Contrail Avoidance: What are the issues from a climate science (or, at least, my) perspective?

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Aviation Reimagined: October 2024

Thanks historically to many colleagues at Reading (especially Emma Klingaman (née Irvine)) and beyond. – they don't (all) necessarily share my views

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Some key questions

1. Can contrails be avoided? YES, and we've known how to for about 70 years!
2. Most importantly: can they be avoided <u>now</u> in a way

(a) that the potential climate benefit can be reliably quantified? NO

(b) that we can guarantee perverse outcomes (i.e., *greater* climate change) are avoided? NO

4. Might it be possible sometime in the future? YES – it can be demonstrated in a "perfect model" environment where we know exactly where contrails will form and have a robust knowledge of their properties

Environmental Research Communications
10.1088/2515-7620/ad6ee5
PAPER

The effect of uncertainty in humidity and model parameters on the prediction of contrail energy forcing

John C Platt[1,*], Marc L Shapiro[2], Zebediah Engberg[2], Kevin McCloskey[1], Scott Geraedts[1], Tharun Sankar[1], Marc E J Stettler[3], Roger Teoh[3], Ulrich Schumann[4], Susanne Rohs[5], Erica Brand[1] and Christopher Van Arsdale[1]

Atmos. Chem. Phys., 24, 5009–5024, 2024
https://doi.org/10.5194/acp-24-5009-2024

Atmospheric Chemistry and Physics
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EGU

Distribution and morphology of non-persistent contrail and persistent contrail formation areas in ERA5

Kevin Wolf[1,a], Nicolas Bellouin[1,2], and Olivier Boucher[1]
[1]Institut Pierre-Simon Laplace, Sorbonne Université/CNRS, Paris, France
[2]Department of Meteorology, University of Reading, Reading, United Kingdom

Environmental Science & Technology
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pubs.acs.org/est
Article

Revisiting Contrail Ice Formation: Impact of Primary Soot Particle Sizes and Contribution of Volatile Particles

Fangqun Yu,* Bernd Kärcher, and Bruce E. Anderson

https://doi.org/10.5194/egusphere-2024-1573
Preprint. Discussion started: 1 July 2024

EGUsphere
Preprint repository

Impact of host climate model on contrail cirrus effective radiative forcing estimates

Weiyu Zhang[1], Kwinten Van Weverberg[2,3,4], Cyril J. Morcrette[4,5], Wuhu Feng[1,6], Kalli Furtado[4,7], Paul R. Field[1,4], Chih-Chieh Chen[8], Andrew Gettelman[9], Piers M. Forster[1], Daniel R. Marsh[10], Alexandru Rap[1*]

/ad5b78
ENVIRONMENTAL RESEARCH
LETTERS
LETTER

Operational differences lead to longer lifetimes of satellite detectable contrails from more fuel efficient aircraft

Edward Gryspeerdt[1,2,*], Marc E J Stettler[3], Roger Teoh[3], Ulrike Burkhardt[4], Toni Delovski[5], Oliver G A Driver[2] and David Painemal[6,7]

Contents lists available at ScienceDirect
Atmospheric Research
journal homepage: www.elsevier.com/locate/atmosres
ELSEVIER

On the fidelity of high-resolution numerical weather forecasts of contrail-favorable conditions

Gregory Thompson[*], Chloé Scholzen, Scott O'Donoghue, Max Haughton, Roderic L. Jones, Adam Durant[*,1], Conor Farrington
SATAVIA, Ltd, Cambridge, UK

Atmos. Chem. Phys., 24, 10409–10424, 2024
https://doi.org/10.5194/acp-24-10409-2024

Atmospheric Chemistry and Physics
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Simulated contrail-processed aviation soot aerosols are poor ice-nucleating particles at cirrus temperatures

Baptiste Testa[1], Lukas Durdina[2], Jacinta Edebeli[2], Curdin Spirig[2], and Zamin A. Kanji[1]

Atmos. Chem. Phys., 24, 7911–7925, 2024
https://doi.org/10.5194/acp-24-7911-2024

Atmospheric Chemistry and Physics
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How well can persistent contrails be predicted? An update

Sina Hofer[1], Klaus Gierens[1], and Susanne Rohs[2]
[1]Institut für Physik der Atmosphäre, Deutsches Zentrum für Luft- und Raumfahrt, Oberpfaffenhofen, Germany
[2]Forschungszentrum Jülich, IEK-8, Jülich, Germany

ENVIRONMENTAL RESEARCH
INFRASTRUCTURE AND SUSTAINABILITY

Feasibility of contrail avoidance in a commercial flight planning system: an operational analysis

A Martin Frias[1,3,*], M L Shapiro[2], Z Engberg[2], R Zopp[1], M Soler[3] and M E J Stettler[4]

Atmos. Chem. Phys., 24, 9219–9262, 2024
https://doi.org/10.5194/acp-24-9219-2024

Atmospheric Chemistry and Physics
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EGU

Understanding the role of contrails and contrail cirrus in climate change: a global perspective

Dharmendra Kumar Singh, Swarnali Sanyal, and Donald J. Wuebbles
Department of Climate, Meteorology & Atmospheric Sciences (CliMAS), University of Illinois Urbana-Champaign, Urbana, IL 61801, USA

Very active research area – just a few recent (2024) papers

Mitigation of aviation's climate impact by contrail avoidance: What could possibly go wrong?

Multiple uncertainties

- Can we reliably predict (persistent) contrail formation?
- Can we reliably predict contrail properties over their lifetime?
- Can we reliably predict contrail *radiative* properties over their lifetime?
- Can we reliably predict the *climate* impact of the contrails?
- Do we know how best to compare CO_2 and non-CO_2 climate impacts?

