Contrail mitigation

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Nicolas Bellouin

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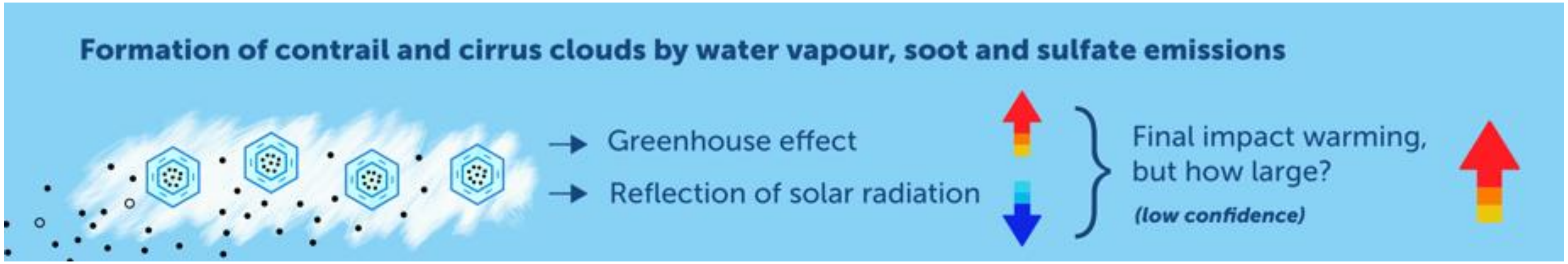
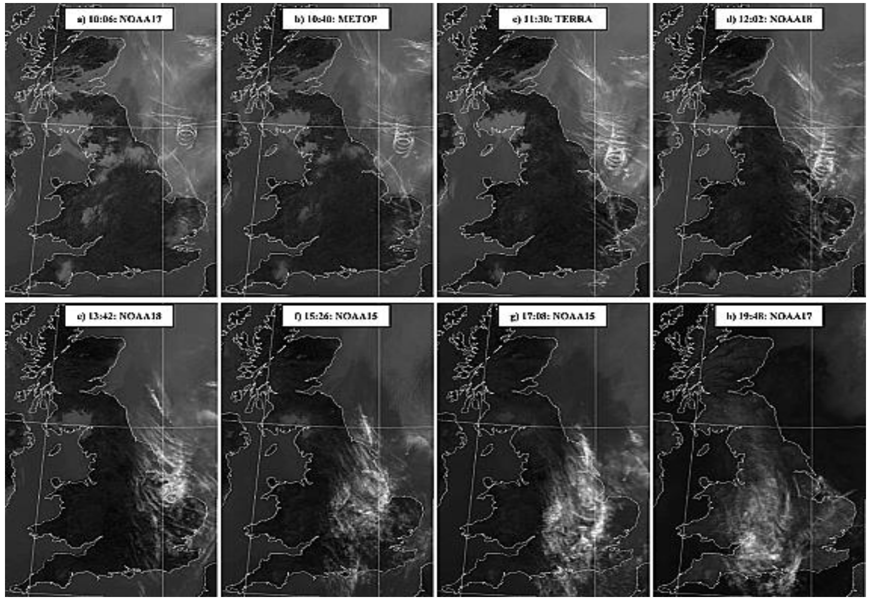
- I am a climate scientist
  - Professor of Climate Processes at the University of Reading (UK)
  - Expertise in climate impact of atmospheric particles (“aerosols”)
  - One of the lead authors of the 2021 report of the Intergovernmental Panel on Climate Change

- Research on aviation-climate interactions since 2020
  - Lead the Climaviation research project on aviation non-CO_2 effects, based at Sorbonne Université in Paris (France)
  - Involved in projects on SAF and aviation non-CO_2, contrail avoidance, and humidity sensors for contrails
  - Member of the Aviation Non-CO_2 Expert Network of the European Aviation Safety Agency

