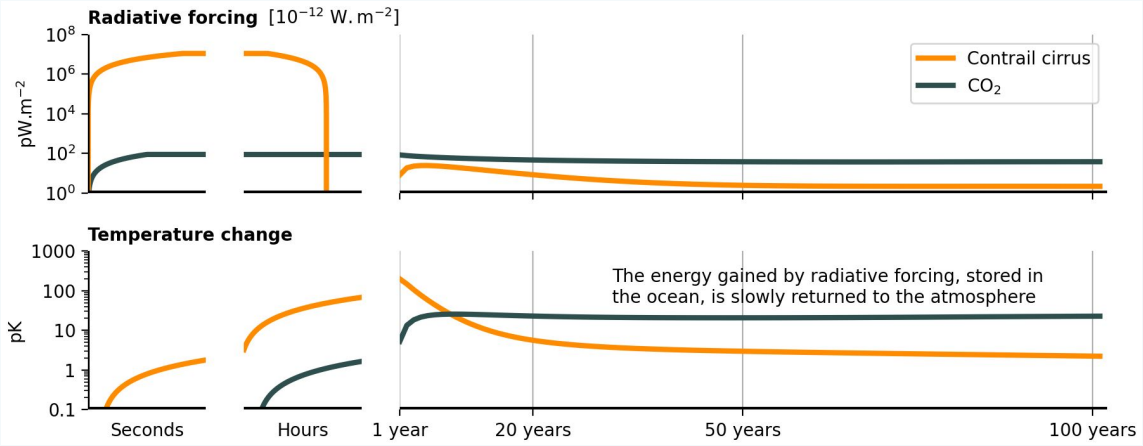
SINCE THEN

Estimates revised downward: contrails now represent about one third of aviation's climate impact.

Lee et al. (2021). Recent estimates: Teoh et al. (2024), Bickel et al. (2025), Zhang et al. (2025).

Short-lived, but strongly warming

Comparing contrails and CO_2 needs a metric, but the choice rarely changes the decision



Typical transatlantic flight: its contrail cirrus vs. its CO_2

18 × CO_2 over 1 year (= $AGWP_1$)

1.4 × CO_2 over 20 year (= $AGWP_{20}$)

0.4 × CO_2 over 100 year (= $AGWP_{100}$)

Warming ratio, contrail / CO_2

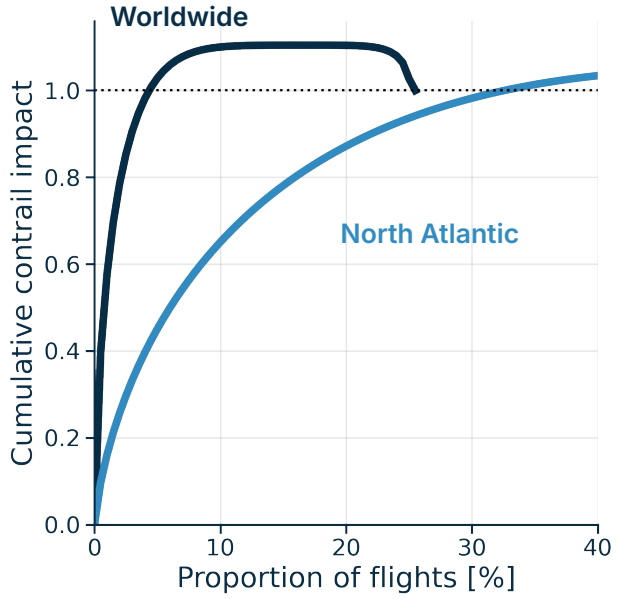
The metric changes the numbers: the CO_2-equivalent of a contrail varies with the metric and time horizon.

But not the decision: avoiding a strongly warming contrail for ~1–2% extra fuel pays off under every metric.

Borella et al. (2024), ACP. EGWP100 (efficacy-weighted GWP) is consistent with the Paris Agreement; the EU non-CO_2 MRV uses EGWP20/50/100.

