Contrails Avoidance – Challenges

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Some key questions

1. Can contrails be avoided? YES, and we've known how 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

Issues that need addressing

- Can we reliably forecast the occurrence of ice-supersaturated regions? *Necessary but not sufficient*
- Can we reliably forecast the *degree* of ice supersaturation (which helps determine the radiative properties of contrails)? *Necessary but not sufficient*
- Do we know the size of the global-mean effective radiative forcing (ERF) of contrails with sufficient confidence? *Necessary but not sufficient*
- Can we reliably calculate the climate impact of the contrail (or an avoided contrail) over its entire lifetime (or avoided lifetime!)? *Necessary*
- How do we compare the climate effect of any extra CO_2 emissions with those of an avoided contrail? *Necessary*

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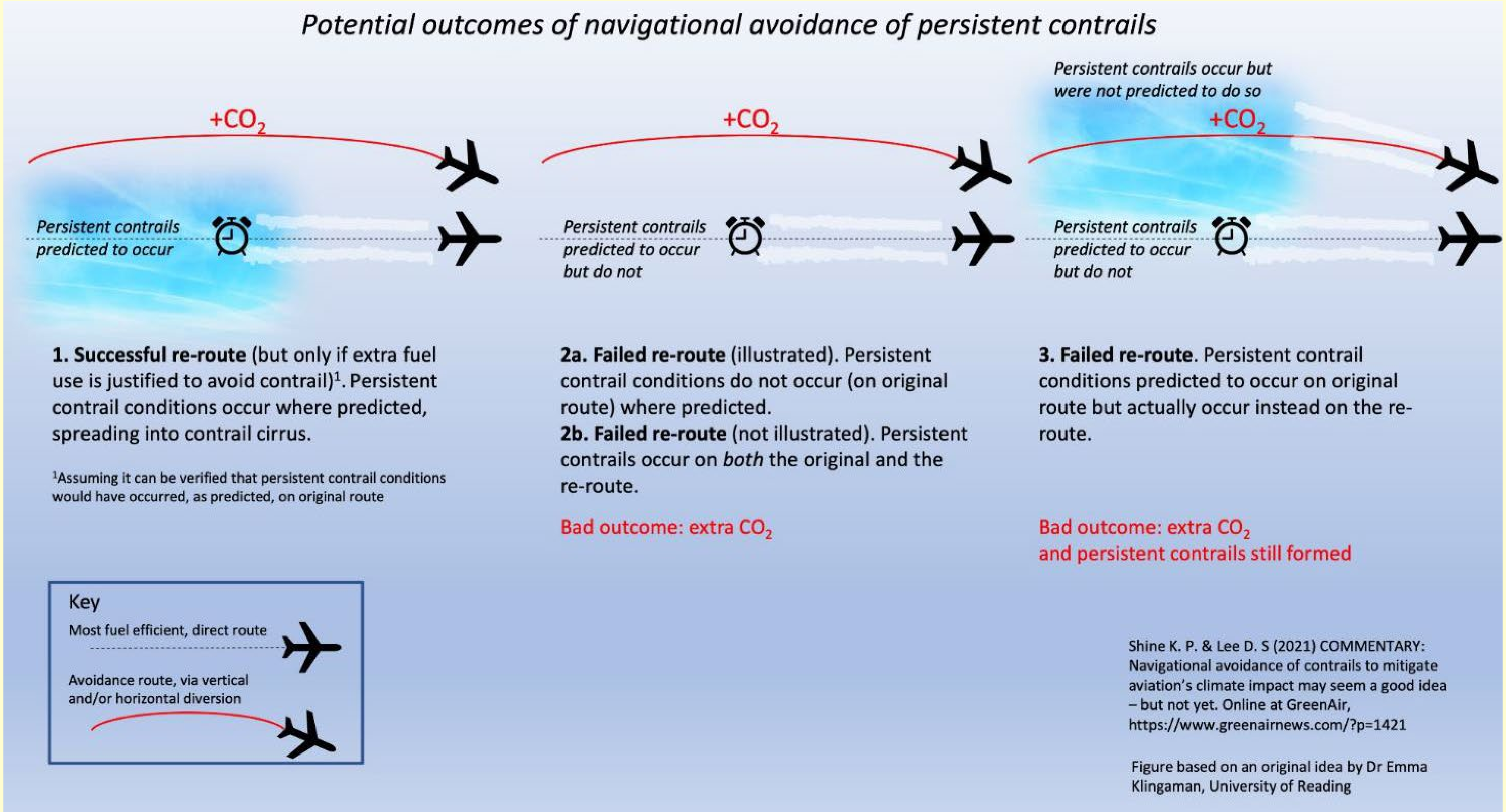
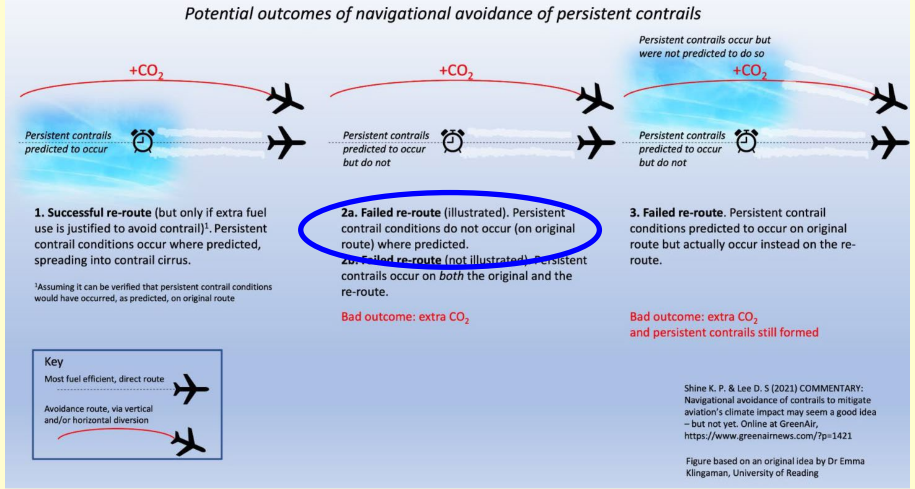
Contrail avoidance?