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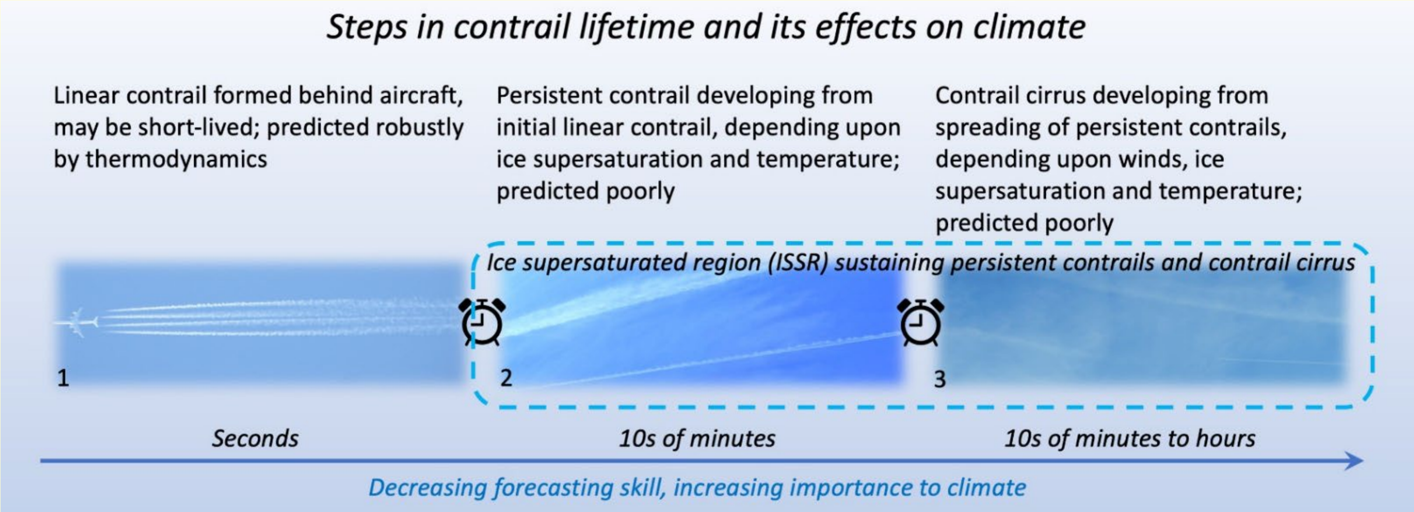
Some contrail basics

- Contrails are "mixing clouds" much like seeing breath on a cold day. Unsaturated air parcels mix and can saturate
- Normally that cloud dissipates quickly as the contrail mixes with more surrounding air
- In the upper troposphere, the surrounding air *can* be "supersaturated with respect to ice" (ISSRs)
- The supersaturated air can condense on the frozen droplets forming ***persistent*** contrails; these can spread to form ***contrail cirrus.***



Lee et al. (2023) Env.Sci:Atmospheres 10.1039/d3ea00091e

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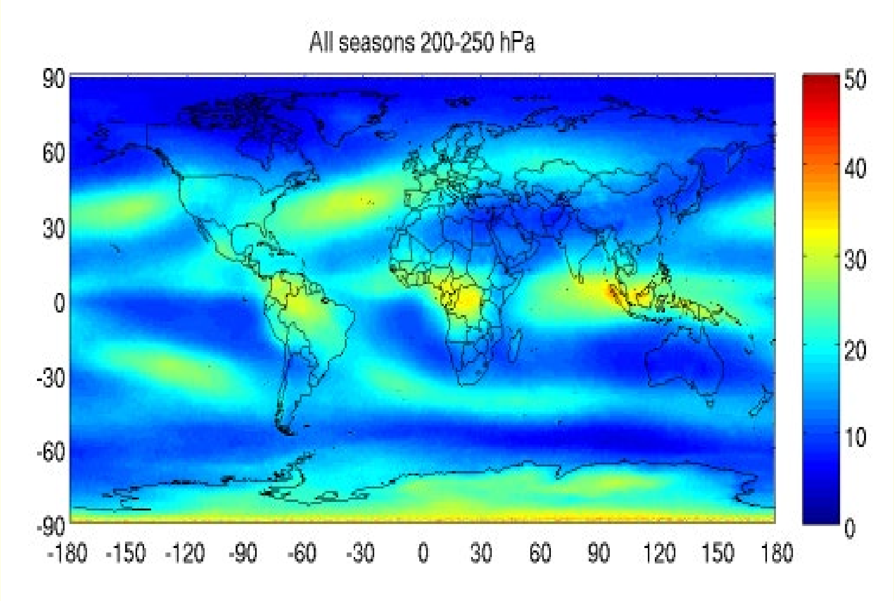
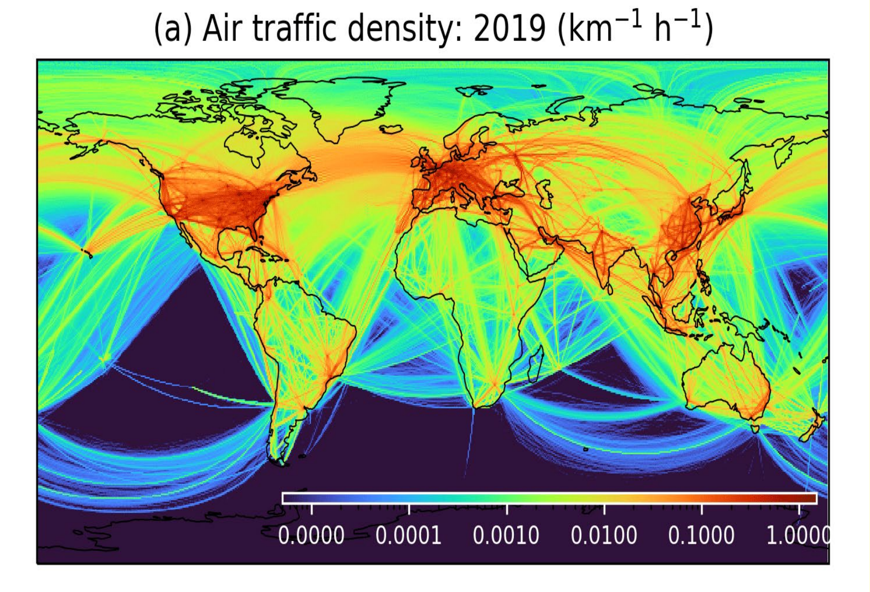
ISSRs frequency; co-location with air traffic determines contrail cirrus distributions





Ice supersaturation occurrence frequencies (from aircraft-calibrated satellite retrievals)

Lamquin et al. 2012 10.5194/acp-12-381-2012

Teoh et al. 2024
10.5194/acp-24-725-2024

ISSRs are patchy in time and in the vertical and horizontal; they are determined by the prevailing weather conditions

