IMPERIAL

State of contrail science in 2026

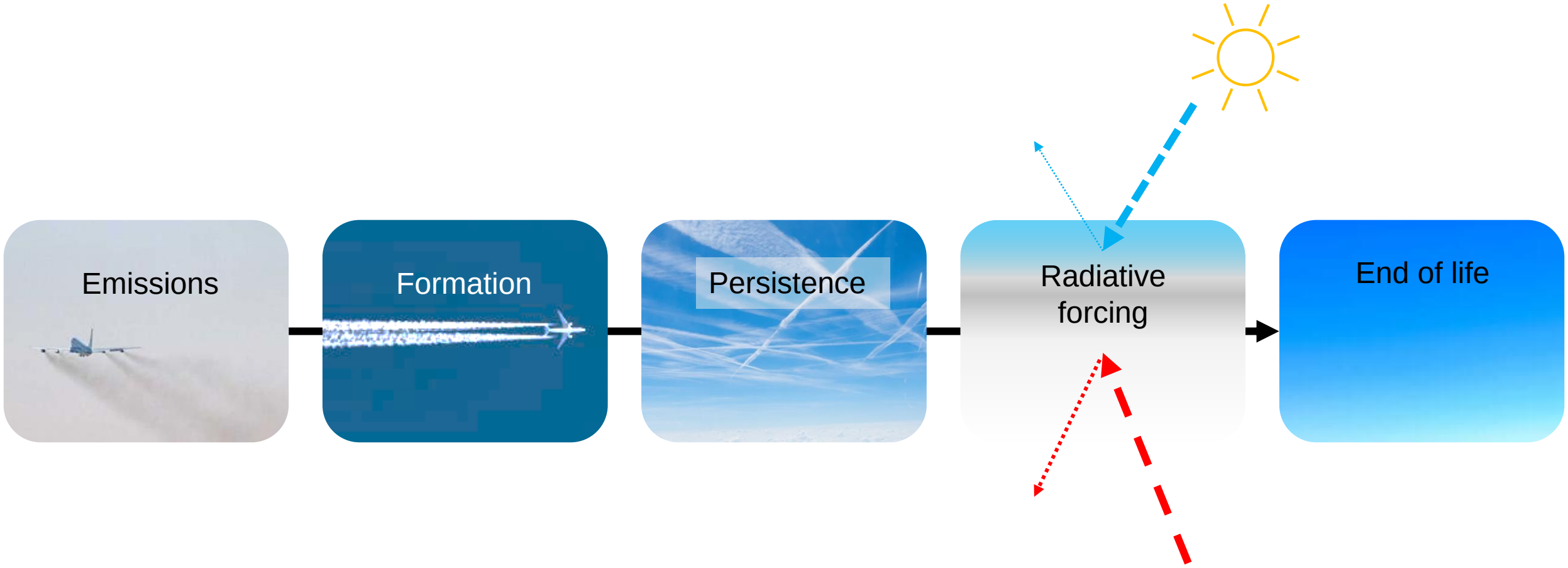
Where are we? What has changed in the past 18 months? And what exciting work is still ahead?

Marc Stettler

Brussels Contrail Conference

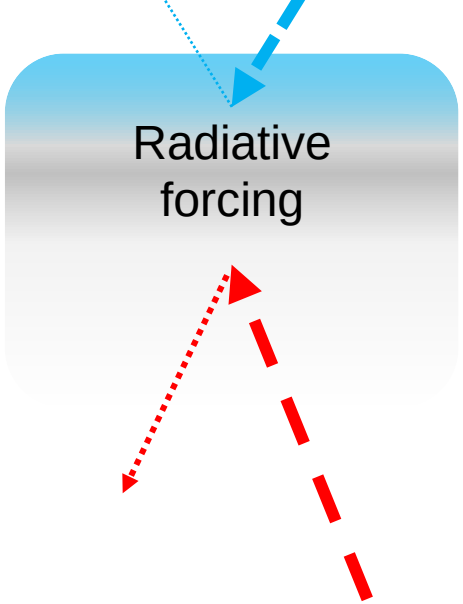
20th October 2026




Emissions
Formation
Persistence
Radiative forcing
End of life

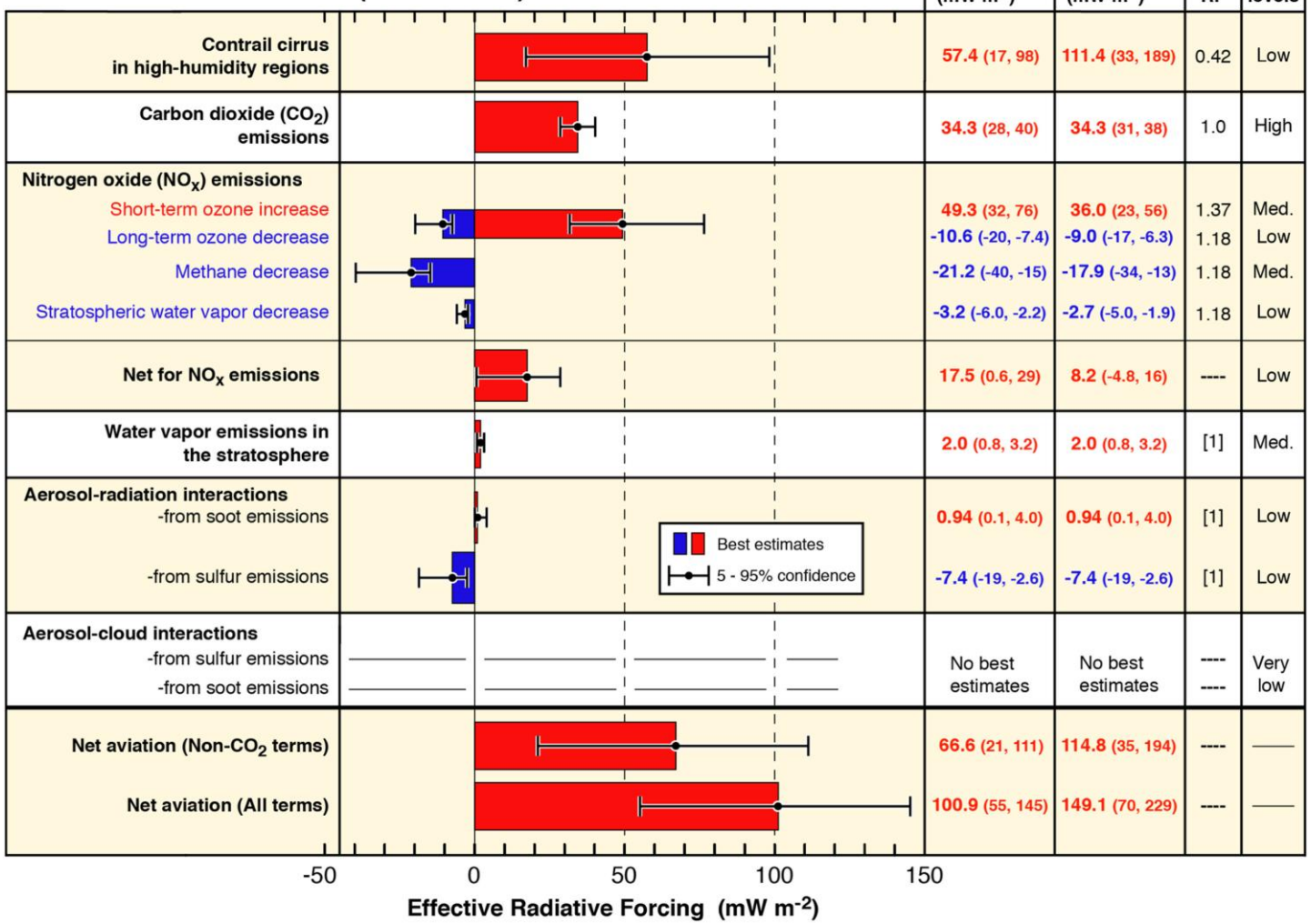
Radiative forcing

"Non-CO2 terms sum to yield a net positive (warming) ERF that accounts for more than half (66%) of the aviation net ERF in 2018."



Global Aviation Effective Radiative Forcing (ERF) Terms
(1940 to 2018)

	ERF (mW m^{-2})	RF (mW m^{-2})	ERF / RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Nitrogen oxide (NO_x) emissions				
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -7.4)	-9.0 (-17, -6.3)	1.18	Low
Methane decrease	-21.2 (-40, -15)	-17.9 (-34, -13)	1.18	Med.
Stratospheric water vapor decrease	-3.2 (-6.0, -2.2)	-2.7 (-5.0, -1.9)	1.18	Low
Net for NO_x emissions	17.5 (0.6, 29)	8.2 (-4.8, 16)	----	Low
Water vapor emissions in the stratosphere	2.0 (0.8, 3.2)	2.0 (0.8, 3.2)	[1]	Med.
Aerosol-radiation interactions				
-from soot emissions	0.94 (0.1, 4.0)	0.94 (0.1, 4.0)	[1]	Low
-from sulfur emissions	-7.4 (-19, -2.6)	-7.4 (-19, -2.6)	[1]	Low
Aerosol-cloud interactions				
-from sulfur emissions	No best estimates	No best estimates	----	Very low
-from soot emissions			----	
Net aviation (Non-CO_2 terms)	66.6 (21, 111)	114.8 (35, 194)	----	——
Net aviation (All terms)	100.9 (55, 145)	149.1 (70, 229)	----	——

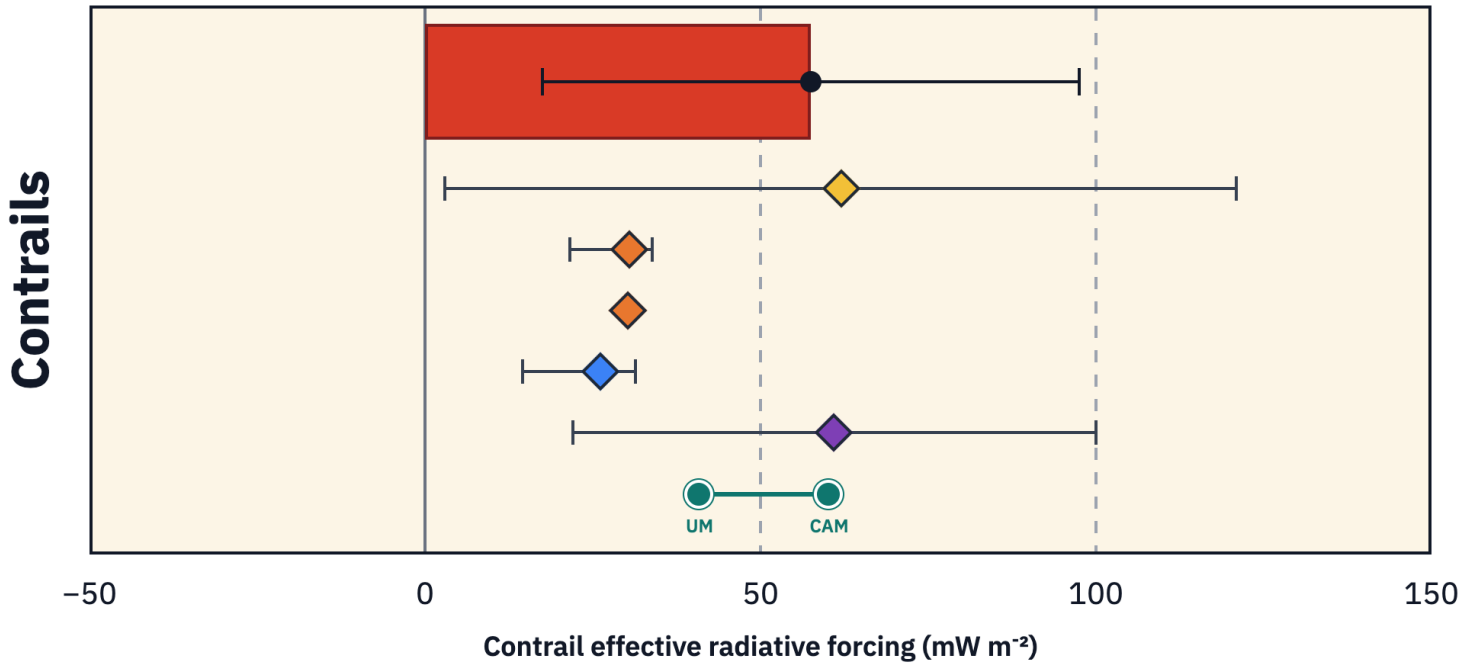


Lee et al., 2021

Update 1: Recent global contrail RF estimates are aligning, consensus contrails are net warming

Contrail forcing: Lee et al. (2021) with newer estimates

Global contrail effective radiative forcing (ERF). Modelled RF values are converted to ERF with the Lee et al. (2021) ratio of 0.42. Teal circles are studies published in 2025–26.