Contrails





Short-lived contrails:
Negligible impact on climate

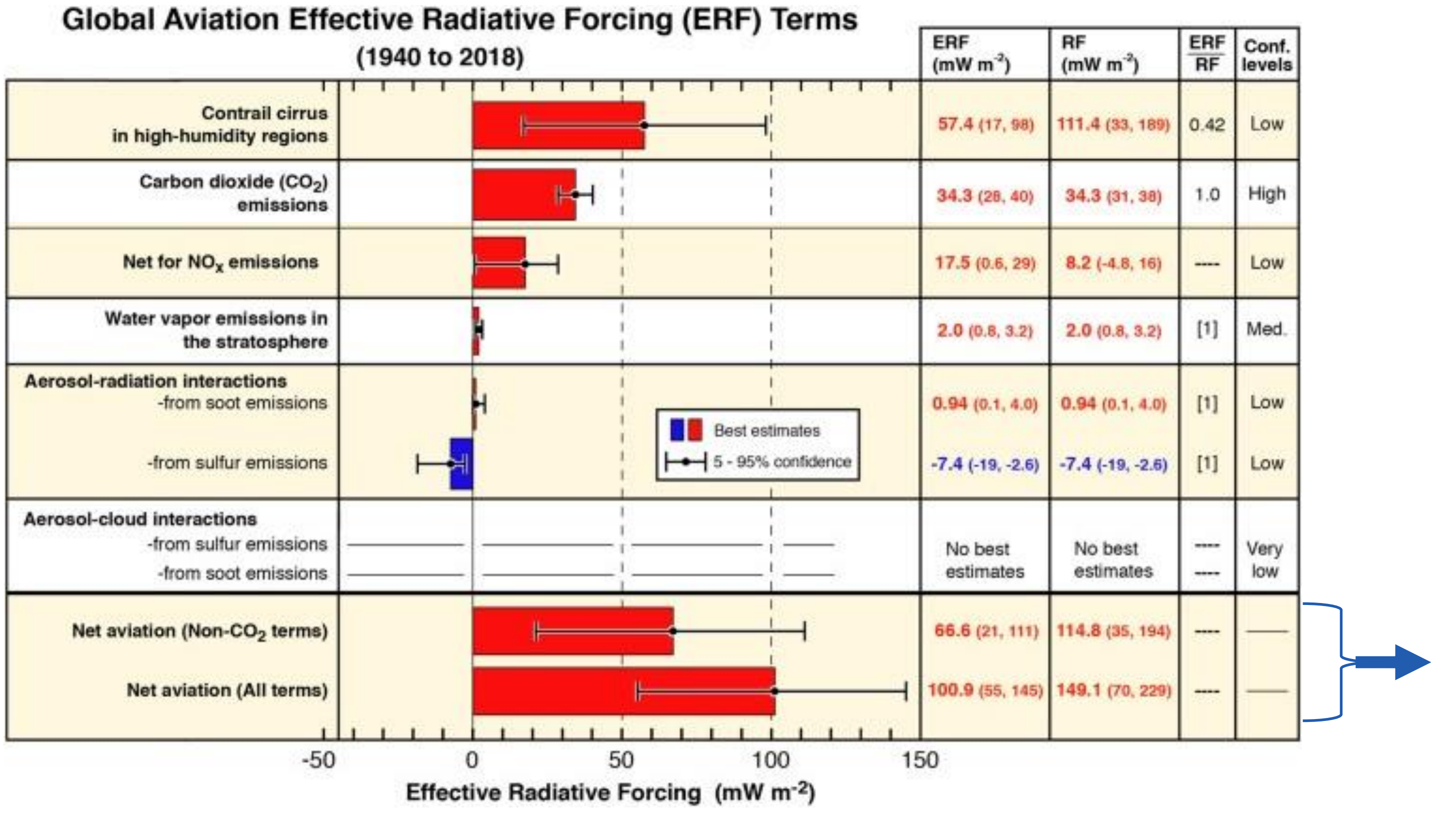
Persistent linear contrails:
~20% of the climate impact[1]

Contrail cirrus:
~80% of the climate impact[1]

[1] Percentages from Kärcher et al. (2018) https://doi.org/10.1038/s41467-018-04068-0