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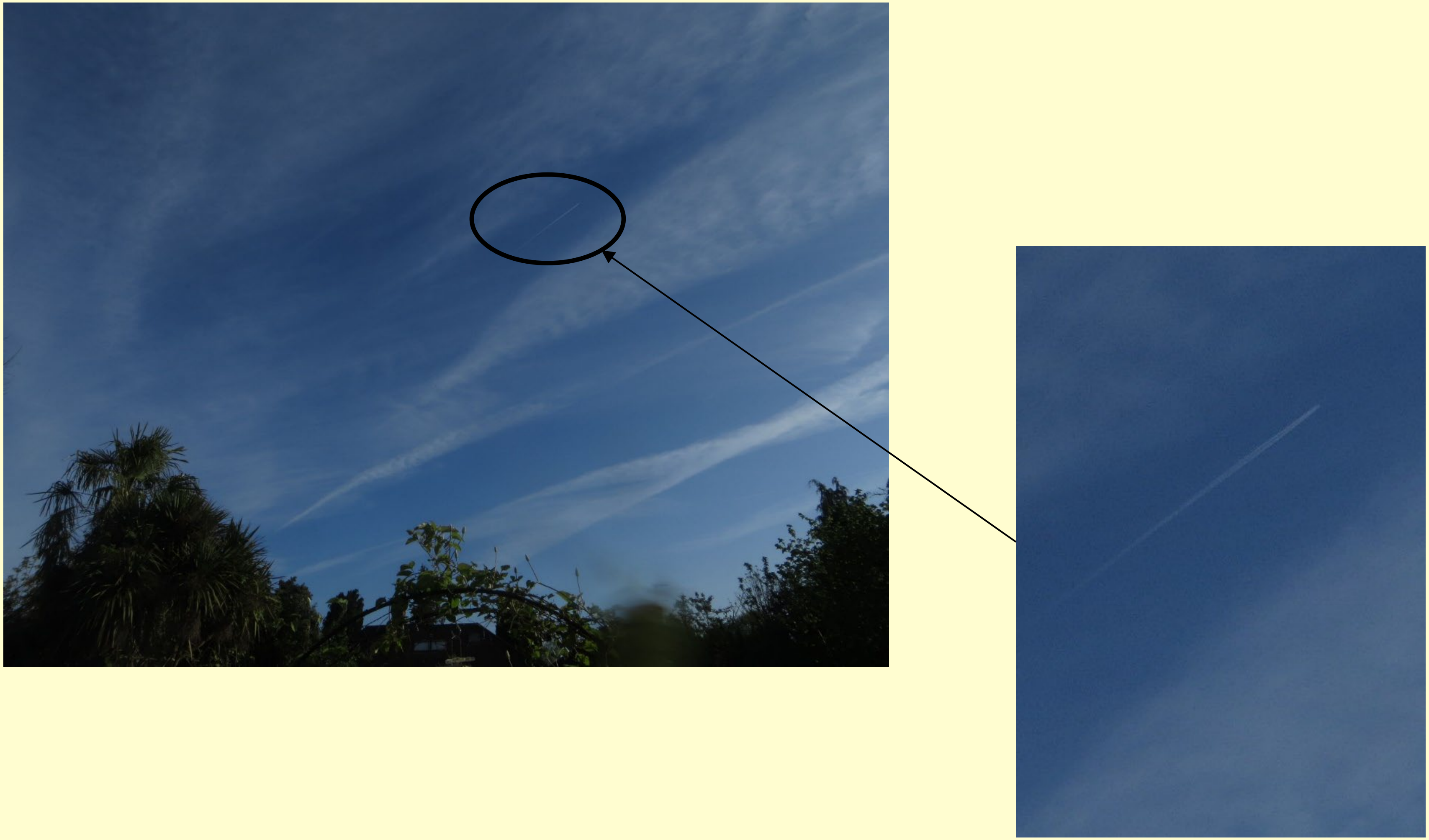
Sometimes persistent, sometimes not



Outcomes of 2021 Maastricht Contrail Avoidance Trial

- Pioneering study of Sausen et al. 2023 (10.1127/metz/2023/1157) where “real-time” decisions were made on whether aircraft could be rerouted based on weather forecasts
- My interpretation of their results
- On 55% of occasions, contrails were predicted but not observed
- On occasions when contrails were either predicted or occurred, the forecast was right only 36% of the time

Cases (3398) where no avoidance action was taken		**Persistent Contrails Predicted**	
		Yes	No
Persistent Contrails Observed	Yes	442	248
	No	543	2165

Wilhelm, L.; Gierens, K.; Rohs, S. (2022) *Appl. Sci. 12*. 10.3390/app12094450

“unreliable prediction of relative humidities is one reason why contrail prediction is not possible for flight routing”

Hofer,S,; Gierens, K and Rohs, S. (2024) 10.5194/acp-24-7911-2024

“the prediction of contrail persistence [is] very difficult”

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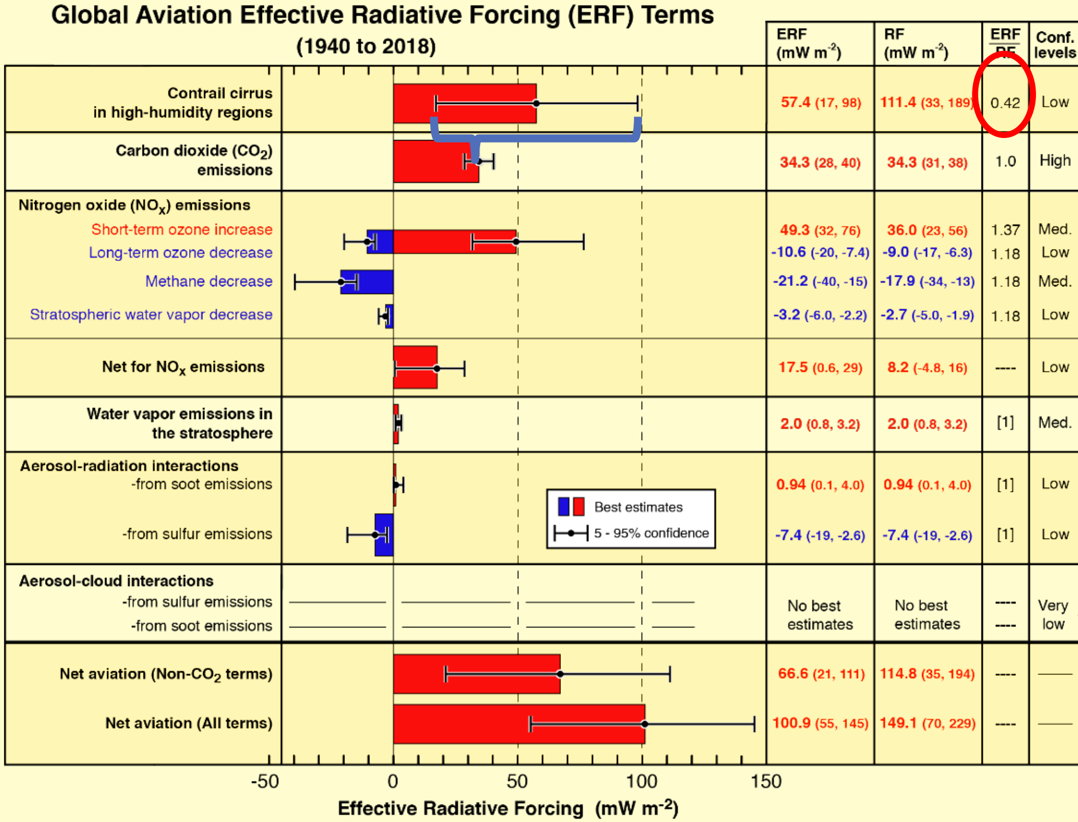
Radiative Forcing due to Aviation



Contrail uncertainty is huge! Could be anything between ≈0.5 and ≈ 3x that of CO_2