Lee et al., 2021 · ERF 57.4 (17–98)

Gettelman et al., 2021
ERF 62 (3–121), ±2 standard deviations

Bier & Burkhardt, 2022
RF 44 (31–49) for 2006, scaled to 2018 by flight distance (×1.65), × 0.42

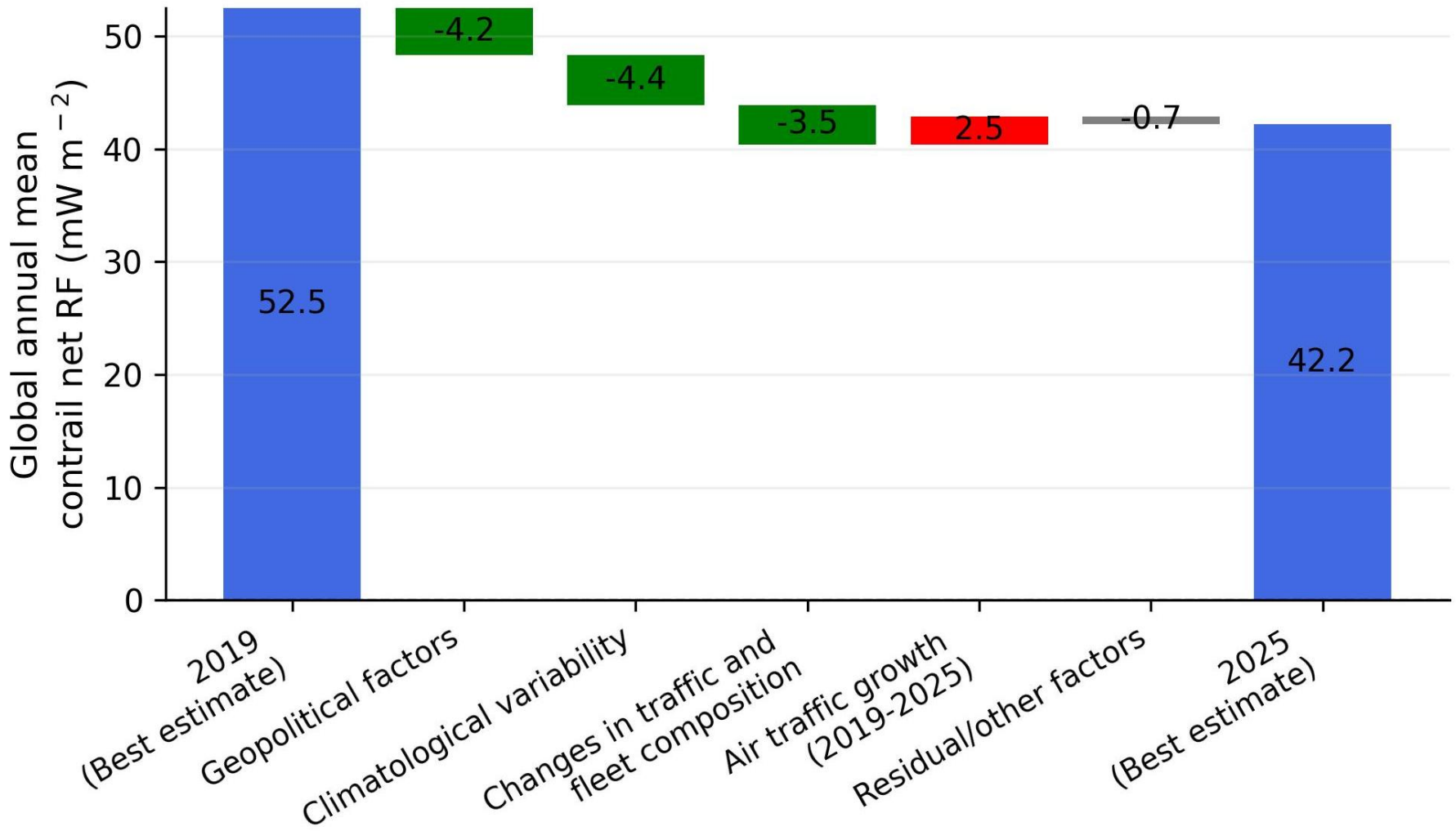
Märkl et al., 2024
RF 72 for 2018 (Jet A-1 fleet) × 0.42; no range given

Teoh et al., 2024
RF 62.1 (34.8–74.8) for 2019 × 0.42; sensitivity range

Quaas et al., 2021
Observed 61 ± 39 for 2019; includes cirrus adjustments, not converted

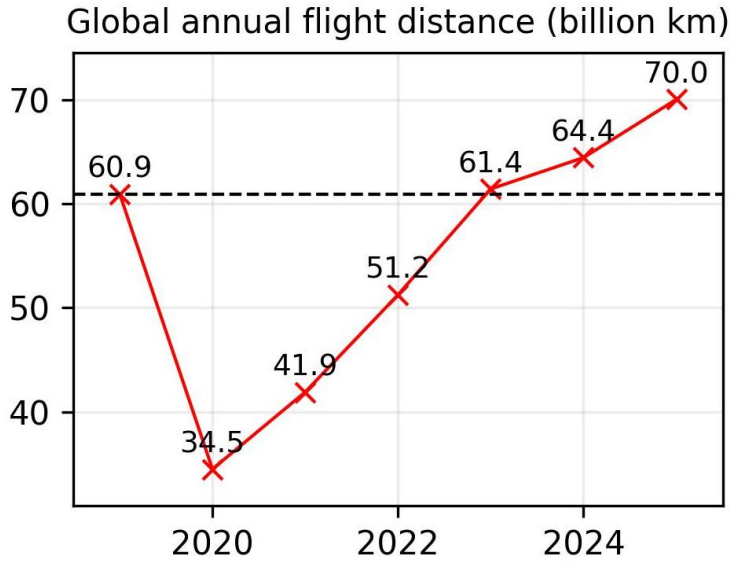
Zhang et al., 2025
One contrail scheme in two climate models (2018): UM 40.8, CAM 60.1

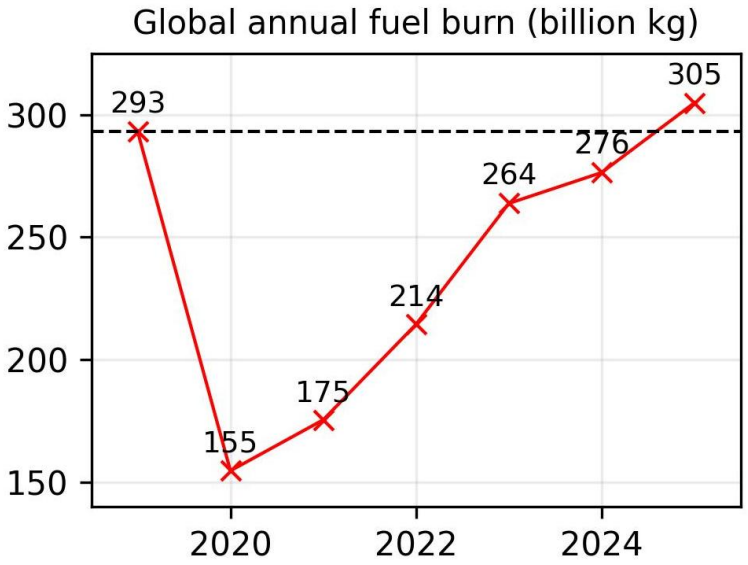
Update 2: Contrail RF has decreased since 2019



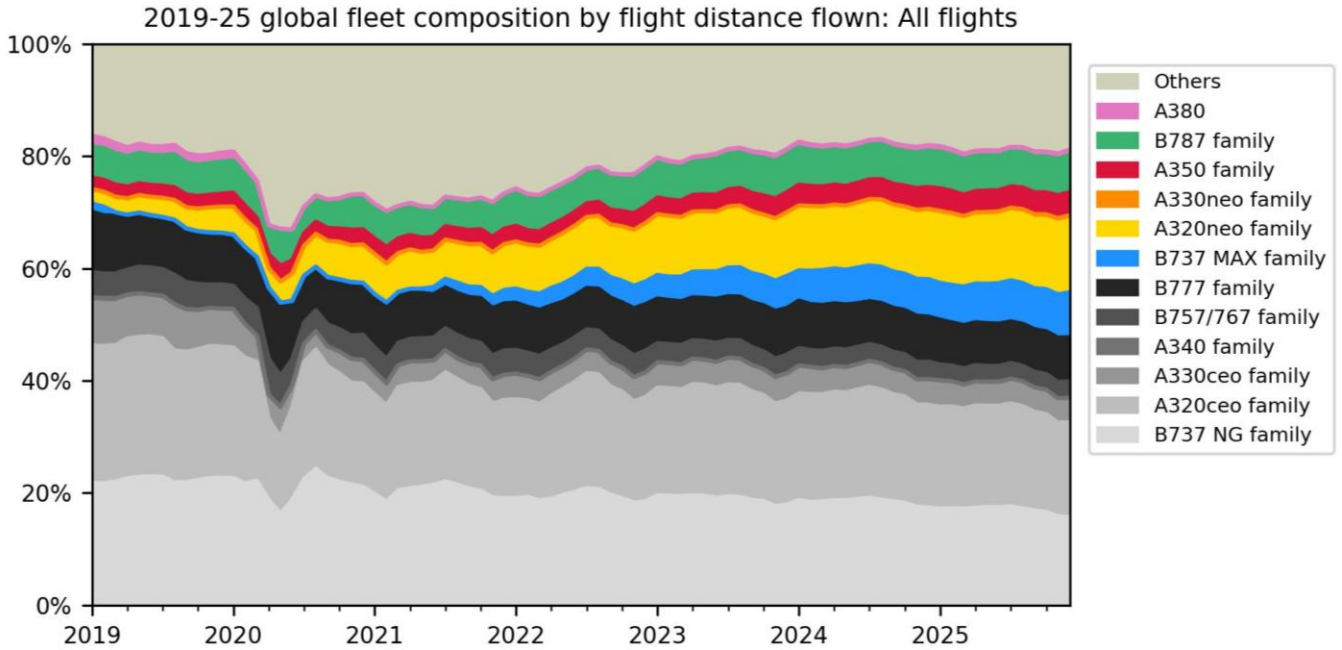
Teoh et al., forthcoming

Air traffic and fuel burn has recovered post-covid, but efficiency has offset growth

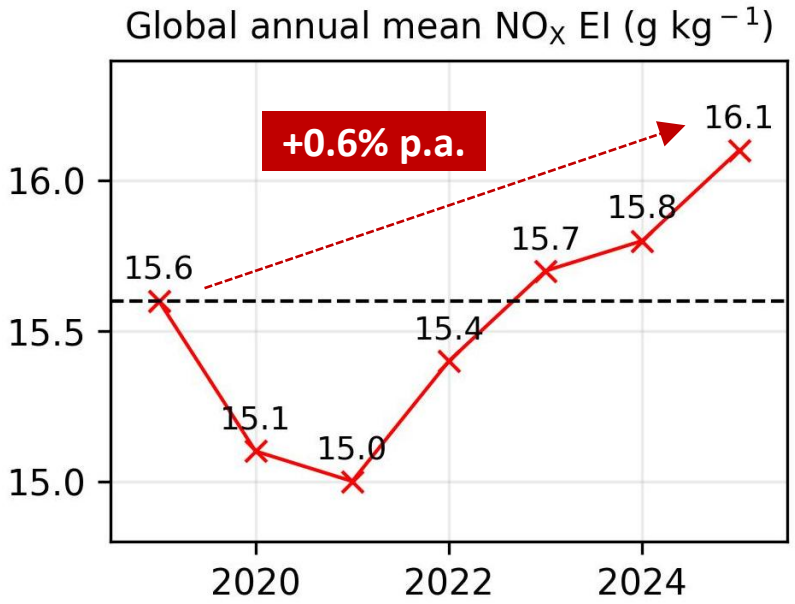


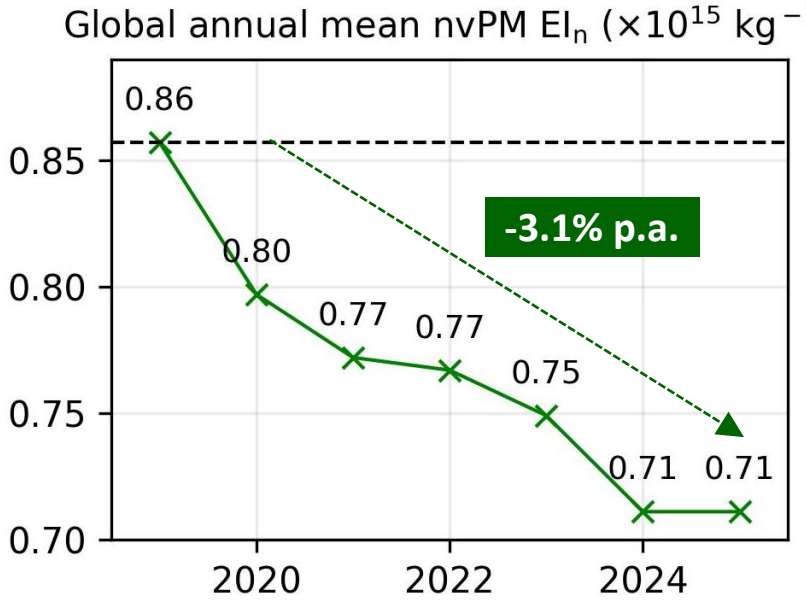


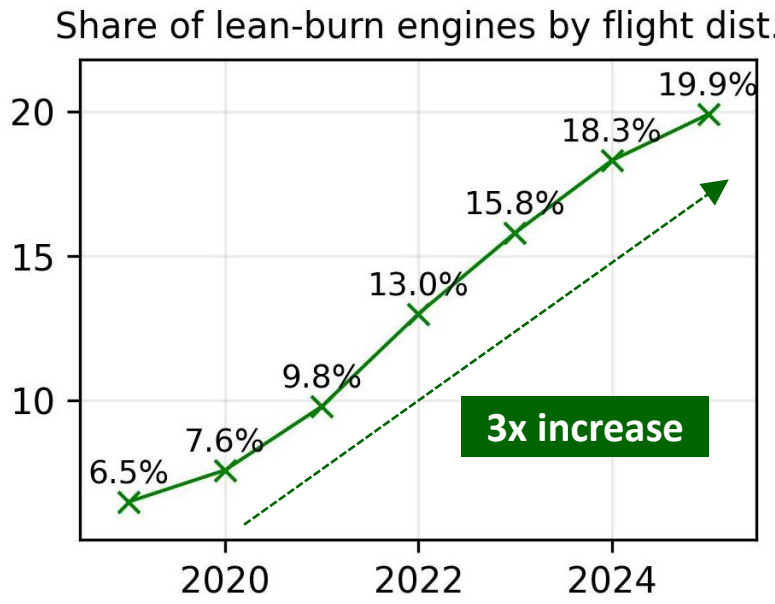
- Mean fuel burn per flight distance: -1.7% p.a.
- Mean fuel burn per tonne-km: -1.0% p.a. (half of ICAO's 2% target)



NOx is up, nvPM is down







- Initial contrail ice crystal number per flight distance, $n_{\mathrm{ice},0}$:

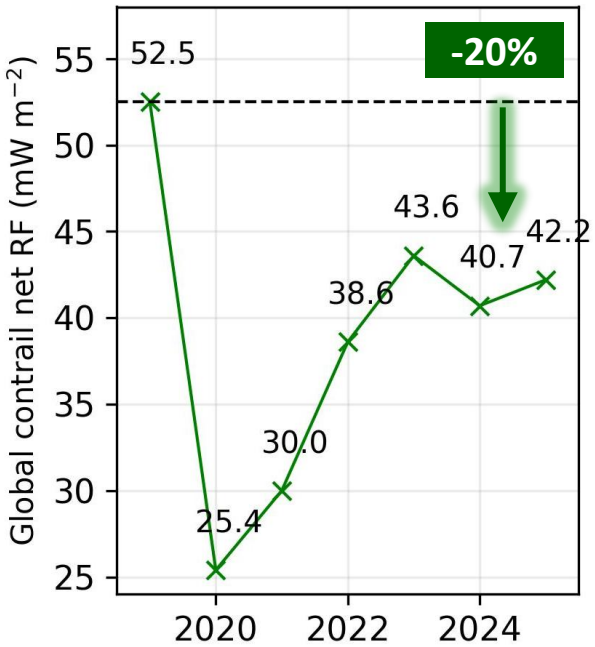
$$n_{\mathrm{ice},0} = (\mathrm{nvPM\ EI_n} \times \mathrm{fuel\ burn\ per\ distance}) + \mathrm{vPM\ activation}$$

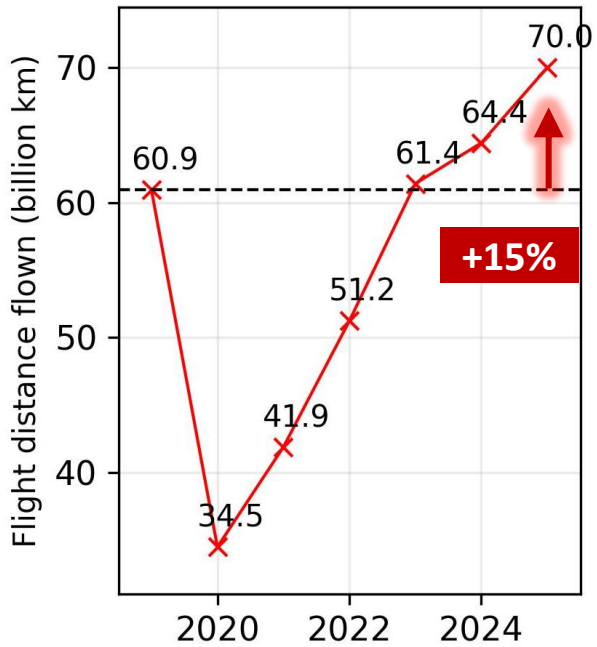
-2.5% p.a. ← (nvPM EI_n × fuel burn per distance) → -3.1% p.a. → -1.7% p.a. → +45% p.a. (from a low base)

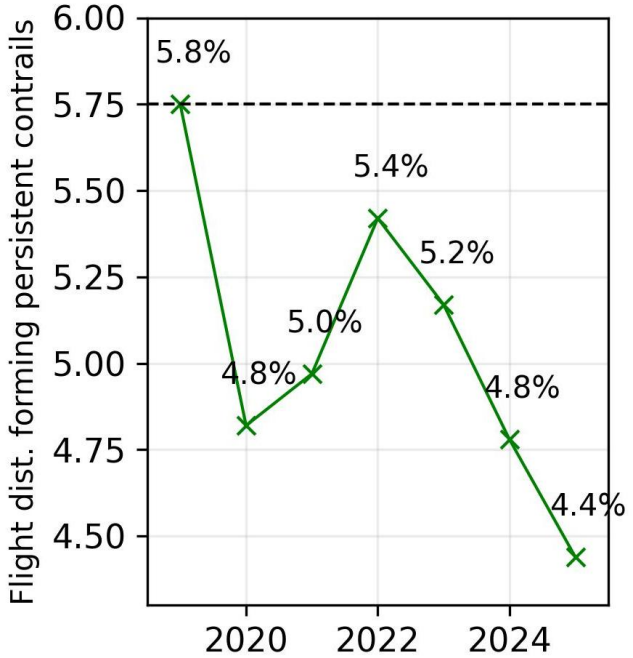
- Fewer and larger ice crystals → Shorter contrail lifetimes → Lower contrail warming intensity

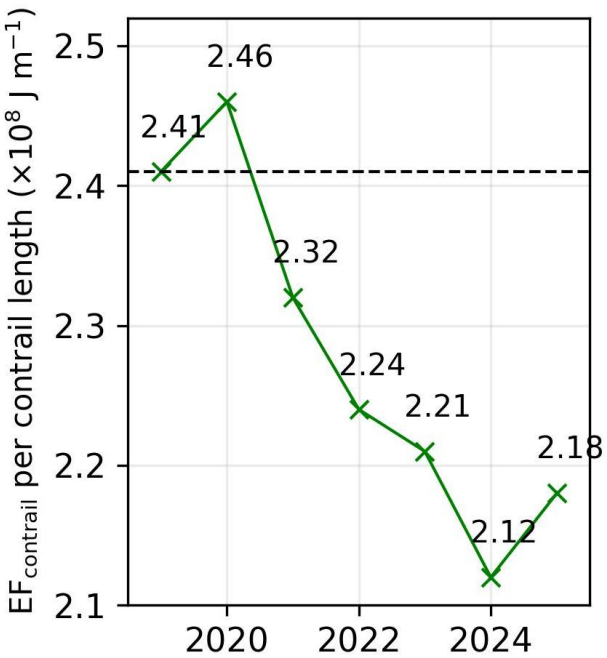
Despite growth in traffic, contrail RF is down

Annual mean contrail net RF ≈ Flight distance flown × Percentage of flight distance forming persistent contrails × Contrail warming intensity



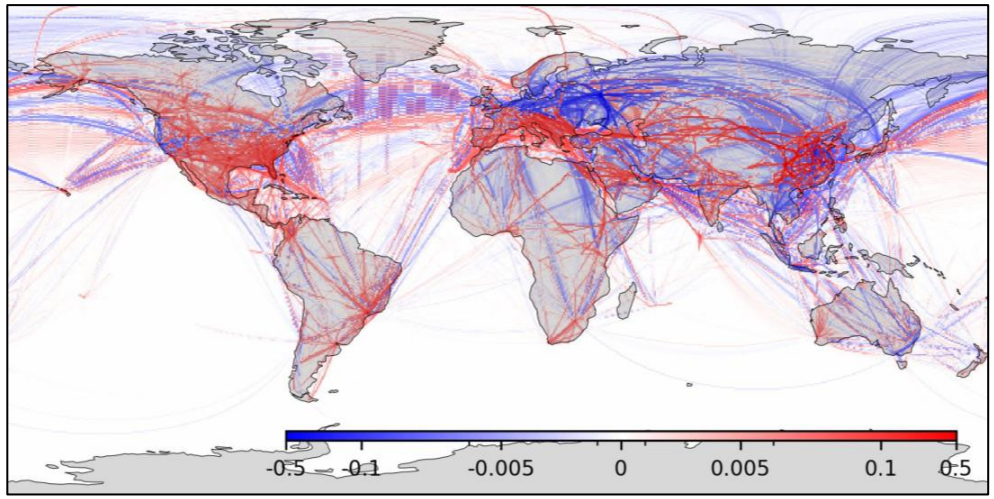




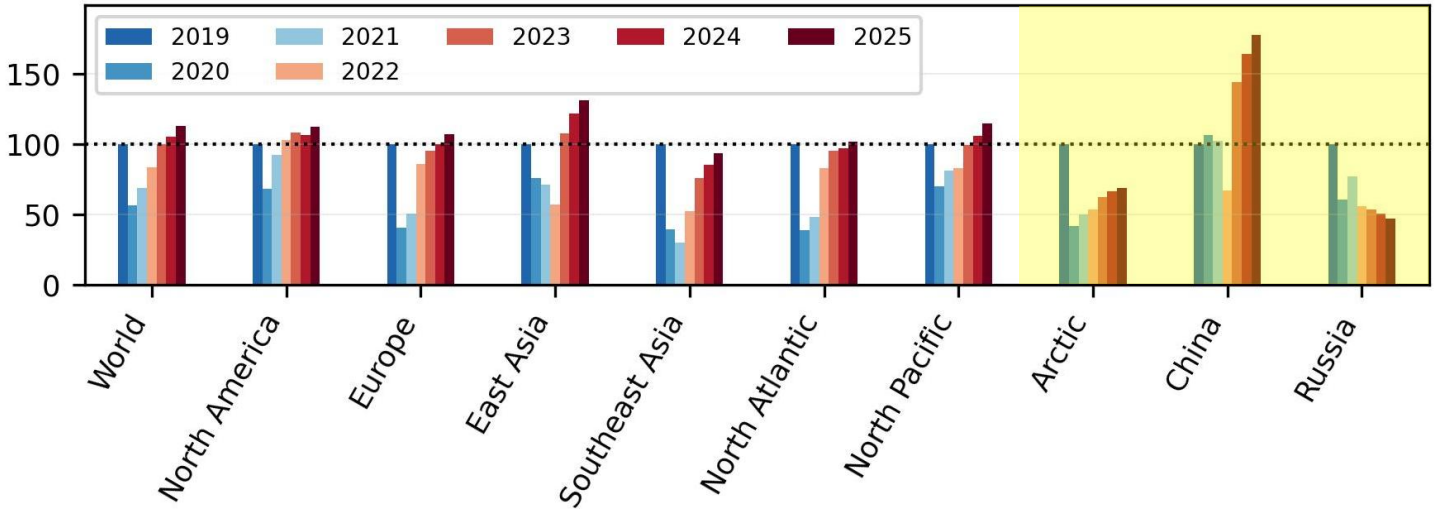


Geopolitics has moved flights away from high contrail forcing regions

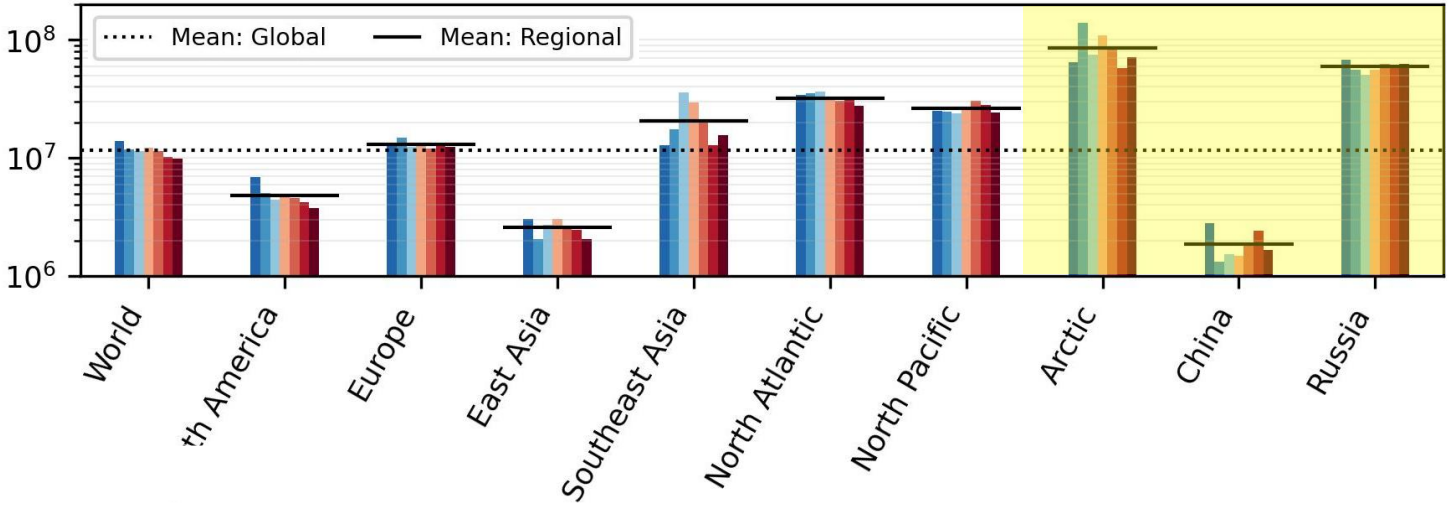
Change in traffic density: 2025 vs. 2019 (km^{-1} h^{-1})



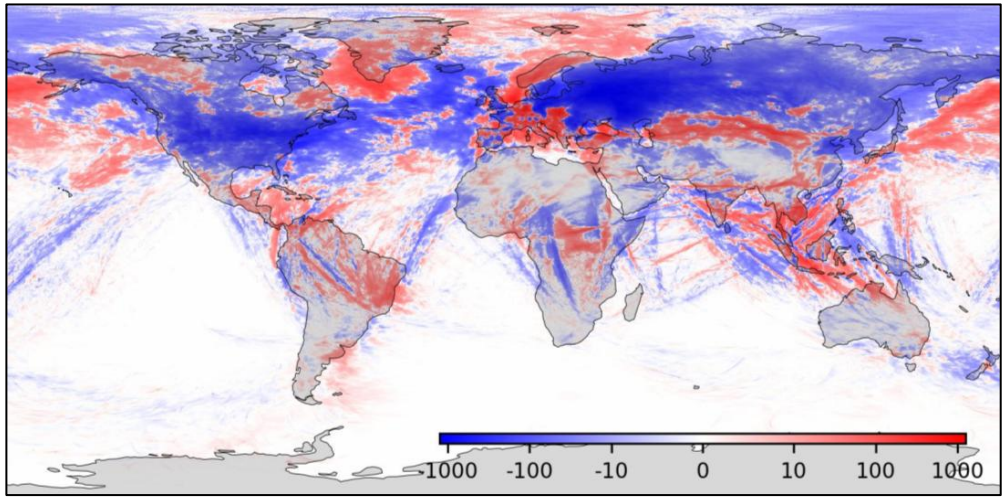
Annual flight distance flown relative to 2019 (%)



Annual mean $EF_{contrail}$ per flight distance flown ($J\ m^{-1}$)