Radiative forcing of aviation

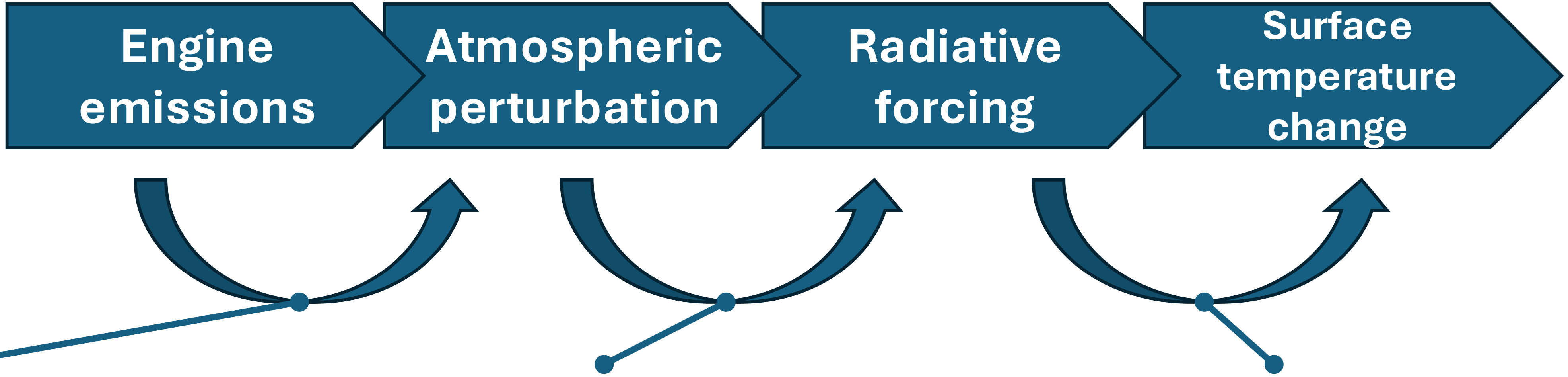
- Effective radiative forcing: imbalance in the Earth's energy budget that triggers climate changes
- Between 1940 and 2018, 2/3 of aviation effective radiative forcing may have been exerted by non-CO_2 effects, and especially contrails.
- Contrails dominate the uncertainty.



Translates into a 0.015°C contribution to global warming from aviation CO_2 and 0.04 ± 0.02°C from aviation CO_2+non-CO_2, ~4% of total warming[2]

[1] Lee et al. (2021) https://doi.org/10.1016/j.atmosenv.2020.117834 [2] Klöwer et al. (2021) https://doi.org/10.1088/1748-9326/ac286e

Contrail research over the past 5 years



Much progress:
- Increasing number of measurements (more in-flight measurements needed)
- Theoretical understanding is good (especially for kerosene)
- Need to be better linked to other elements of the chain

Some progress:
- Estimates of contrail radiative forcing from satellite imagery
- Larger number of climate models able to represent contrail cirrus
- Model/model and model/observation comparisons remain difficult

Very challenging:
- Only two estimates from independent climate models
- Involves longstanding difficulties with simulating the atmospheric water budget, especially clouds
- Small perturbation, only observable indirectly in exceptional circumstances (e.g. Covid)

Contrails vs. aviation CO_2

Engine emissions → **Atmospheric perturbation** → **Radiative forcing** → **Surface temperature change**

A typical 2-engine flight emits[1] (among other compounds):

- **8500 kg of CO_2**
- **3300 kg of water vapour**
- **0.1 kg of soot**

per hour

Ingredients for contrail formation

- **Contrails are more efficient** than aviation CO_2 at exerting a radiative forcing per unit mass
- But **CO_2 is much longer lived**

- For the same radiative forcing, **contrails may be 40-60% less efficient** than CO_2 at warming the surface per unit radiative forcing[2]