Outcomes of 2021 Maastricht Contrail Avoidance Trial

- Pioneering study of Sausen et al. 2023 (10.1127/metz/2023/1157)
- Our interpretation of their results
- Case 2a Failed Reroute: 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



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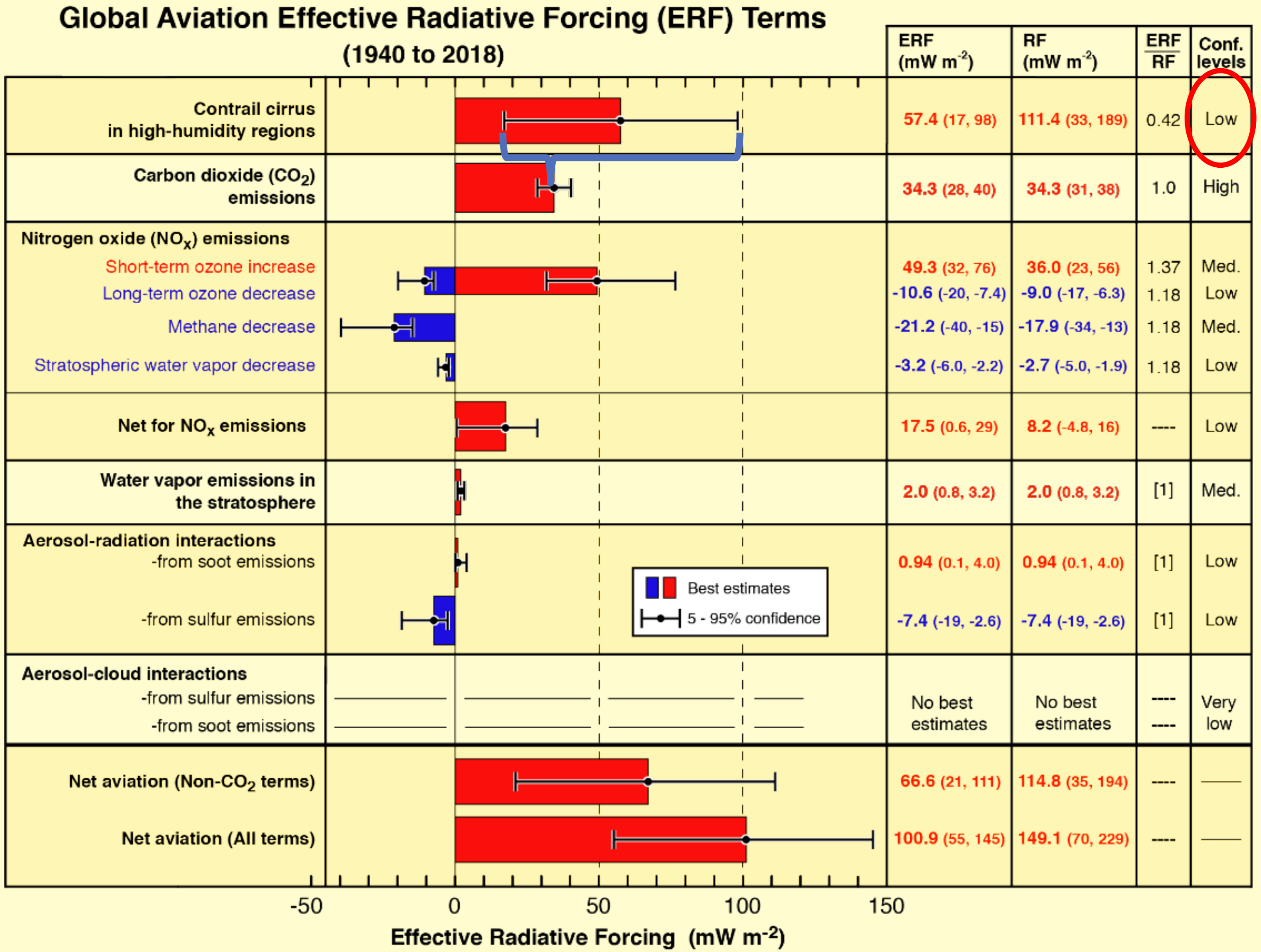
Climate Impact of Aviation