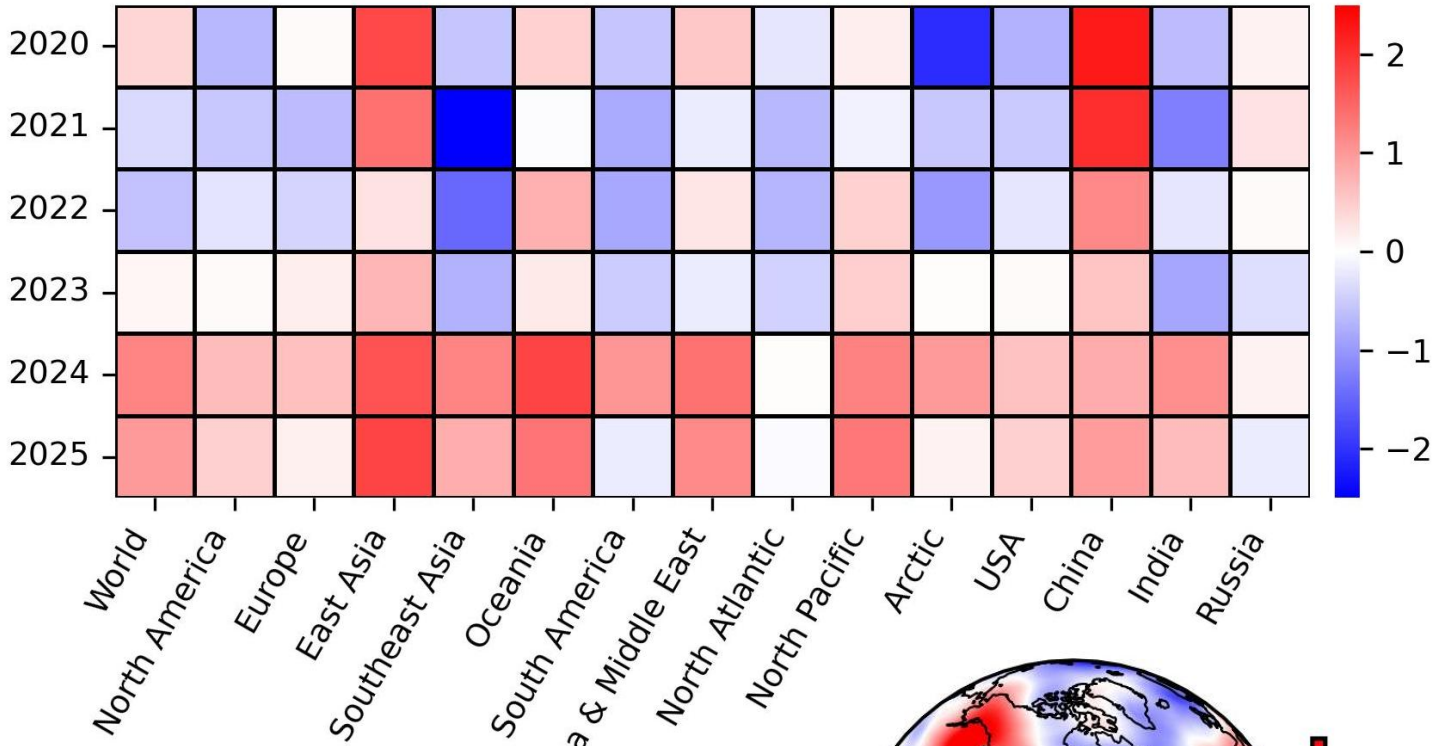


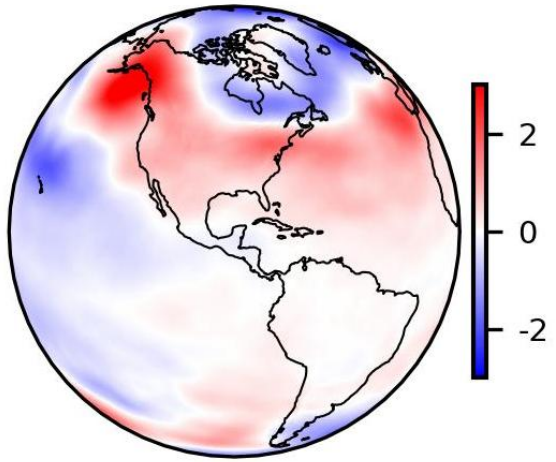
Change in contrail net RF: 2025 vs. 2019 ($mW\ m^{-2}$)



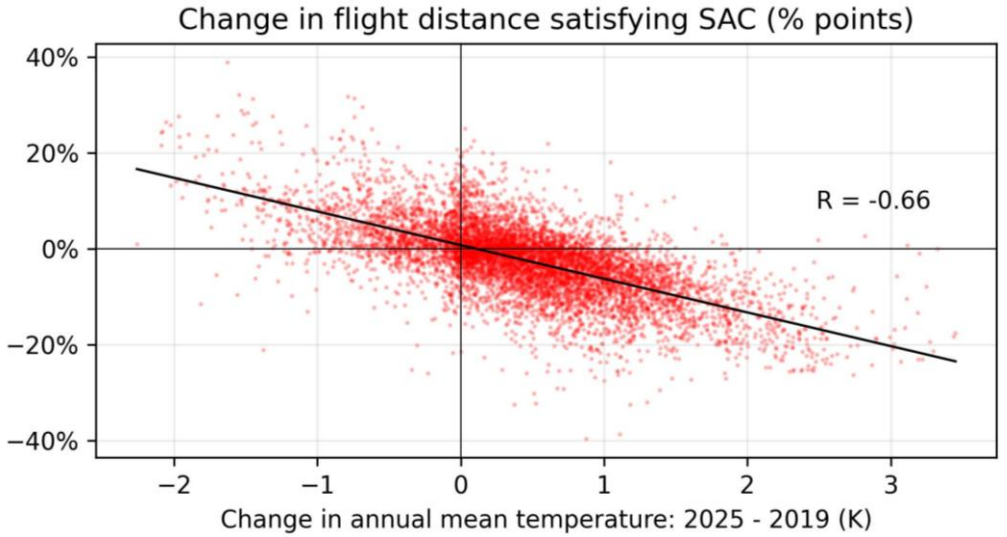
Warmer temperatures have also reduced contrail RF

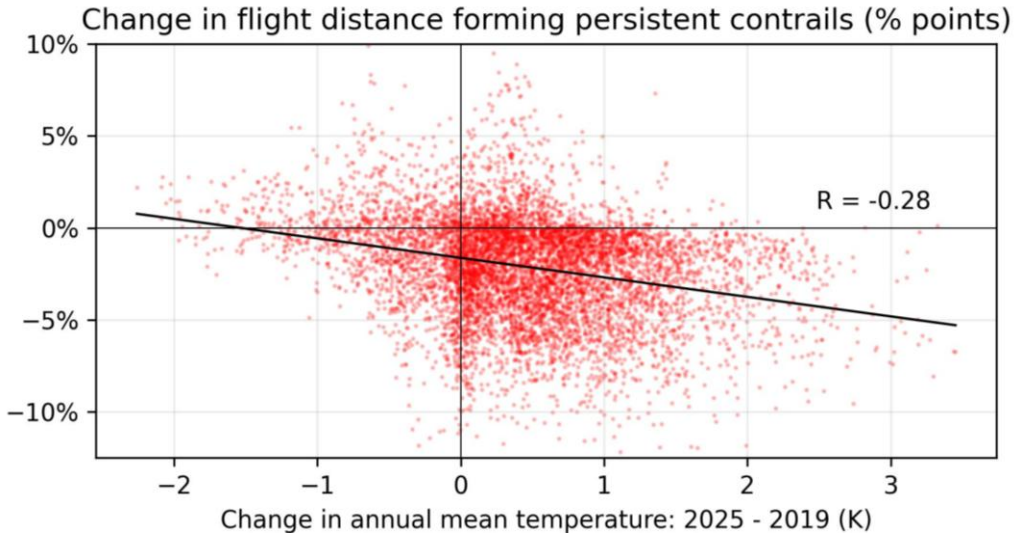
Annual mean temperature change along flight trajectories vs. 2019





Change in annual mean temperature at FL390: 2025 - 2019



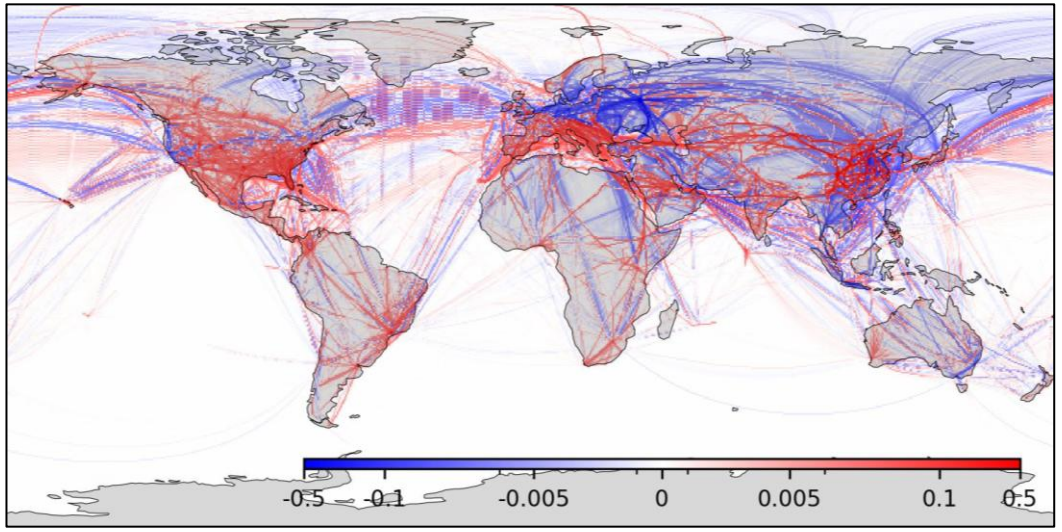


Update 2: Contrail RF has decreased since 2019

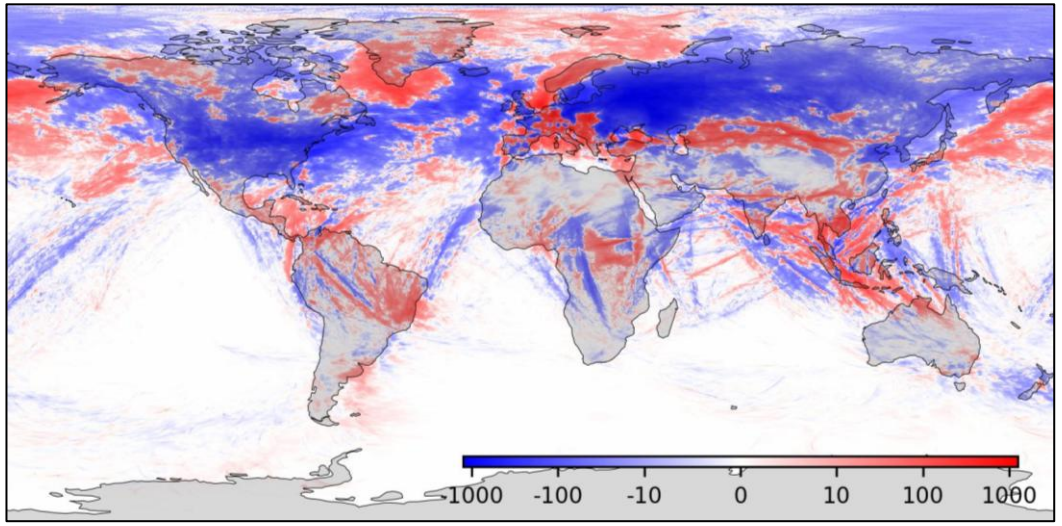
Summary

- First continuous seven-year global assessment of aviation emissions and contrail forcing (2019–25)
- **Higher global aviation activity**: Global flight distance in 2023–25 was 1–15% higher than 2019
- **Improved fuel efficiency**: Fuel (and CO_2) per tonne-km fell by 1% per year, but achieving only half of ICAO's aspirational target
- **Mixed non-CO_2 trends**: Annual mean NO_x EI rose by 0.6% per year, while nvPM EI_n fell by 3.1%
- **Lower contrail warming**: 2023–25 global contrail net RF remained 17–23% below 2019 levels.

Change in traffic density: 2025 vs. 2019 (km^{-1} h^{-1})

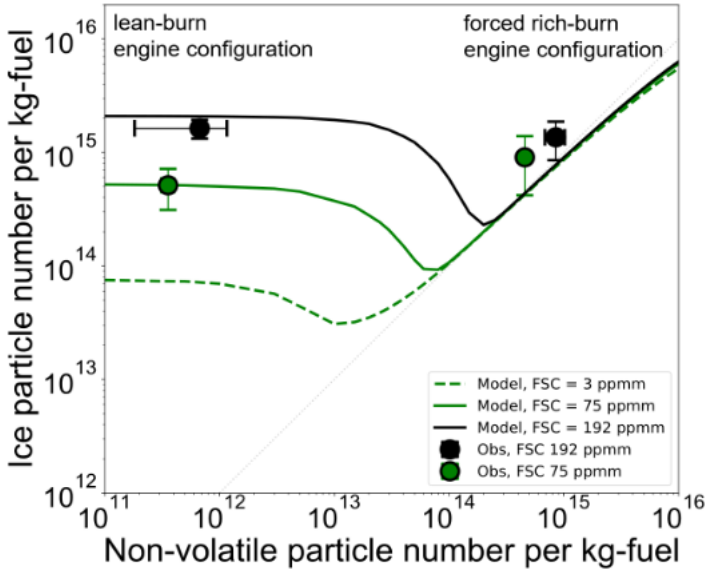


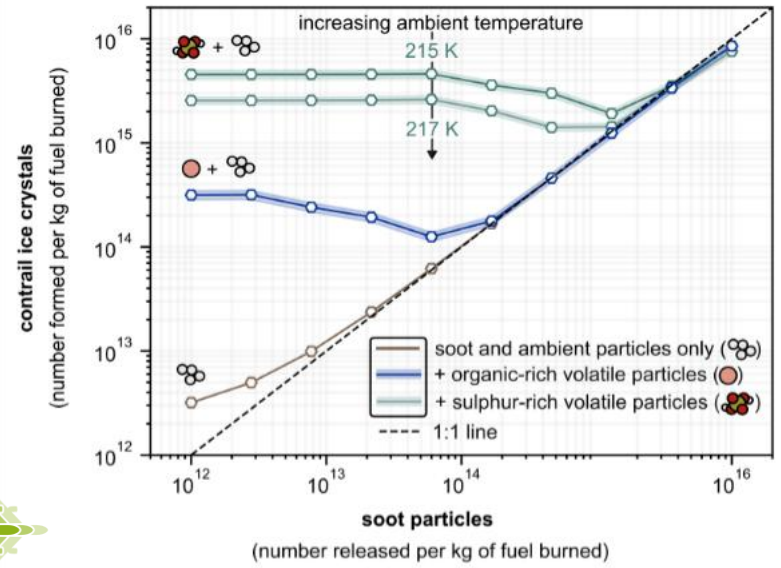
Change in contrail net RF: 2025 vs. 2019 (mW m^{-2})



Update 3: Lower soot emissions does not always give fewer ice crystals

- **Lean-burn** engines cut soot (nvPM) emissions by up to 1,000 times. But these engines have shown to make almost the same number of contrail ice crystals.
- **Other particles** (sulphur, organic vapours and lubrication oil) can activate water droplets when nvPM is low.
- **Fuel sulphur** affects the number of particles and is a fuel desulphurization is lever for contrail mitigation (and air quality improvements).
- Engine wear / degradation affects particle emissions.