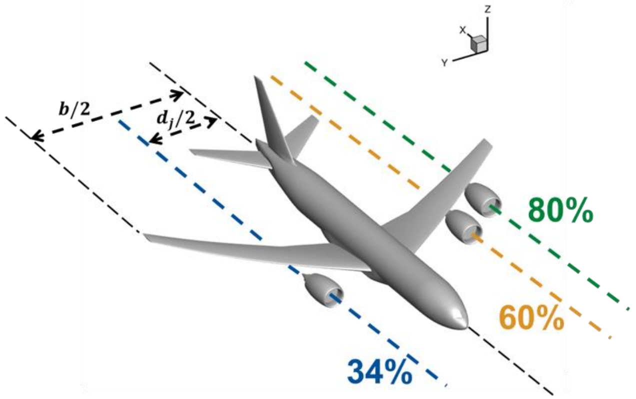
Overall, if a flight forms a warming contrail, total warming caused by the flight will initially be mostly due to contrails for 5-15 years after the flight, then be mostly due by carbon dioxide.[3]

[1] EASA Environmental Report 2019 [2] Bickel et al. (2025) https://doi.org/10.1175/JCLI-D-24-0245.1
[3] Borella et al. (2024) https://doi.org/10.5194/acp-24-9401-2024

Contrail mitigation: Aircraft design

- Larger aircraft produce larger contrails[1]

- But aircraft design exerts little control over final contrail properties
  - Atmospheric conditions are the primary driver of contrail evolution
  - Confirmed by model simulations of different engine positions[2], aircraft shapes, …

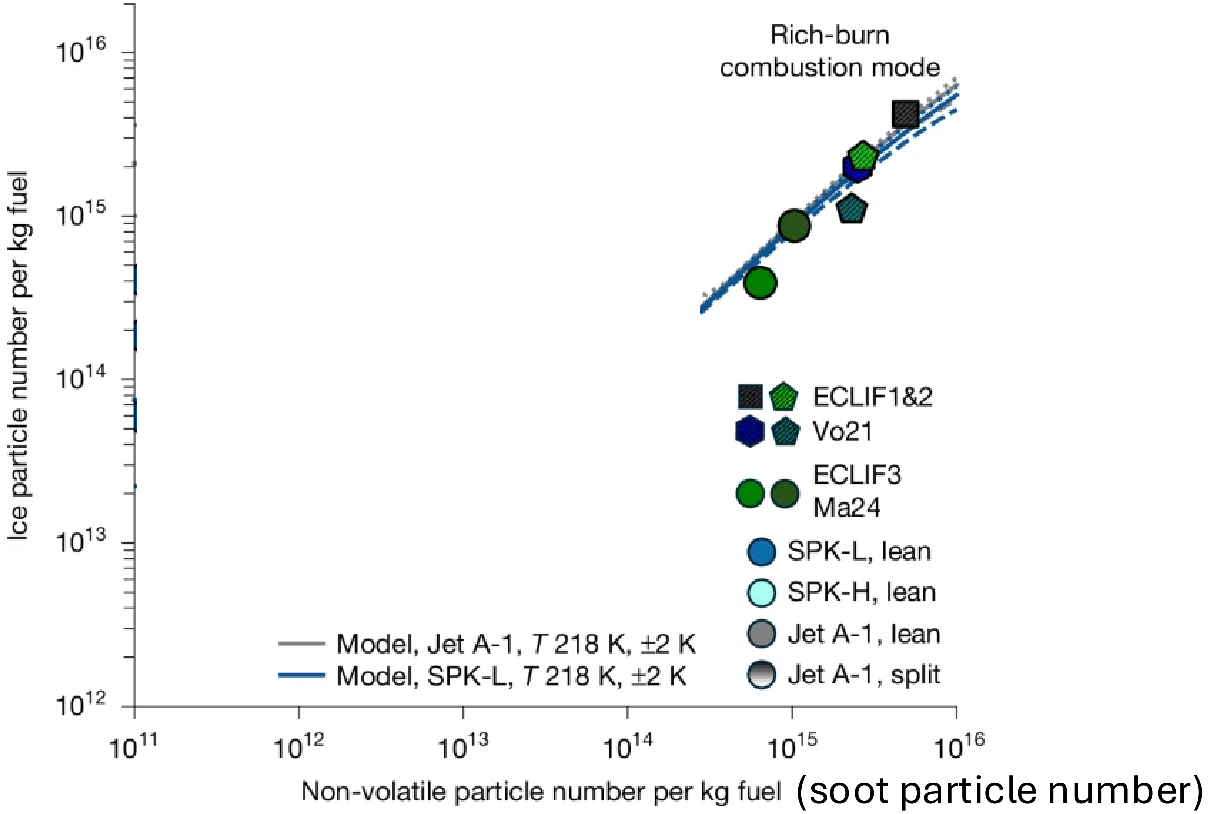


[1] Jeßberger et al. (2013) https://doi.org/10.5194/acp-13-11965-2013 [2] Annunziata et al. (2025) https://doi.org/10.1016/j.ast.2025.110703