Other non-CO_2 aviation forcings depend on the “where and when” of emissions

Some of this *highly uncertain* forcing may originate from processing of soot particles in contrails. Size and sign remains poorly constrained

Aviation CO_2 RF (about 35 mW m^{-2}) causes about 1.5% of the total effect of CO_2 from human activities

When non-CO_2 effects are included, aviation contributes 1.3 to 14% of the total climate effect of human activities (neglecting any aerosol-cloud forcing)

Lee et al. (2021) Atmospheric Environment 10.1016/j.atmosenv.2020.117834

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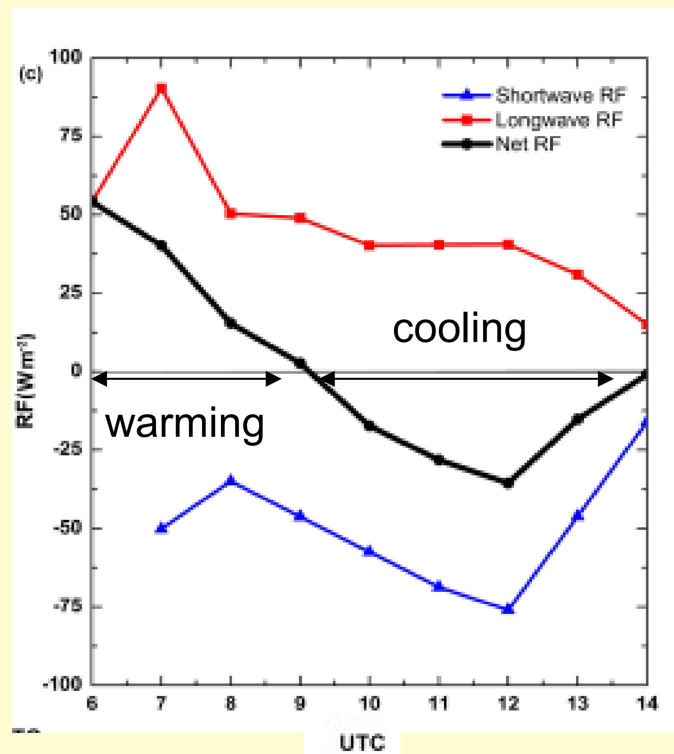
Contrail case studies – compensation between (modelled) longwave and shortwave forcing

Key points

1. The net forcing is a relatively small residual of shortwave ("solar") forcing and longwave ("infrared") forcing; the **sign** of the net forcing can vary
2. This net forcing **evolves** during the contrail-cirrus lifetime; it needs to be tracked as it moves with the wind, as insolation changes, and as cloud properties change

Observations of microphysical properties and radiative effects of a contrail cirrus outbreak over the North Atlantic

Ziming Wang[1,2], Luca Bugliaro[1], Tina Jurkat-Witschas[1], Romy Heller[1], Ulrike Burkhardt[1], Helmut Ziereis[1], Georgios Dekoutsidis[1], Martin Wirth[1], Silke Groß[1], Simon Kirschler[1,3], Stefan Kaufmann[1], and Christiane Voigt[1,3]



10.5194/acp-23-1941-2023

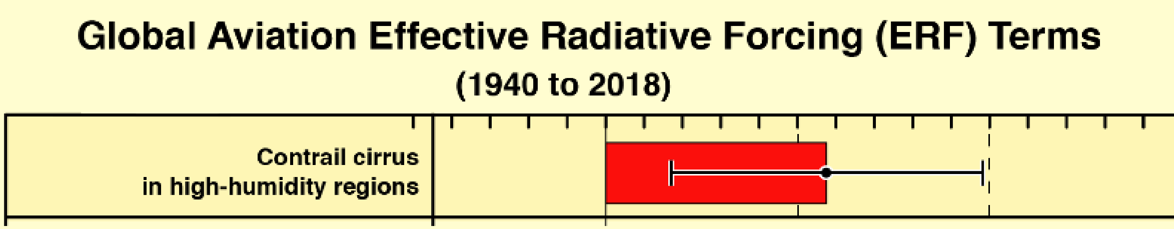
Radiative Forcing is a proxy for climate change

RADIATIVE FORCING (RF): The change in top-of-atmosphere energy budget due to e.g., contrails, in absence of (almost) any other change

Most contrail-climate studies calculate this

EFFECTIVE RADIATIVE FORCING (ERF): RF plus any "rapid adjustments" - atmospheric changes (e.g., cloudiness, humidity) that occur in absence of any surface temperature change.

IPCC's preferred forcing definition. Adjustments need to be calculated using Earth System Models - **very few studies** for contrails. All indicate ERF/RF between 0.31 and 0.65 - see Lee et al. (2021) assessment and Bickel DLR PhD thesis.



	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

Contrails occur at the "expense" of natural cirrus clouds

Bickel 10.57676/mzmg-r403; Bickel et al. 2020: 10.1175/JCLI-D-19-0467.1

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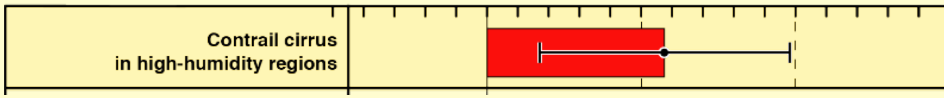
Understanding of contrail RF is still evolving

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

Since Lee et al. (2021) e.g.,

- Zhang et al. (2024): “contrail cirrus ERF of the year 2018 to be 41 $mW\ m^{-2}$ in the UM and 60 $mW\ m^{-2}$ in CAM …[and] find a factor of 8 uncertainty … due to existing uncertainty in contrail cirrus optical depth

Since Lee et al. (2021) e.g.,

- Bier and Burkhardt (2022): parameterizing microphysical processes in the jet and vortex phase: “Global mean RF is **44** $mW\ m^{-2}$ … 22% lower than … (our) previous study”
- Teoh et al. (2024) “we estimate that the 2019 global contrail net RF could range between **34.8** and **74.8** $mW\ m^{-2}$”
- Quaas et al. (2021) … satellite observations of COVID impact “… translates to a global RF of **61** ± 39 $mW\ m^{-2}$.”

All are lower than the Lee et al. best estimate

Teoh et al. 10.5194/acp-24-6071-2024;
Zhang et al. 10.5194/egusphere-2024-157
Quaas et al. 10.1088/1748-9326/abf686;
Bier and Burkhardt 10.1029/2022JD036677

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Radiative Forcing is ***only*** a proxy for climate change!