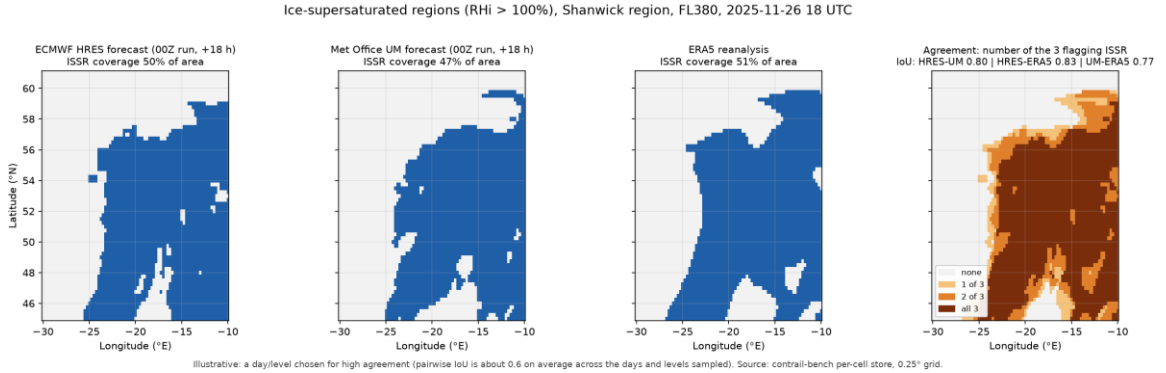


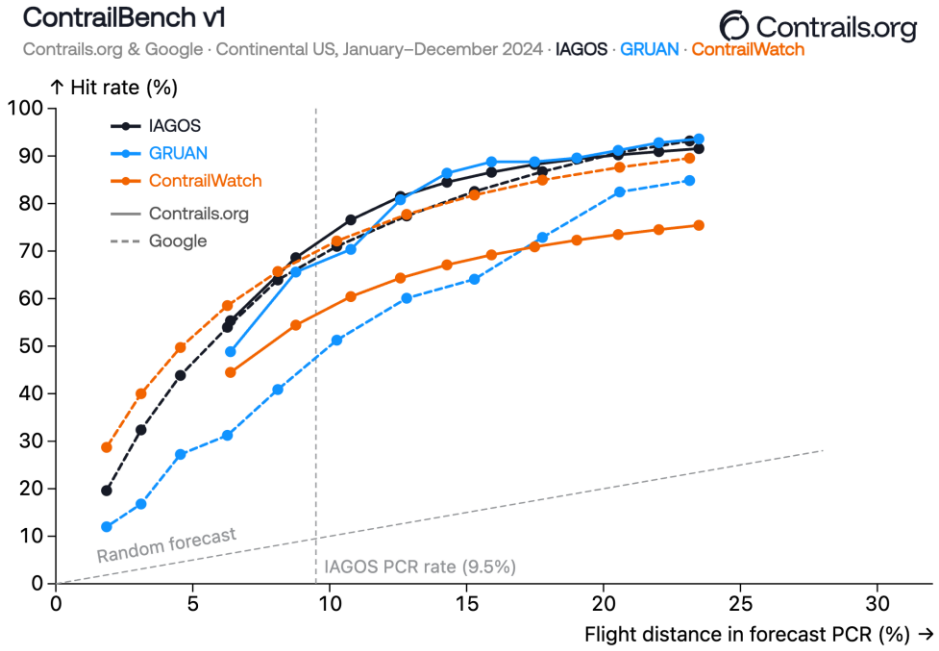


Dischl et al., 2025 Fuel sulfur content can modulate contrail ice crystal numbers
Ponsonby et al., 2025 An updated microphysical model for particle activation in contrails: the role of volatile plume particles
Voigt et al., 2026 Substantial aircraft contrail formation at low soot emission levels
Dischl et al., 2026 Mitigating aviation's environmental impact through alternative fuels and cleaner engines

Update 4: Contrail forecasts can be benchmarked and improved

- Forecasts of ice supersaturated regions (ISSRs) differ but there is **substantial overlap** between models
- Forecasts show **low pointwise accuracy** compared to humidity measurements, small spatial errors
- **Improvements** in ISSR forecasts
- Forecasts show good **stability** on timescales relevant for flight planning
- **ContrailBench** compares contrail forecasts with airliner sensors, weather balloons and satellite contrail detections. One forecast found about 60% of observed persistent contrail regions

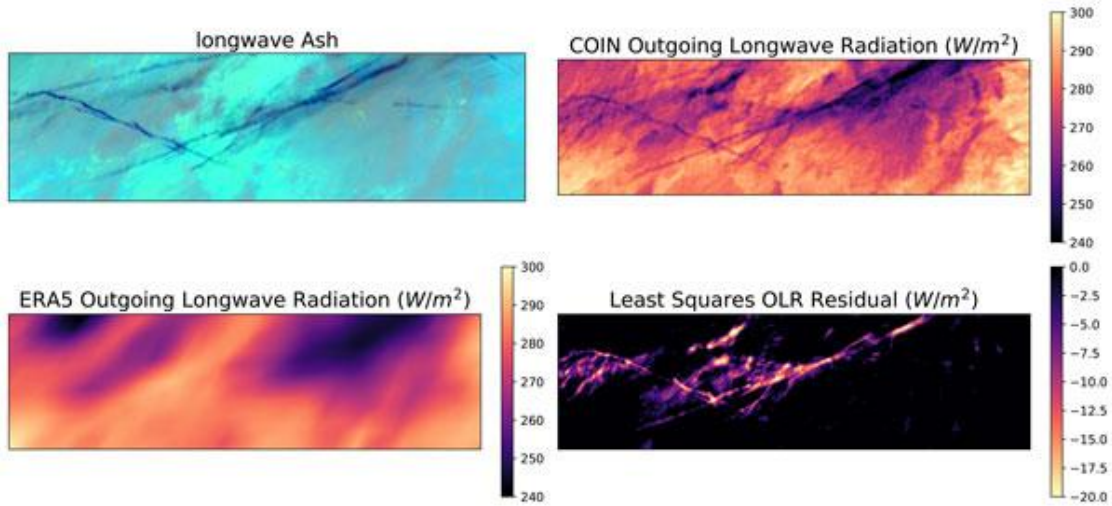




Driver et aal., 2025, The ice supersaturation biases limiting contrail modelling are structured around extratropical depressions
Dean et al., 2025, Impact of forecast stability on navigational contrail avoidance
Hanst et al. 2025, Predicting ice supersaturation for contrail avoidance: ensemble forecasting using ICON with two-moment ice microphysics
Arriolabengoa, et al., 2025 Modeling and verifying ice supersaturated regions in the ARPEGE model for persistent contrail forecast
Hildebrandt et al., 2026 Variability of ice supersaturated regions at flight altitudes: evaluation of ERA5 reanalysis using IAGOS in situ measurements
Hodgson & Abbott, Introducing ContrailBench: measuring contrail forecasts against reality

Update 5: Measuring contrails and their warming effect

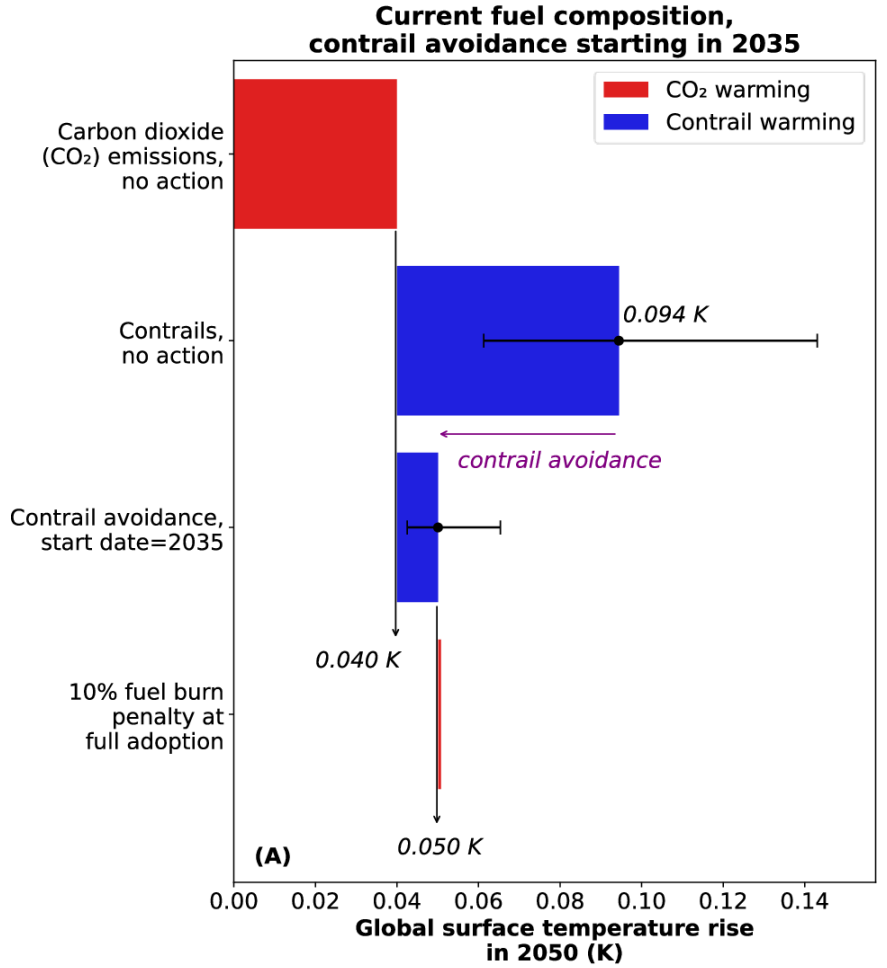
- Automated contrail **detections** (ContrailWatch)
- **Progress** towards what satellites can see of contrails
- A new method measures the **longwave warming** from contrails up to 12 hours old, and RF estimates align with CoCiP
- About 90% of persistent contrails form inside **existing cirrus**, in agreement with global models.
  - In daylight, a contrail inside cirrus can make the cloud reflect more sunlight, so it can cool slightly. At night, it only warms. Satellite lidar shows that the net global effect is warming and a model study also finds net warming in most conditions.
- **Night-time contrails, and contrails in clear air or thin cirrus, give the most certain warming**



Driver et al., 2025 Factors limiting contrail detection in satellite imagery
Sarna et al., 2025 Benchmarking and improving algorithms for attributing satellite-observed contrails to flights
Sonabend-W et al., 2026 Observing long-lived longwave contrail forcing
Petzold et al., 2025 Most long-lived contrails form within cirrus clouds with uncertain climate impact
Seelig et al., 2025 Quantification of the radiative forcing of contrails embedded in cirrus clouds
Verma & Burkhardt, 2026 Contrail Formation Within Cirrus: Contrail Induced Perturbations and Cirrus Adjustments