Contrail mitigation: Fuel composition[1]

- Emission reductions can be achieved by changing fuel composition.
  - Fuels with higher hydrogen content produce less soot.
    - Kerosene: 13.5% to 15% hydrogen content by mass, average 13.8%.
    - SAF and hydroprocessed kerosene: ~15%
    - Soot emission reductions observed in many ground and airborne tests

[2]



- Several in-flight measurements behind aircraft[2] confirm that reducing soot emissions reduces ice crystal number
  - Matches theoretical understanding
  - Leads to reduced radiative forcing
  - But...

[1] For more details, see EASA ANCEN background note 3 at https://www.easa.europa.eu/en/research-projects/ancen-nonco2
[2] Voigt et al. (2026) https://doi.org/10.1038/s41586-026-10286-0

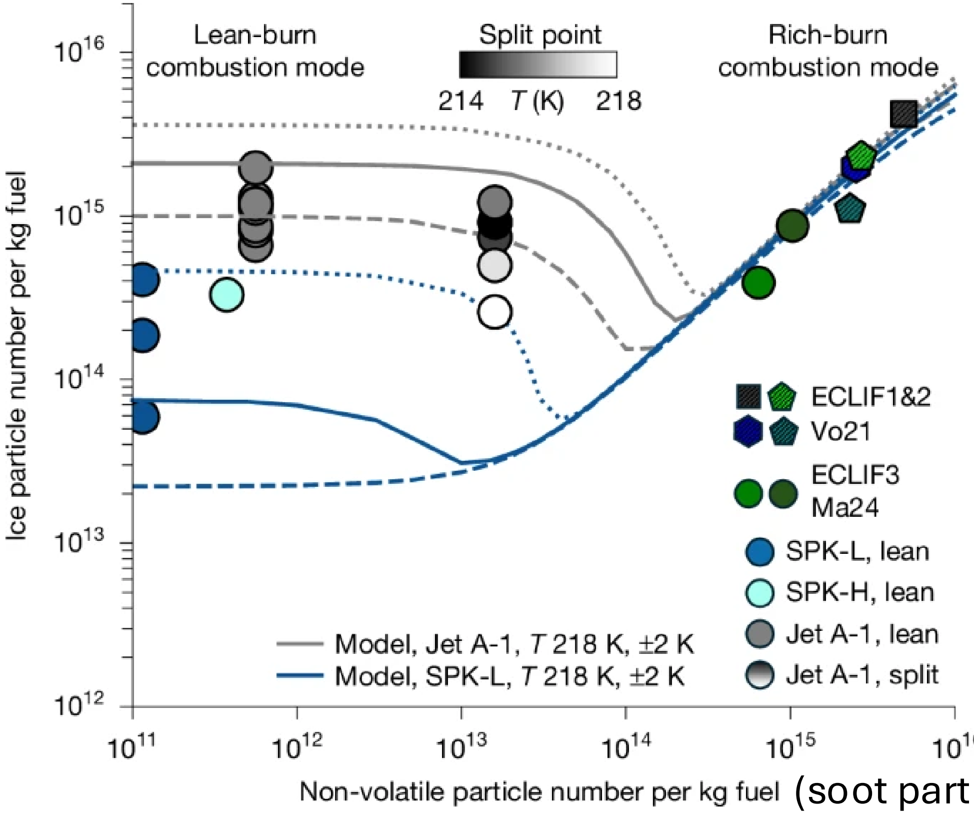
Contrail mitigation: Engine technology[1]