RADIATIVE FORCING (RF):

EFFECTIVE RADIATIVE FORCING (ERF):

SURFACE TEMPERATURE CHANGE ΔT_S: impact of ERF on surface temperature, including climate feedbacks driven by this surface temperature change

Equilibrium surface temperature response

$$\Delta T_s \approx \lambda \, RF$$

λ is climate sensitivity in K (W m^{-2})$^{-1}$

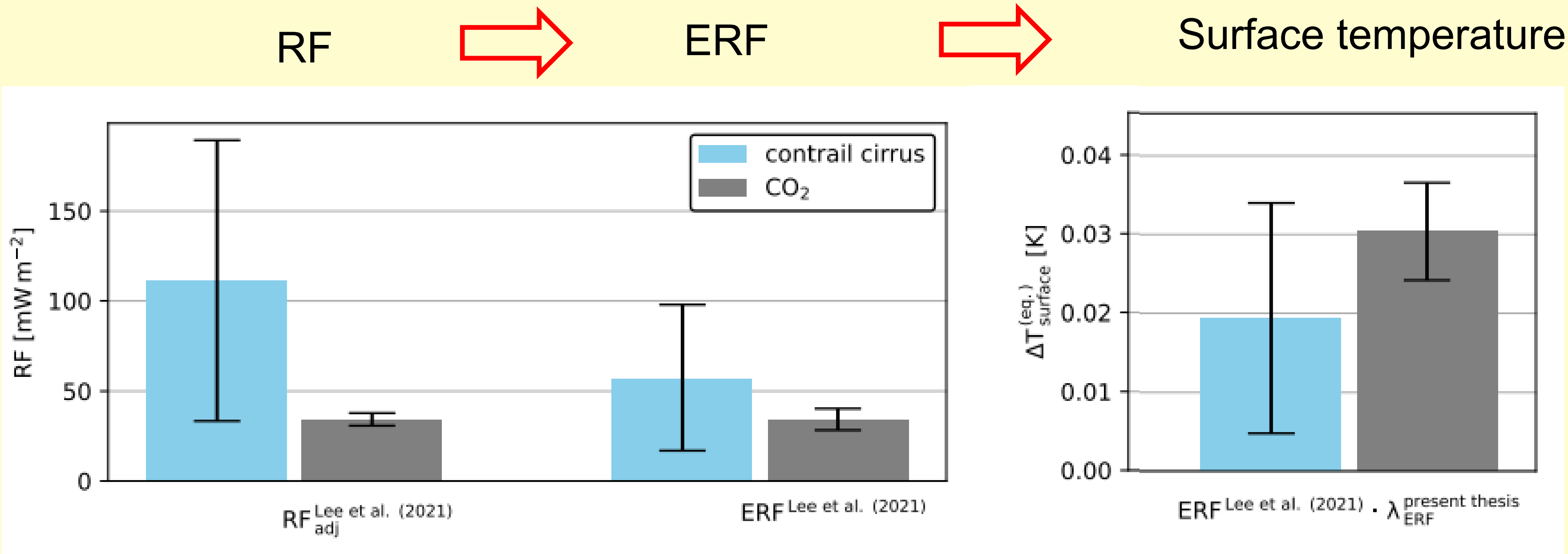
λ is a chronic climate science uncertainty, that also depends on the nature of the radiative forcing (Ponater et al., 2021). Only one contrail calculation … so far.

Bickel's results indicate contrails *may* have **much reduced** efficacy (about 0.4 of λ_{CO2}) due to distinct cloud feedbacks

This reduction acts **in addition** to the ERF/RF reduction

Ponater et al. https://doi.org/10.3390/aerospace8020042
Bickel 10.57676/mzmg-r403

Simple illustration of how perspective of contrail importance can change



- Based on ERF and efficacy computed in a single ESM

Bickel 10.57676/mzmg-r403

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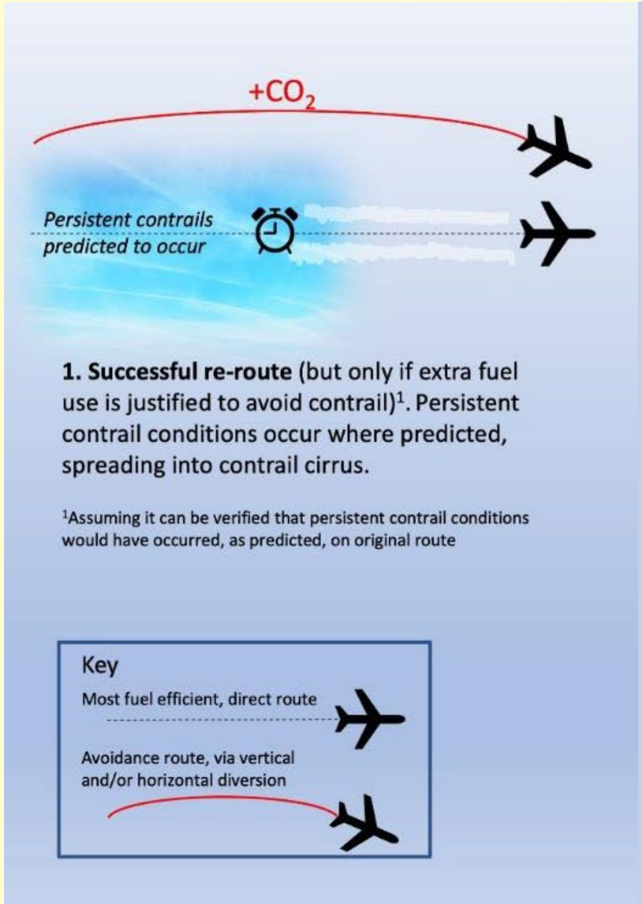
Contrail avoidance – potential outcomes



Lee et al. (2023) Env.Sci:Atmospheres 10.1039/d3ea00091e

Accepting that minimum *fuel* routes are not necessarily minimum *cost* routes, and several alternative minimum fuel routes may be present on a given day …