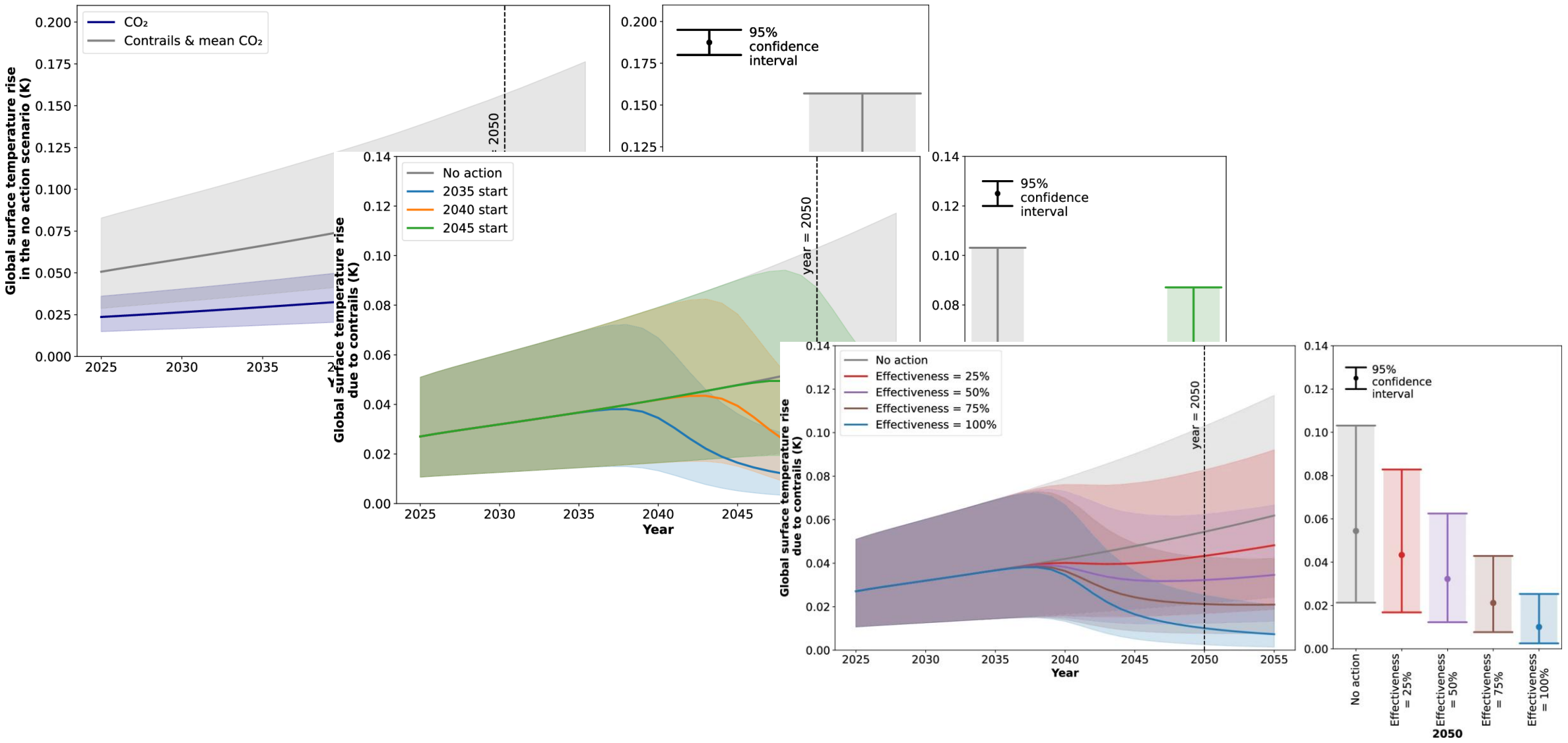
Update 6: Studies agree that contrail avoidance very likely gives a net climate benefit

- **The extra CO_2 is small compared with the contrail benefit**. If 1% more fuel cuts contrail warming by 4%, there is a 67% chance of a climate benefit over 100 years (Prather)
- **Starting early is more important than being perfect**. Even if avoidance works only 25% of the time and uses 10% more fuel, there is a more than 90% chance of a net benefit. A 10-year delay costs more than low accuracy (Smith)
- Decisions can now **include uncertainty** for each flight (Borella)
- A **large airline trial** shows when pilots flew the avoidance plans, contrails decreased by 62%. But only 112 of the 1,232 eligible flights (about 9%) flew these plans, so the overall decrease was 11.6%. No significant difference in fuel use (Sankar)



Prather et al., 2025 Trade-offs in aviation impacts on climate favour non-CO_2 mitigation
Smith et al., The climate opportunities and risks of contrail avoidance
Borella et al., 2026 Concept of risk-aware contrail avoidance strategies
Sankar et al., (in-review) Efficacy of Scalable Airline-led Contrail Avoidance

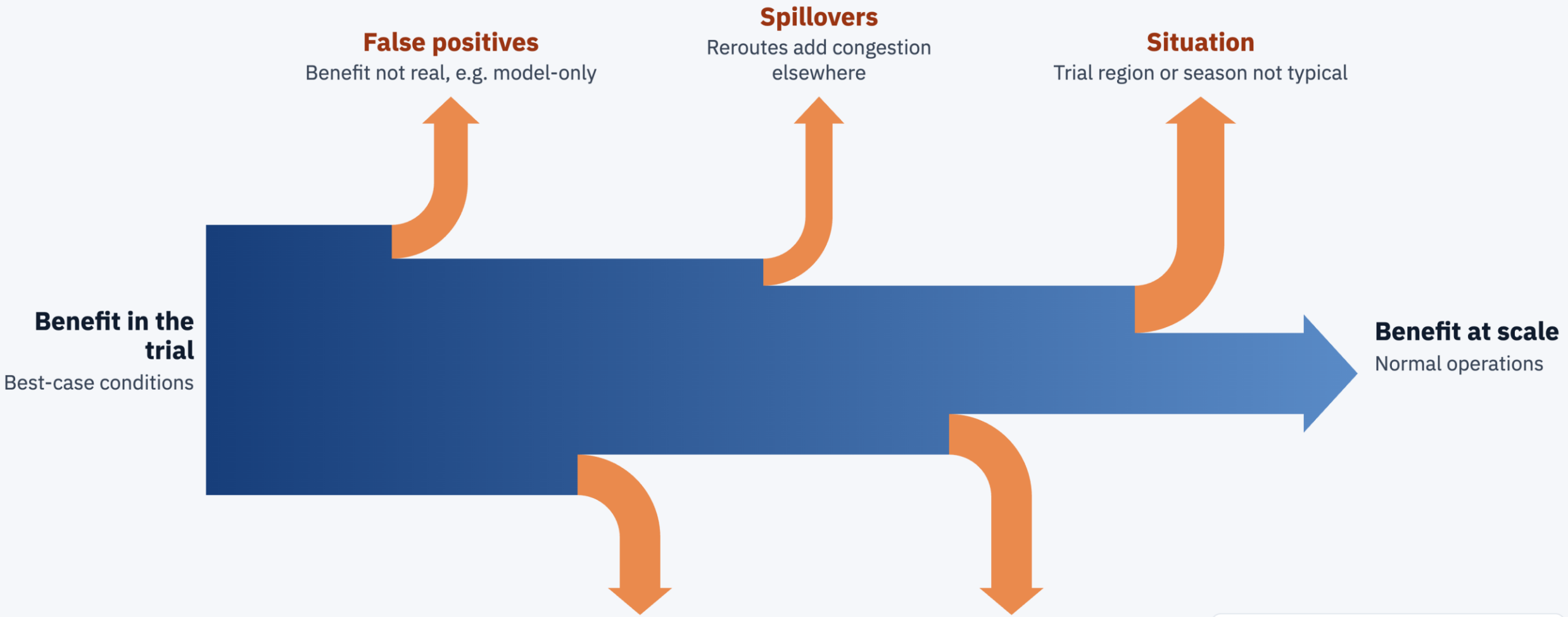
Without contrail mitigation, contrails will warm the planet more than CO2 in 2050



Smith et al., The climate opportunities and risks of contrail avoidance

The voltage drop: why benefits shrink at scale

Five threats to scaling (List, 2024), applied to contrail avoidance

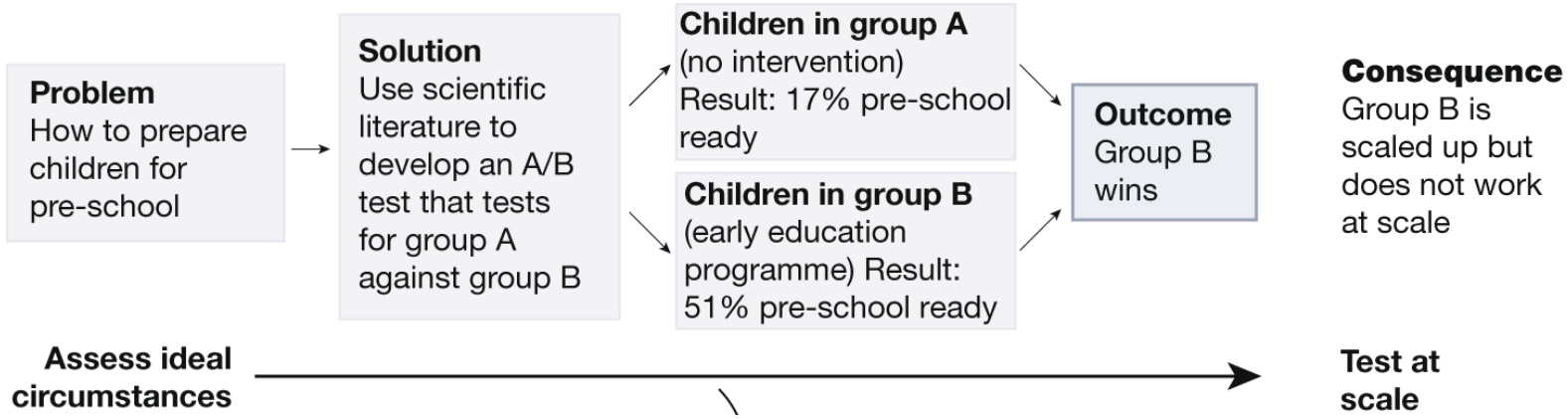


Real example
62% fewer contrails on flights that flew the plan; 11.6% across all eligible flights

Band widths are illustrative. The threats can occur together, in any order.

Option C thinking

Create the evidence that provides greater scaling confidence in the original design alongside the efficacy test