A few flights, most of the impact

Contrail warming is concentrated in a small number of flights



2–3%

WORLDWIDE

of flights cause 80% of contrail warming

10–15%

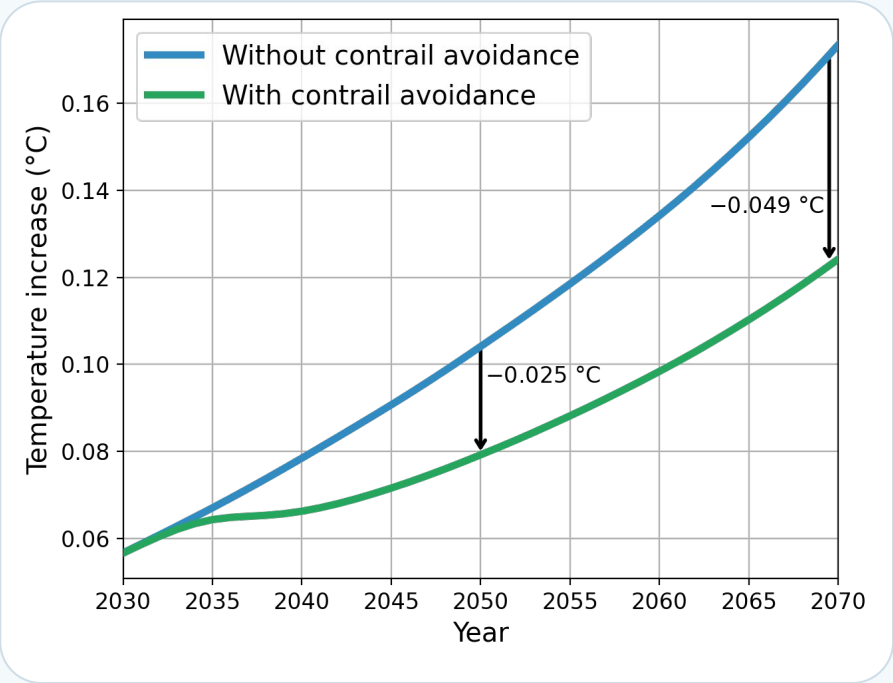
NORTH ATLANTIC

of flights cause 80% of contrail warming

Targeted action: no need to change every flight, only a few well-chosen ones.

Contrail Explorer data (contrails.org); Teoh et al. (2024).

The potential of contrail avoidance



"The most significant climate risk associated with contrail avoidance is inaction."

Smith et al. (2026), Nature Communications

Mitigation from 2030, 50% effective by 2040, +0.2% fleet fuel, ICAO LTAG IS1. Klima calculations with AeroMAPS + FaIR.

Two levers to reduce contrail warming

1 Navigational avoidance

Fly around, below or above the regions where strongly warming contrails form.

- Led by airlines, air traffic control, or both
- Works with today's fleet and fuels

2 Cleaner combustion

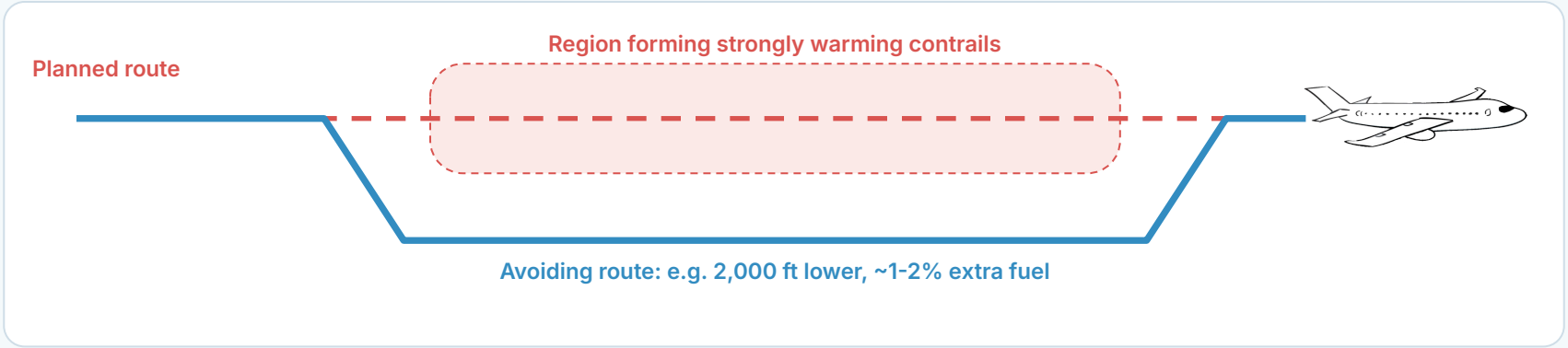
Change the fuel or the engine so that contrails contain fewer ice crystals and warm less.

- Sustainable aviation fuels, hydrogenated kerosene
- Engine technology

Complementary, not exclusive, and none is a substitute for cutting CO_2.

What is navigational contrail avoidance?

Small, targeted detours around thin layers of humid air



WHEN CAN IT BE DONE?

STRATEGIC (MONTHS AHEAD)

Scheduling: Adapt timing and aircraft using contrail climatology.

PRE-TACTICAL (HOURS AHEAD)

Flight planning: Reroute using available weather forecasts.