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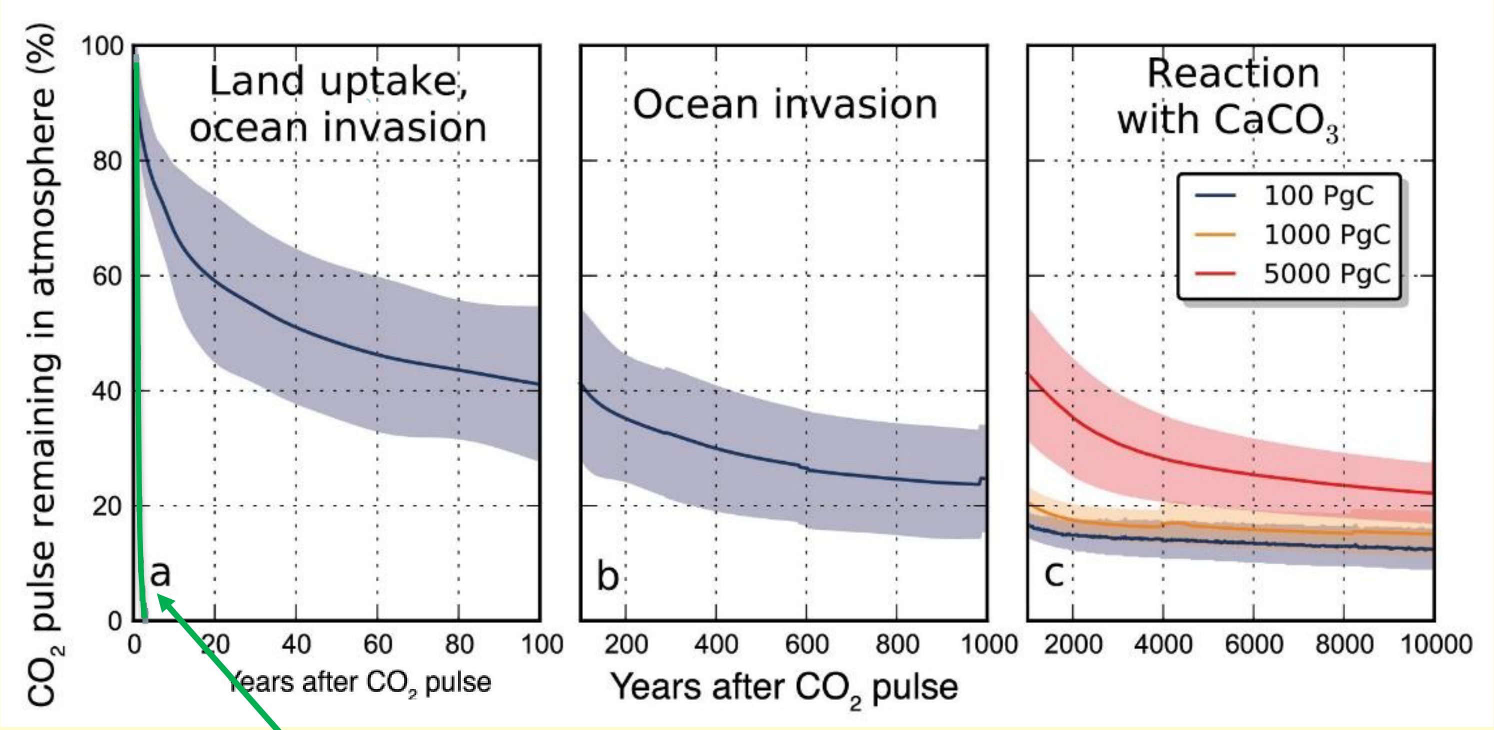
Comparing contrail climate effects with CO_2

The long persistence time of CO_2 – one of its most troublesome aspects

Pulse of CO_2 (100 PgC) emitted at time zero

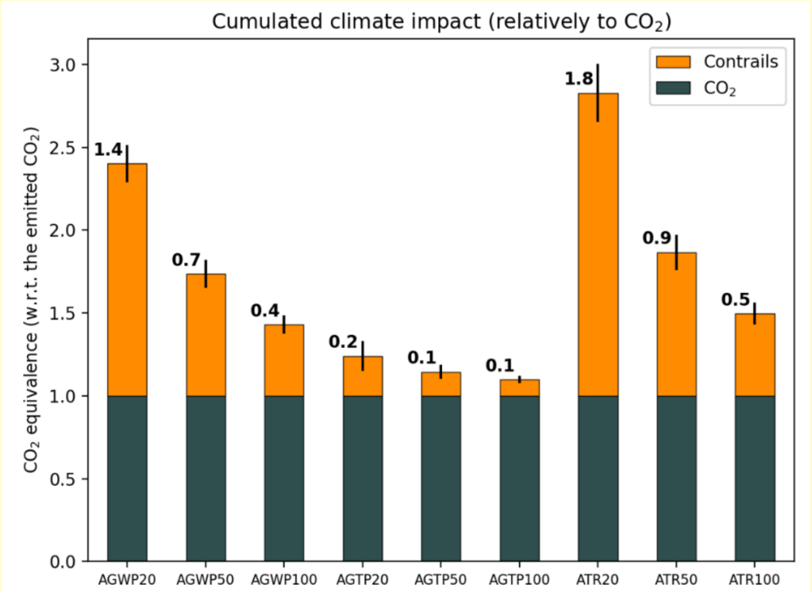


A contrail (with a hugely exaggerated lifetime!)

IPCC AR5 WG1 (2013) Box 6.1 Figure 1

Metric and efficacy uncertainties

Recent study by Borella et al. 2024 ACP
CO_2 equivalence of North Atlantic flights in 2019 depends on metric choice and time horizon choice
(Uncertainties in contrail forcing and efficacy not represented here)



Global warming potential | Global temperature potential | Average temperature response

The metric should match the policy aim

10.5194/acp-24-9401-2024

See also:

https://doi.org/10.1038/s43247-024-01423-6

Alternative climate metrics to the Global Warming Potential are more suitable for assessing aviation non-CO_2 effects

Check for updates

Liam Megill[1,2], Kathrin Deck[2] & Volker Grewe[1,2]

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Concluding … issues that need addressing

- Reliable forecasting of the occurrence of ice-supersaturated regions
- Reliable forecasting of the *degree* of ice supersaturation (which helps determine the radiative properties of contrails)
- Knowing the size of the radiative forcing of contrails (or the avoided contrail) with sufficient confidence
- Verifiable knowledge of the climate impact of the contrail (or an avoided contrail) over its entire lifetime (or avoided lifetime)
- Consensus on how to compare the climate effect of any extra CO_2 emissions with those of an avoided contrail

My view: the Technology Readiness Level for climate mitigation via contrail avoidance is in the "exploratory" phase (**TRL≈2** – would need to be 9 for application)

It can be demonstrated in a "perfect model" environment; we are well short of doing so in the real world

Any increase in CO_2 emissions as part of a mitigation strategy appears risky, when multiple uncertainty factors are at play