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

Some of this *highly uncertain* forcing originates from processing of soot particles in contrails

Lee et al. (2021) Atmospheric Environment https://doi.org/10.1016/j.atmosenv.2020.117834

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Radiative Forcing is a proxy for climate change

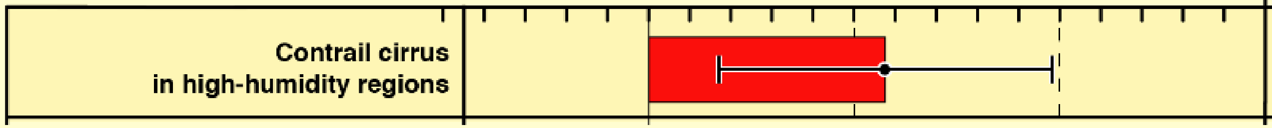
RADIATIVE FORCING (RF): The change in top-of-atmosphere energy budget due to a constituent (e.g., contrails or more CO_2) in absence of (almost) any other change

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 preferred forcing definition. Adjustments need to be calculated using Earth System Models - **few studies** for contrails. All indicate ERF/RF between 0.31 and 0.65 - see Lee et al. (2021) assessment and Bickel et al. Contrails reduce natural cirrus cloudiness

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

Bickel et al. https://elib.dlr.de/196064/1/IUGG2023_Bickel_et_al_poster_portrait_final.pdf

Understanding of contrail RF is still evolving

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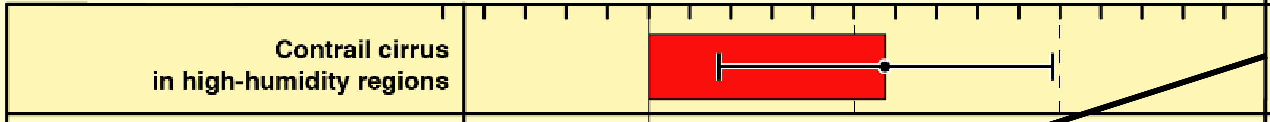

ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Conf. levels
57.4 (17, 98)	111.4 (33, 189)	0.42	Low

Gettelman et al. (2021) "Contrail ERF is estimated at 62 ± 59 mW m^{-2}"

- 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. (2023) "Our 2019 global annual mean contrail net RF (**62.1** mW m^{-2}) is 44 % lower than current best estimates for 2018"
- Quaas et al. (2021) … satellite observations of COVID impact "… translates to a global RF of **61** ± 39 mW m^{-2}."