NEOFUELS/VOLCAN

- Lean-burn combustion technology has the potential to reduce soot emissions significantly.
  - Yet with kerosene, little to no decrease in ice crystal number is observed
  - Sulfur emissions form particles that take over the role of soot in ice crystal formation

- Then, just combine lean-burn and a low-sulfur fuel, like SAF?
  - Contrail formation still happens![3]
  - Role of background atmospheric particles? Particles from oil venting? Others?
  - Radiative forcing might be weaker

[2]



(soot particle number)

[1] For more details, see EASA ANCEN background note 3 at https://www.easa.europa.eu/en/research-projects/ancen-nonco2

[2] Voigt et al. (2026) https://doi.org/10.1038/s41586-026-10286-0 [3] Miller et al. (in prep.) https://doi.org/10.5194/egusphere-egu26-2854

Contrail mitigation: Contrail avoidance (1/3)

- Three steps:
  - Forecast the regions where persistent contrails form
  - Deviate flights to avoid those regions
  - Verify that avoidance was successful

- Requirements:
  - Ability to predict contrail formation
  - Ability to predict contrail persistence
  - Ability to predict contrail climate impact

- No need to deviate many flights: Expect that few flights exert most of the impact
  - But we cannot yet confidently predict which flights

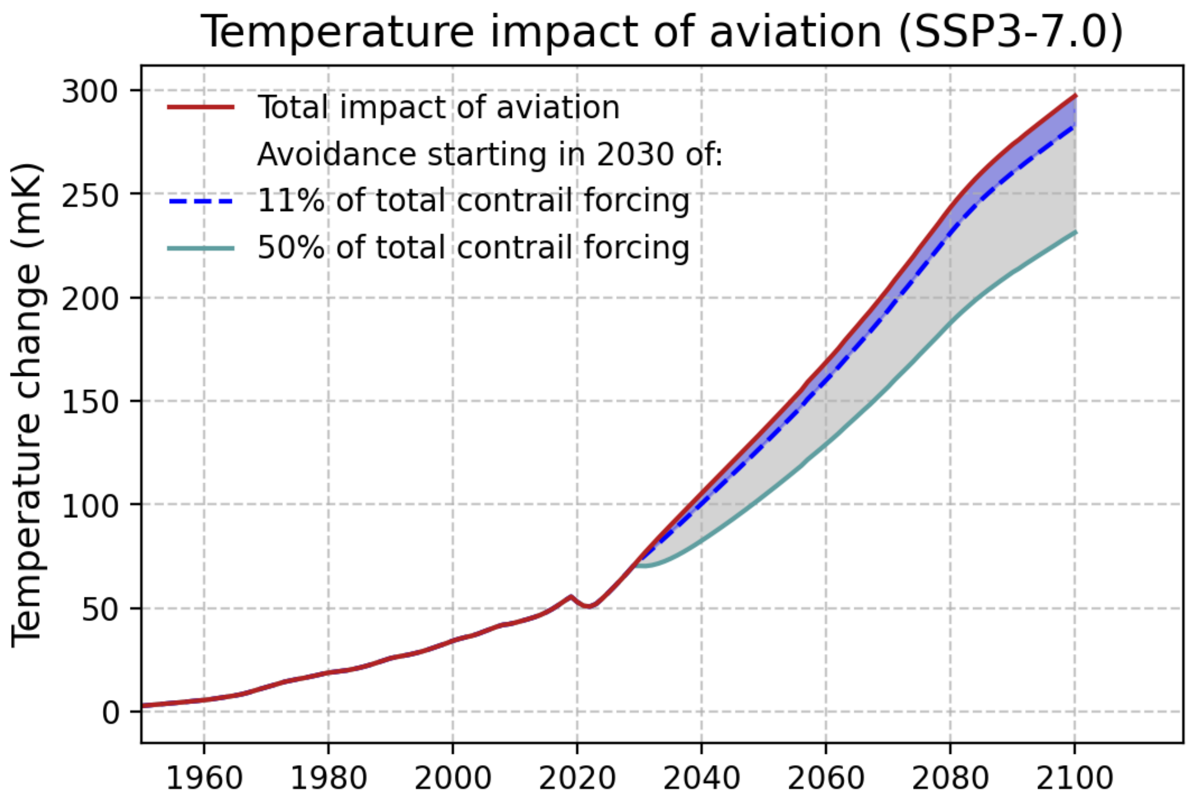
- First ever real-world trial within Maastricht Upper Area Control in 2020.[1]

- Found that avoiding persistent contrail formation is possible on average.
  - But many open questions.
  - Several trials since and ongoing, involved 100s of flights.