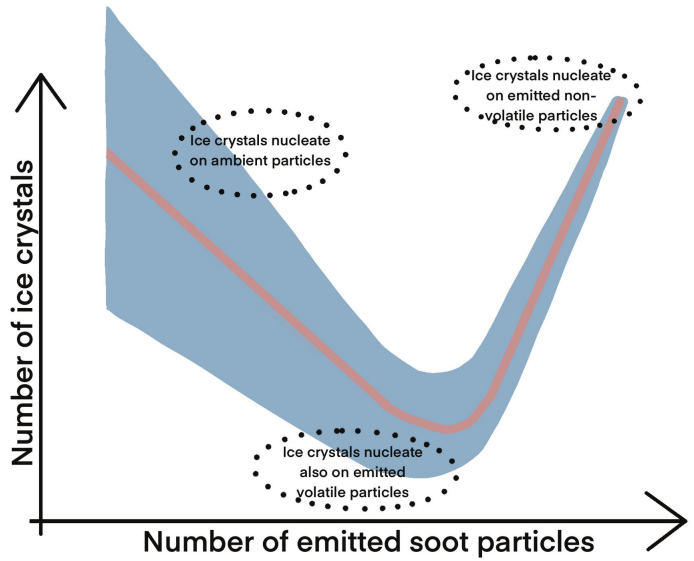
TACTICAL (IN FLIGHT)

Tactical: Adjust with the latest observations and nowcasts.

Led by airlines, air traffic management, or both.

Changing the exhaust: fuels and engines

Fewer soot particles mean fewer ice crystals, and shorter-lived contrails



−80% ice crystals
→ about −50% contrail cirrus forcing

RICH-BURN ENGINES

Clear benefit

Less soot gives fewer, larger crystals that fall faster. SAF can be targeted at contrail-prone flights.

LEAN-BURN ENGINES

Less certain

Soot is already very low: volatile and ambient particles take over, and contrails still form (and maybe oil).

Burkhardt et al. (2018); Märkl et al. (2024); Teoh et al. (2022); Bier et al. (2022); Voigt et al. (2026), Nature.

Two kinds of uncertainty

Some need research, others can be quantified and managed

KNOWLEDGE GAPS

Limits of our fundamental understanding

- May shift the overall estimate of contrail impact
- Hard to quantify
- Need research: field campaigns, observations, models

PREDICTION UNCERTAINTIES

Limits of our forecasting and modelling tools

- Weather forecasts (humidity at cruise level), contrail models
- Can be quantified, e.g. with ensemble forecasts
- Can be accounted for flight by flight

Uncertainty will never be zero, as for any weather-dependent decision in aviation (turbulence, icing, storms).

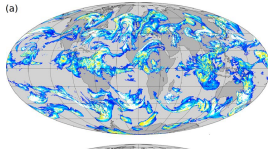
Which knowledge gap matter, for which lever

KNOWLEDGE GAP	NAVIGATIONAL AVOIDANCE	COMBUSTION
Fresh contrail properties ice crystal number and size	Low	High (lean-burn), Low (rich-burn)
Radiative impact sunshade vs. greenhouse effect	Low (night), Medium (day)	Low (night), Medium (day)
Contrail interactions with other contrails and clouds	Low (sparse), Medium (dense)	Low
Atmospheric adjustments how natural clouds respond	High	High

Start where risk is low (night-time, less dense airspace, the most warming contrails) **and prioritise research on atmospheric adjustments.**

Science is moving fast

Recent advances are already closing gaps



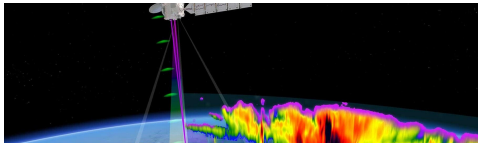
Weather models

ICON and ARPEGE improved the simulation of ice supersaturation.



Humidity sensors

Accurate, low-maintenance probes for airliners in development.



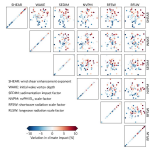
Satellites

EarthCARE and MTG-I1 in orbit, Sterna coming.



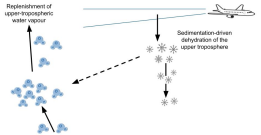
Flight campaigns

Measuring how fuels and engines change ice crystals.



Model comparison

ContrailMIP, ContrailBench, parameter ensembles test contrail models.



Atmospheric adjustments

On going work on how natural clouds respond to contrails.

Hanst et al. (2025); Arriolabengoa et al. (2025); Dyroff et al. (2026); Dischl et al. (2026); Eastham et al. (2026); Juvin-Quarroz et al. (2025).

Key takeaways

1

A major, fast lever

About a third of aviation's climate impact, concentrated on a few flights, with benefits within years.

2

Real but manageable uncertainties

Major scientific advances already reduced uncertainties, and this should not stop testing actual strategies.

3

Inaction is the biggest risk

Start where the science is most robust, and learn by conducting trials, while scientific advancements are being made.



From climate science to sustainable flights

audran.borella@klima.aero