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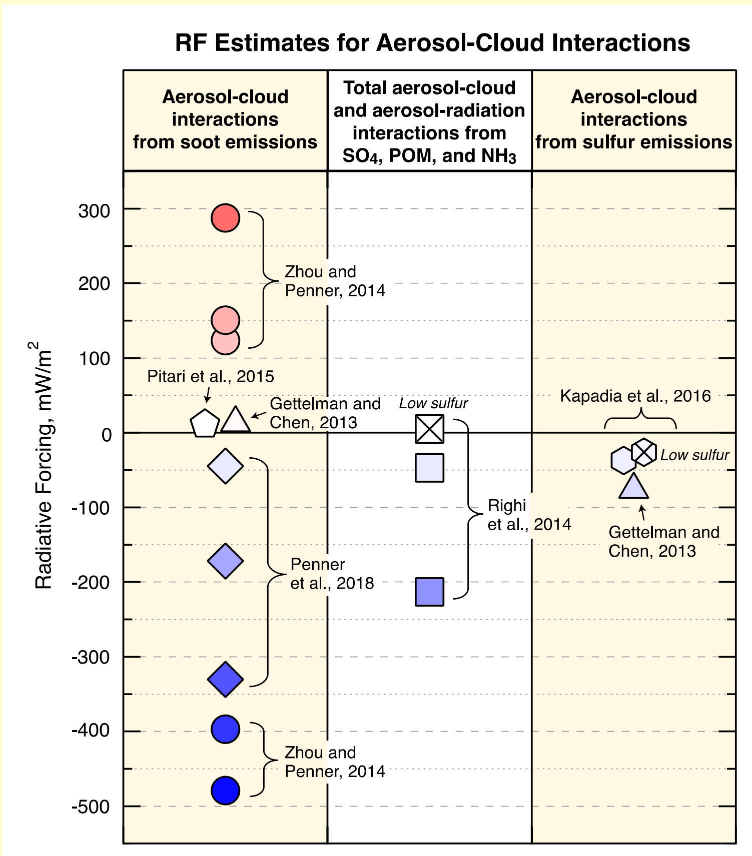
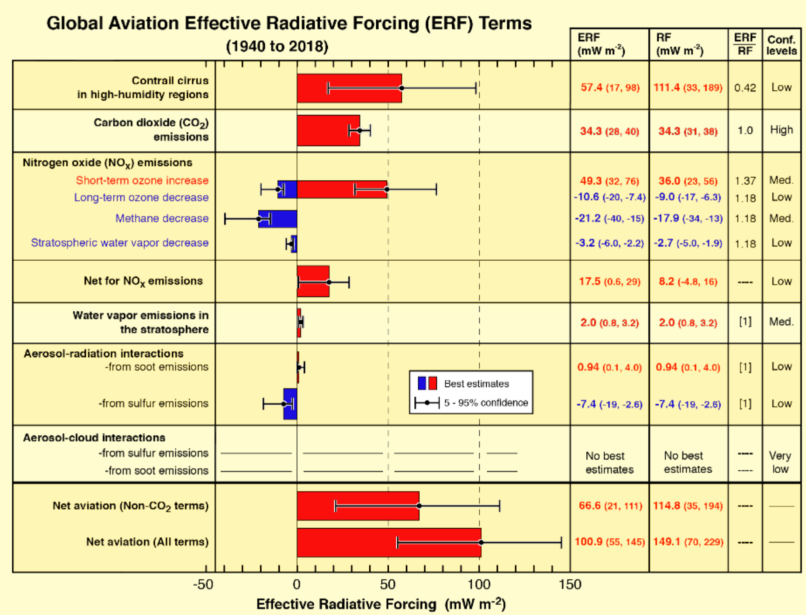
Aerosol-cloud interactions

- A key uncertainty – aviation soot "processed" in contrails may affect the radiative properties of other clouds



Key takeaway – no best estimates are available for aerosol-cloud interactions and the net sign is unconstrained but the forcing is potentially large



Lee et al. (2021) Atmospheric Environment

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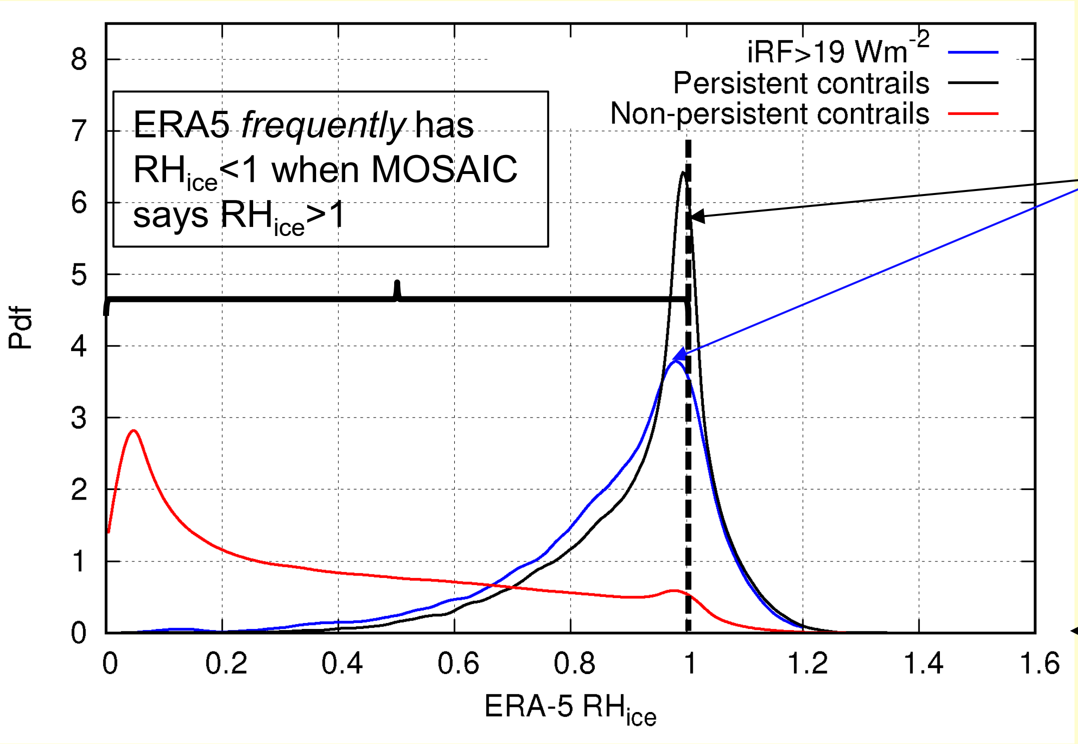
How well are ISSRs forecast?

- In-situ observations of relative humidity (IAGOS/MOZAIC) from in service aircraft (mainly Europe/N.America/N. Atlantic) with one major meteorological ("ERA5") reanalyses (not forecasts!)



MOZAIC data indicates persistent (black) or particularly thick ones (blue) contrails

The ERA5 humidity at the same times and locations

Wilhelm, L.; Gierens, K.; Rohs, S. (2022) *Appl. Sci. 12*. 10.3390/app12094450

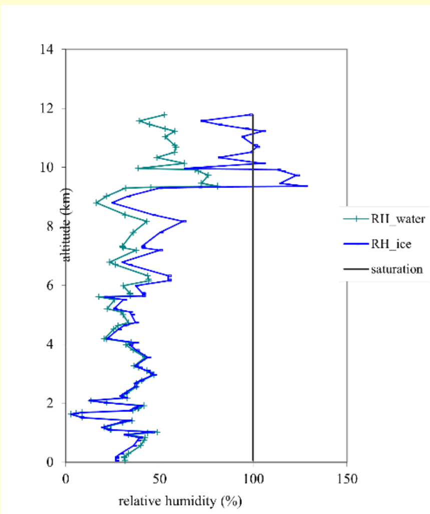
"unreliable prediction of relative humidities is one reason why contrail prediction is not possible for flight routing"