[1] Sausen et al. (2024) https://doi.org/10.1127/metz/2023/1157

Contrail mitigation: Contrail avoidance (2/3)

- Calculations with reduced-complexity climate model OSCAR Aviation[1]
- Avoiding 50% of contrail forcing removes ~0.03°C of warming over 2030-2050
  - About ~3-4% of the 0.8 to 1°C warming over 2025-2050 depending on future emission scenario
- In 2100, avoidance does not invert the warming trend from aviation
  - But offsets up to 25 years of market growth



[1] Lecouffe et al. (in prep.)

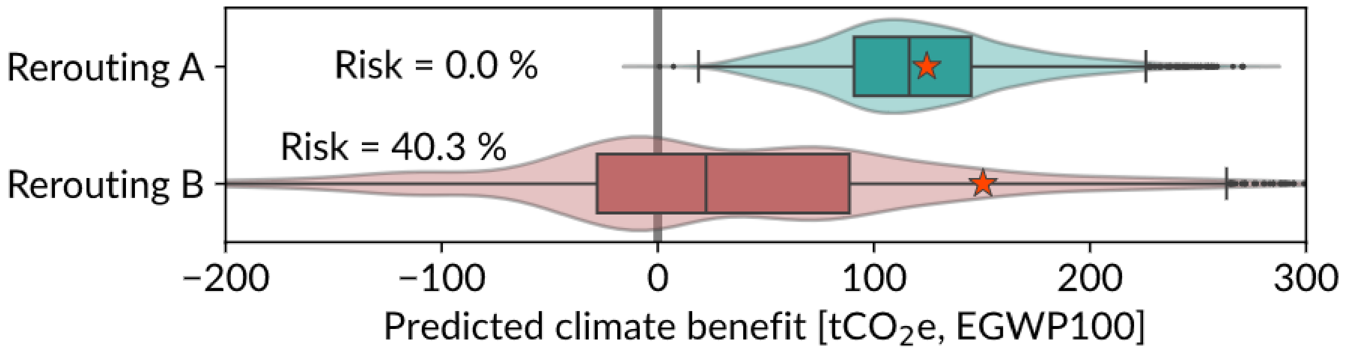
Contrail mitigation: Contrail avoidance (3/3)

- Uncertainties are here to stay so we are learning to translate them into risk
  - Supports decision making
- Frequent humidity measurements by commercial aircraft would much benefit weather forecasts
- Avoidance can (and will!) fail when:
  - Contrail formation regions are not where predicted
  - Avoided contrail would have evolved/lasted differently than predicted
  - Avoided contrail was in fact cooling
  - Extra fuel burn exceeds the climate gain of avoided contrails
  - …

Weather forecast uncertainties

Climate impact uncertainties

Joint uncertainty



[1] Borella et al. (submitted) https://doi.org/10.5194/jecats-2026-2

What is realistically achievable over the next 5-10 years?

- Several large, ongoing research projects
  - Funded by EU Horizon, SESAR JU, UKRI and UK ATI, FAA, national governments, aviation industry, …
  - Need to maintain momentum: benefit of EU non-CO_2 MRV

- Moderate decrease in global contrail climate impact uncertainty
  - More research teams now working on the topic
  - Climate model intercomparison project dedicated to contrails

- Enhanced contrail prediction capabilities
  - Improved forecasting of upper atmospheric humidity
  - Design and deployment of humidity sensors on commercial aircraft

- Large-scale contrail avoidance trials
  - At the scale of several air traffic management sectors: thousands of flights
  - Many eyes on the same region: on-board measurements, forecasters, contrail modellers, climate scientists, satellite observations