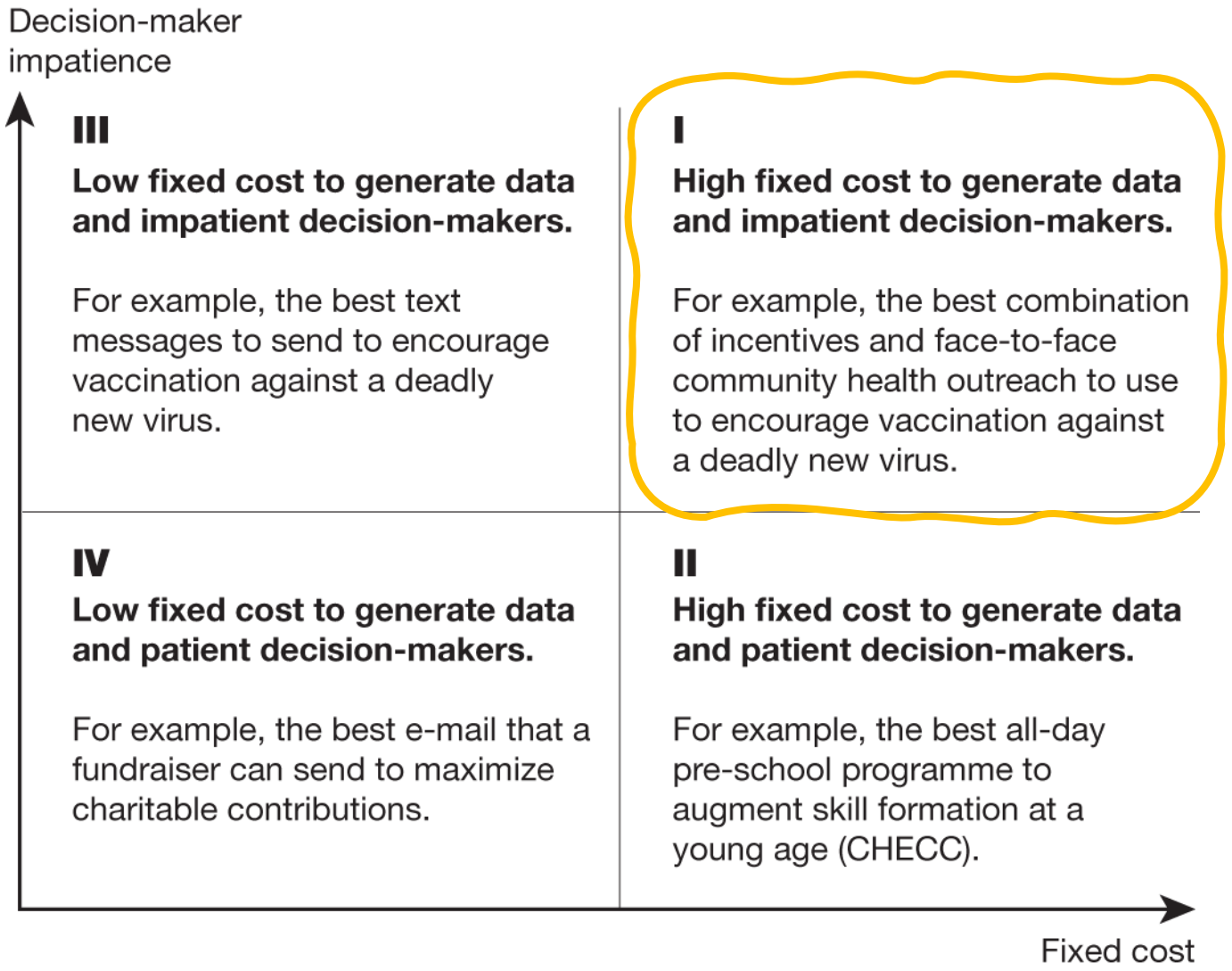




List, 2024 Optimally generate policy-based evidence before scaling

Two dimensions that affect how to think about trials

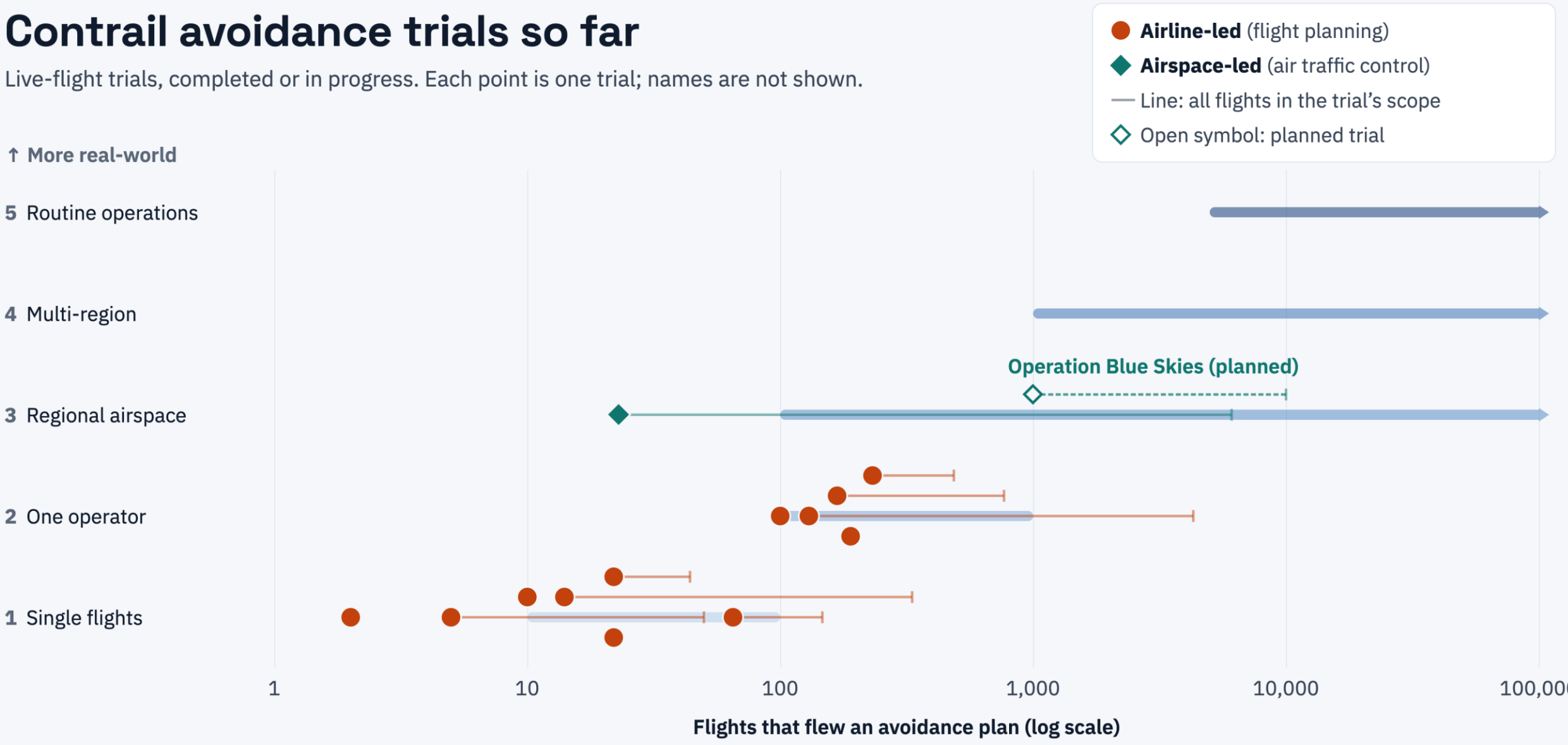
Contrail avoidance is urgent and costs are high



List, 2024 Optimally generate policy-based evidence before scaling

Contrail avoidance trials so far

Live-flight trials, completed or in progress. Each point is one trial; names are not shown.



No flight numbers yet: In progress ● ● ● Completed ◆

Source: contrail trial tracker, October 2026. Avoidance trials flown live only. Airspace-led trials are placed on the regional row.

Contrails.org

So what?

Address uncertainty in science and effectiveness

1. There have been substantial scientific developments that establish new ‘firm ground’

2. Contrails are net warming, nighttime* contrails are always warming

3. Trials should aim to create the evidence that provides greater scaling confidence in the original design alongside the efficacy test

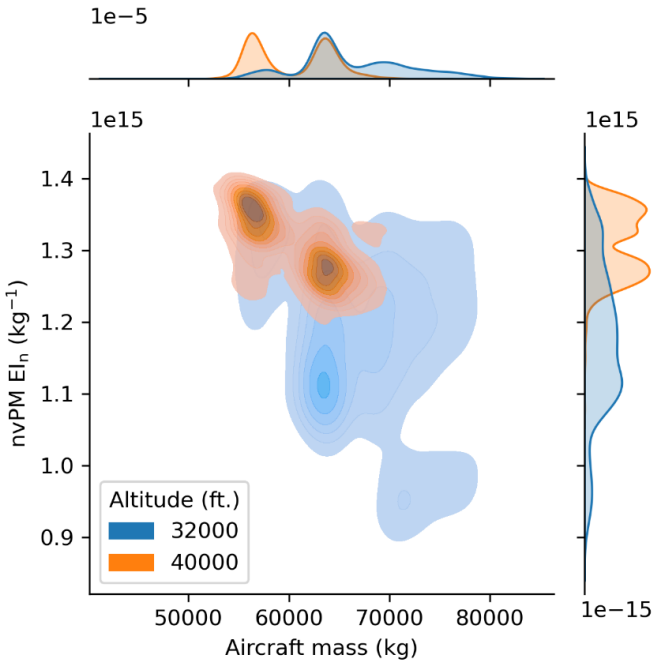
*what matters is that the contrail persists in the night, not the formation time



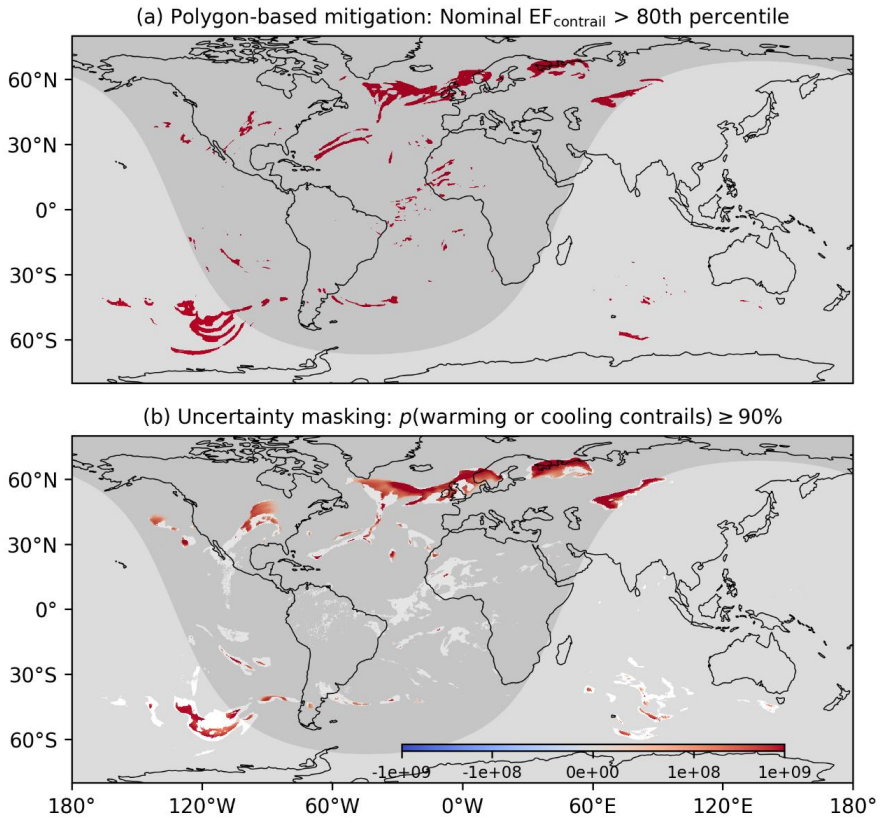
Prototype contrail forecast and implementation

Scaling contrail forecasts

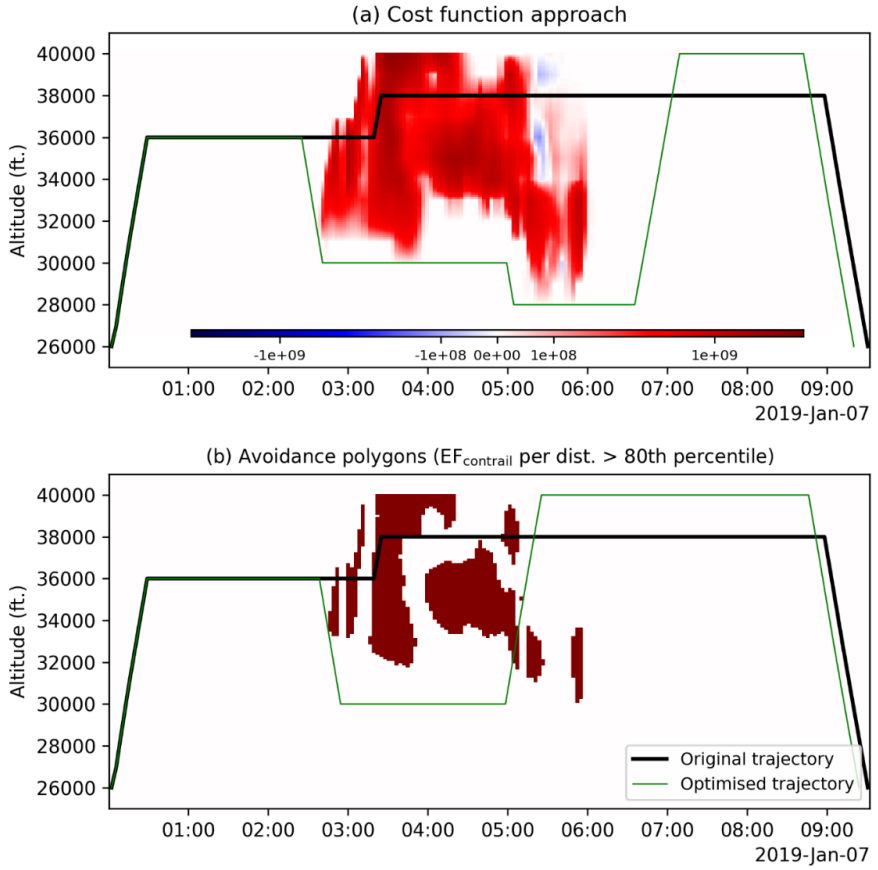
Aircraft classes



Uncertainty masking



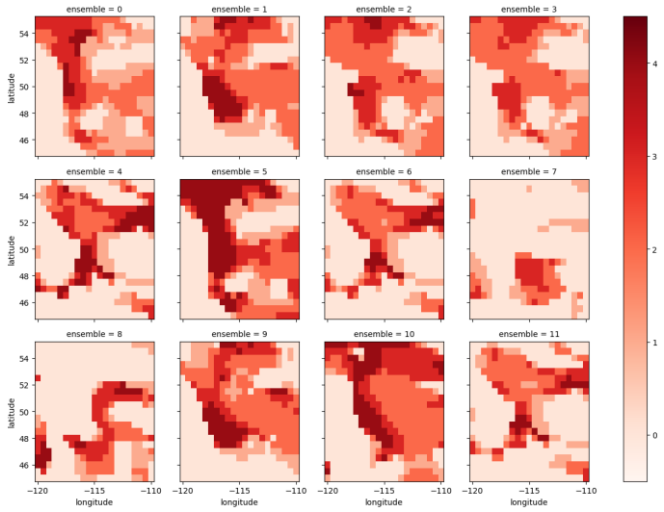
Trajectory optimization



Engberg et al. Geosci Model Dev. 2025.
https://doi.org/10.5194/gmd-18-253-2025

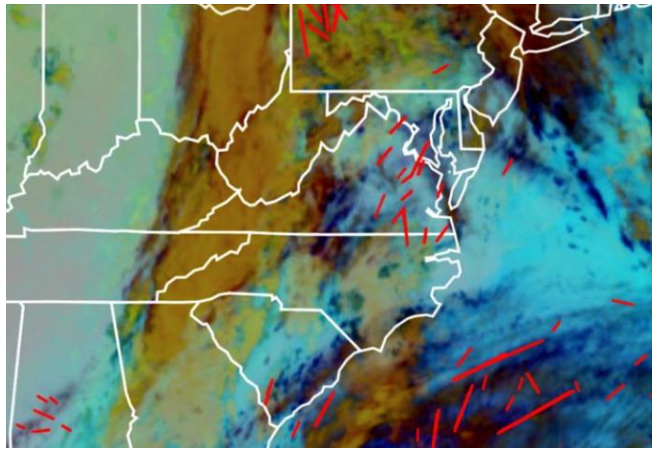
Focus on high-probability high-forcing regions in forecast

Use weather model ensembles and observations to generate expected values of contrail warming