Hofer,S,; Gierens, K and Rohs, S. (2024) 10.5194/acp-24-7911-2024

"the prediction of contrail persistence [is] very difficult"

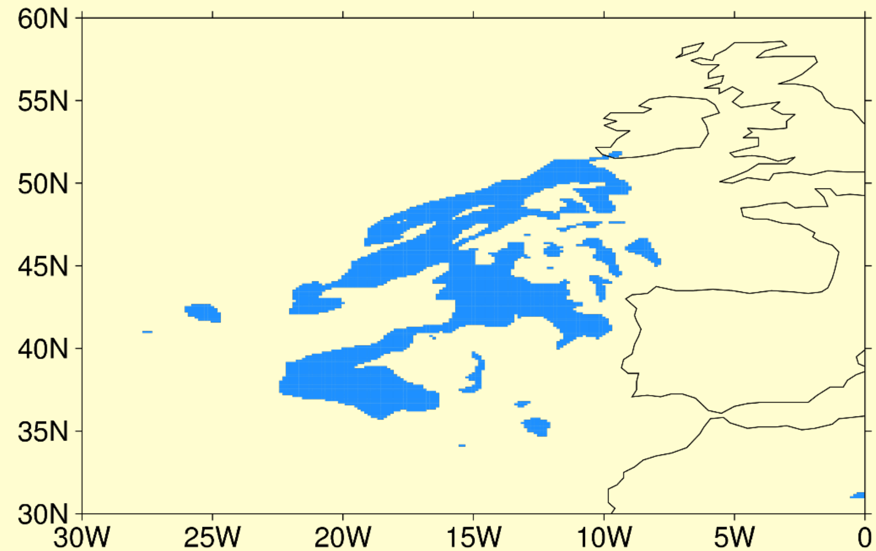
Ice super-saturated regions (ISSR)

ISSR layers have mean depth of ≈1 km but this is very variable and can have complex vertical structure



Relative Humidity Profiles wrt to water and ice
Herstmonceux, UK
12:00 on 5 May 2016

… and very patchy on a day-to day basis in the horizontal



ECMWF Analysis (best estimate) of ISSRs
FL390 12:00 06 January 2016
From Emma Irvine and Jenny Handsley

The vertical, horizontal and temporal patchiness of ISSRs is a serious issue for contrail avoidance strategies

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In a perfect-model world …

What if we knew *exactly* where the ISSRs are, and *exactly* what radiative forcing any contrail (or avoided contrail) cause?

e.g. Case study as part of long-finished EU project ATM4E, led by Sigrun Matthes, DLR, Germany

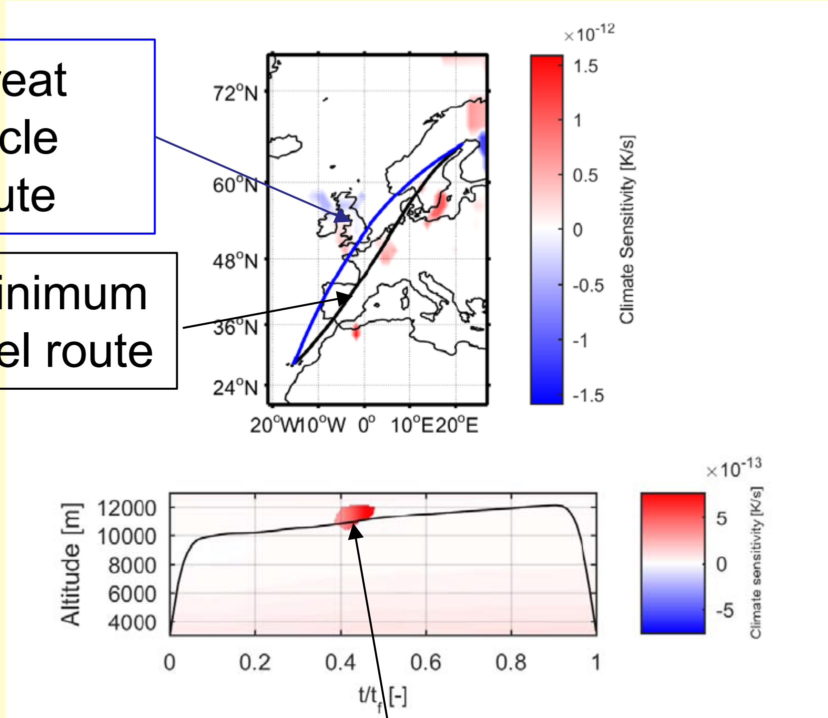
ATM4E SESAR JOINT UNDERTAKING

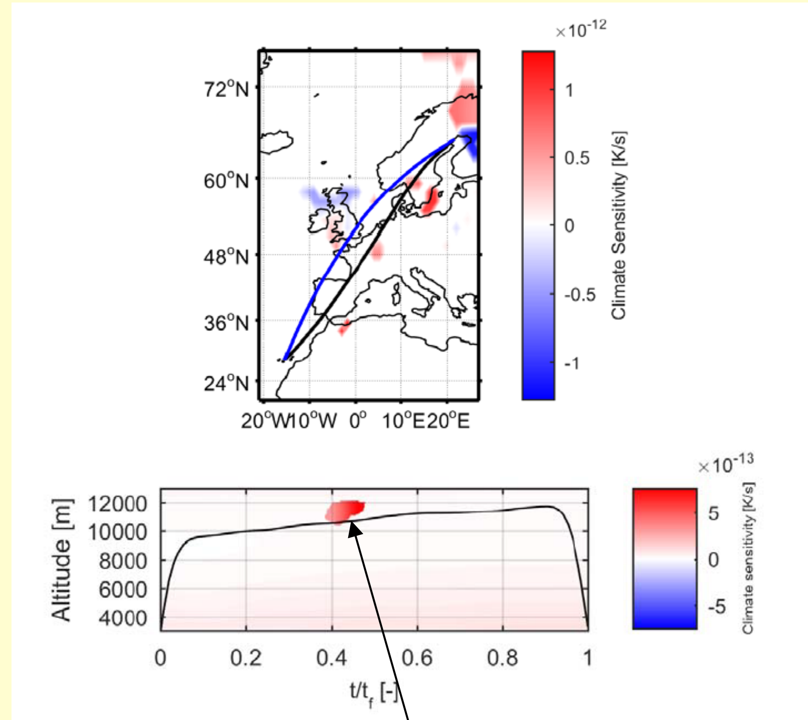
See how re-routing would change "total" climate impact

Case Study Lulea (Finland) to Gran Canaria

Great circle route

Minimum fuel route





An ISSR patch which would cause positive contrail RF if flown through

Vertical deviation avoids most of ISSR:
increases fuel use by 0.5%,
reduces climate impact by 8-10% for a range of climate metrics

Matthes et al. 2020 10.3390/aerospace7110156

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