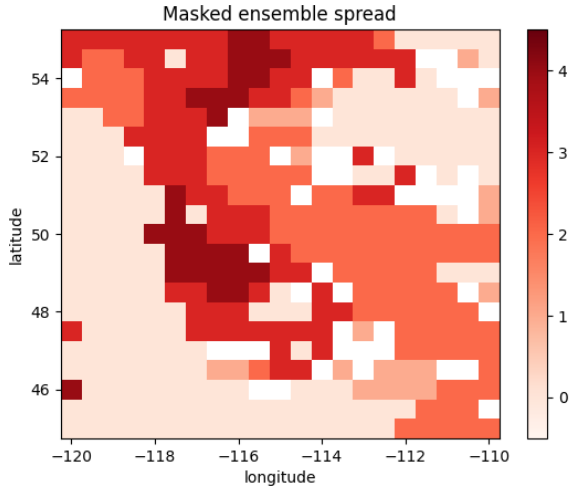
Generate contrail forecast ensembles

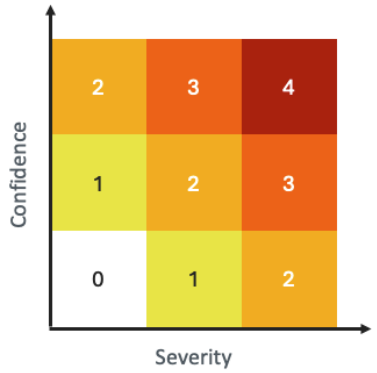
+



Assimilate observation sources

→

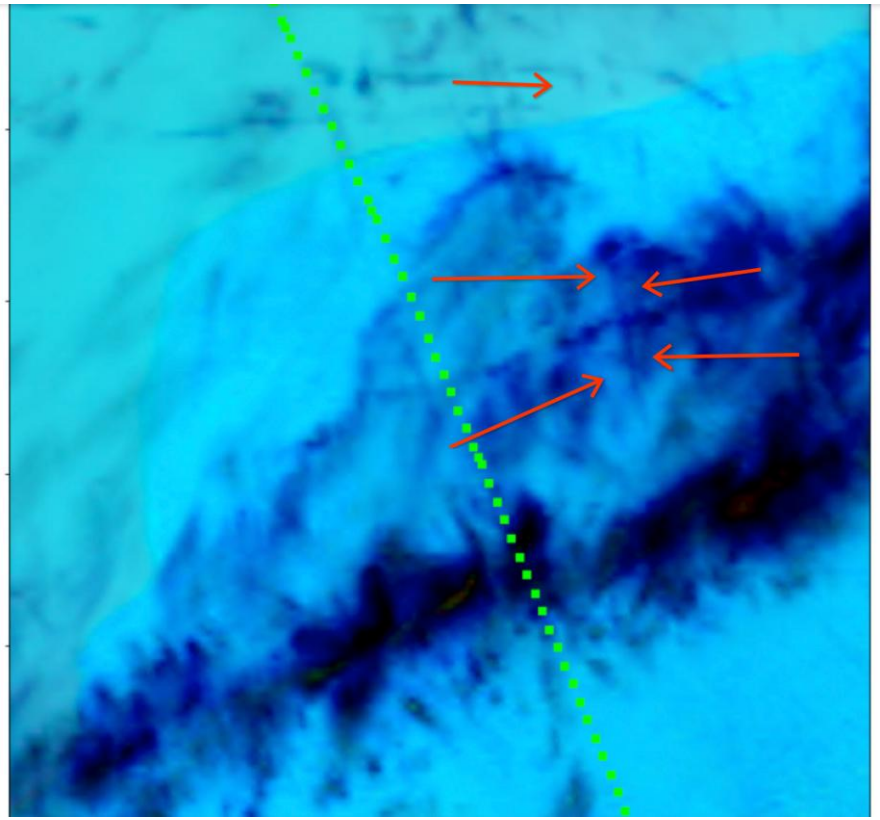


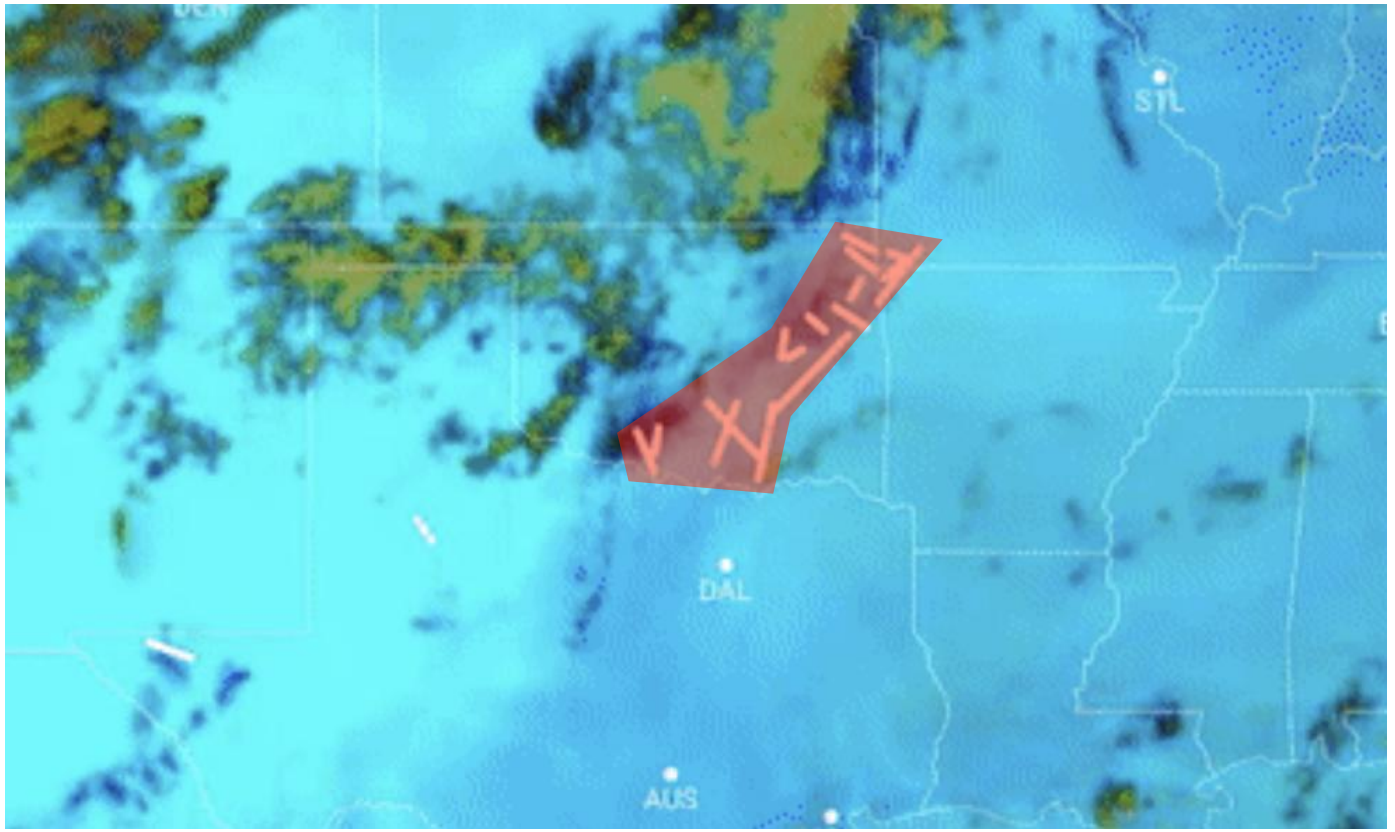


High-probability high impact contrail regions

Verify interventions with observational data

Ensure forecast / nowcast pipelines lead to reduction in contrail formation and contrail outbreaks overall





https://sites.research.google/contrails/

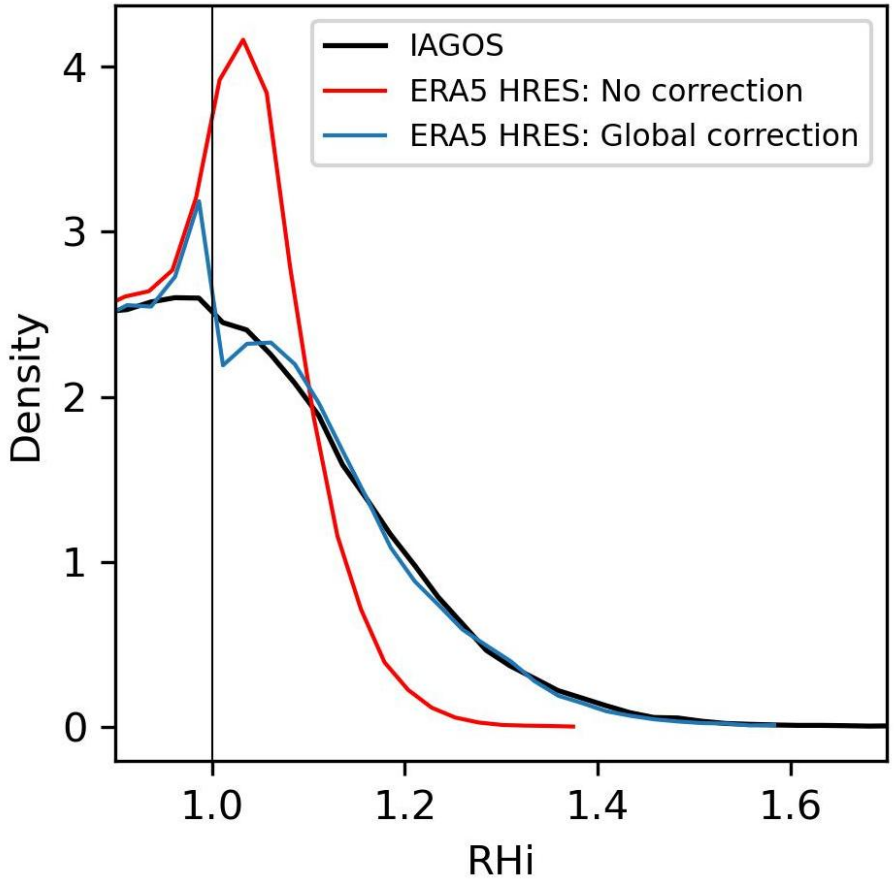
Persistence

There are limited measurements of humidity at cruise altitudes



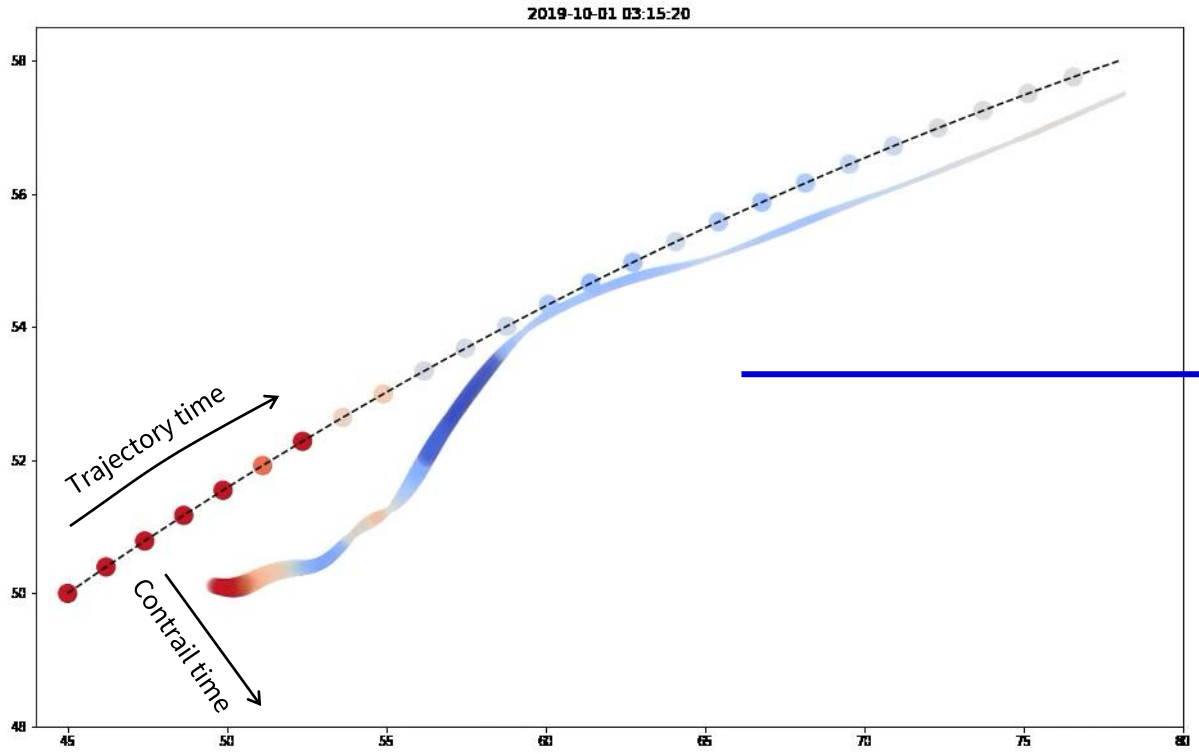
IAGOS
IN-SERVICE AIRCRAFT FOR A GLOBAL OBSERVING SYSTEM

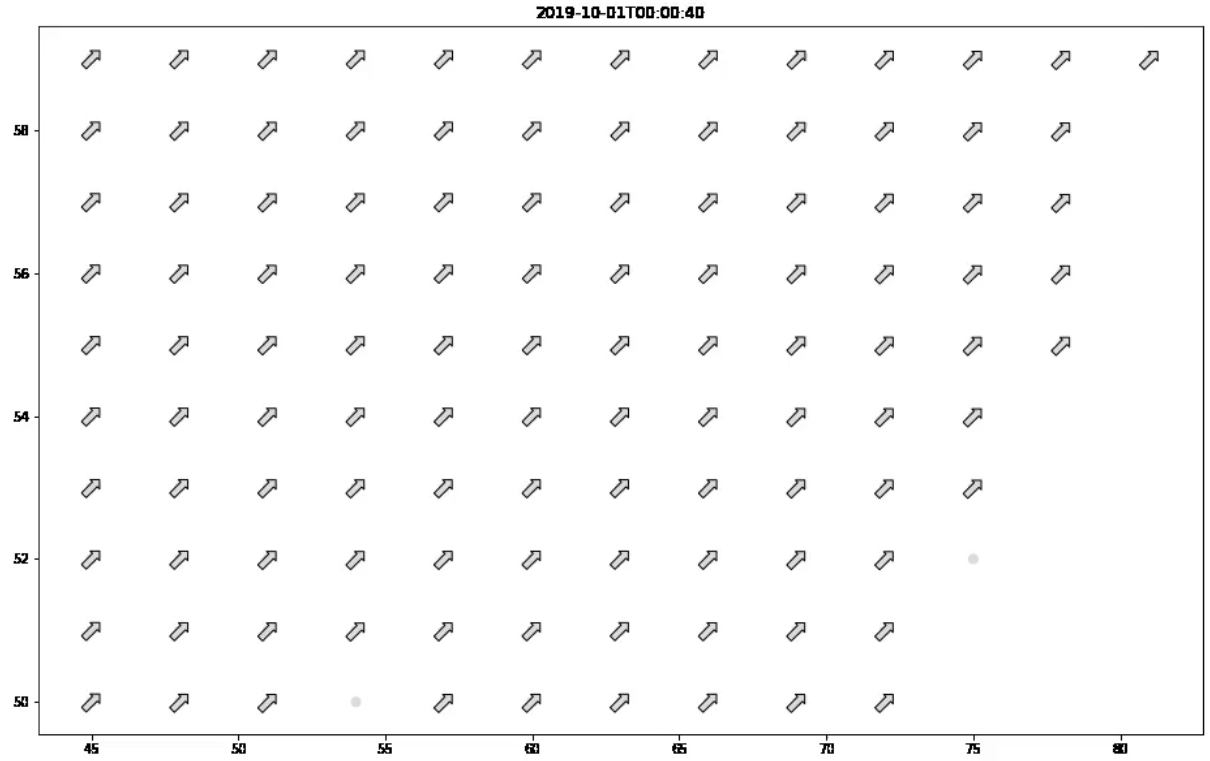




Contrail forecast and implementation

“CoCiP Grid”





Engberg et al. Geosci Model Dev. 2025.
https://doi.org/10.5194/gmd-18-253-2025

2021-12-01 00:02