Teoh et al. 10.5194/egusphere-2023-1859; Quaas et al. 10.1088/1748-9326/abf686
Gettelman et al. 10.5194/acp-21-9405-2021; Bier and Burkhardt 10.1029/2022JD036677

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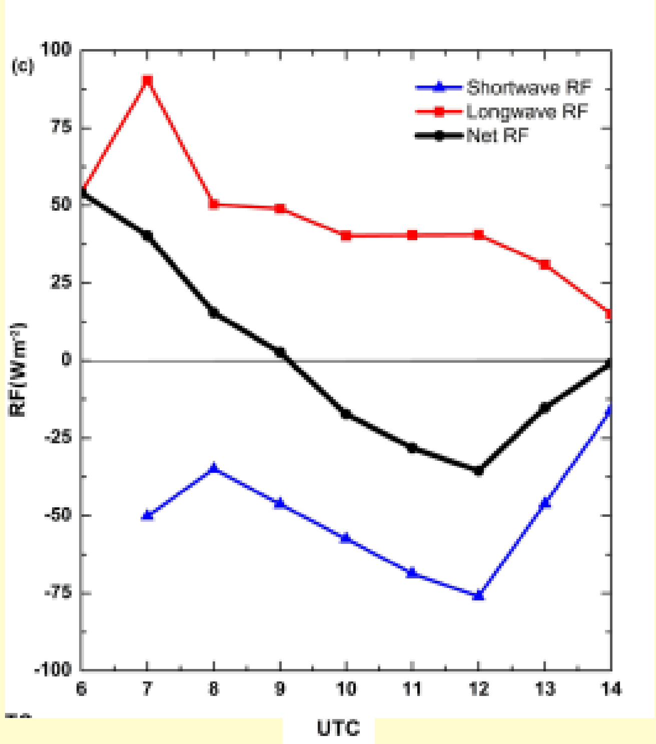
Contrail case studies – compensation between (modelled) longwave and shortwave forcing

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

Key points

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

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

RADIATIVE FORCING (RF): The change in top-of-atmosphere energy budget due to a constituent (e.g., contrails or more CO_2) in absence of (almost) any other change

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

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

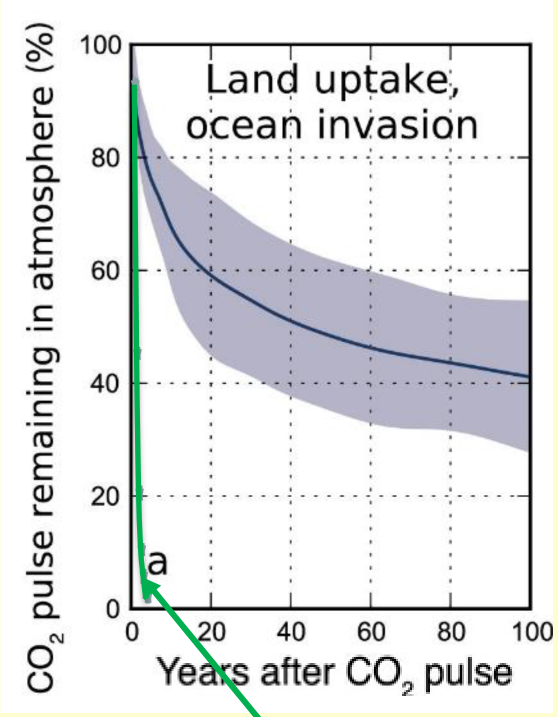
ΔT_S needs to be calculated using Earth System Models – unsafe to assume feedback "efficacy" is the same for ERF from CO_2 and contrails (Ponater et al., 2021). Early Bickel et al. results indicate contrails *may* have **much reduced** efficacy (about 0.4). This would act **in addition** to the ERF/RF reduction

Ponater et al. https://doi.org/10.3390/aerospace8020042
Bickel et al. https://elib.dlr.de/196064/1/IUGG2023_Bickel_et_al_poster_portrait_final.pdf

Comparing contrail climate effects with CO_2

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

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

Calculating the CO_2-equivalence of contrail cirrus formed (or avoided) for a single flight is <u>much</u> more challenging. Global-mean values are not appropriate for this!

<u>Estimated</u> CO_2-equivalence ($TgCO_2\ yr^{-1}$) of contrail cirrus from entire **global** fleet in 2018, calculated using various metrics. CO_2 emissions are ≈ **1000 Tg.**

Metric	Time Horizon		
	20	**50**	**100**
Global warming potential (GWP)	2400	1100	650
Global Temperature Potential (GTP)	700	110	90

From Lee et al. (2021) without uncertainties; GTP values assume efficacy =1

Our take home messages

- Understanding of contrail climate effects is evolving; we are not confident that they are the biggest *current* contributor to aviation-induced climate change
- Even with reliable contrail avoidance, the climate gain is *exceedingly* hard to estimate on a flight-by-flight basis. Perverse outcomes are possible
- For individual flights, alternative minimum-fuel routes may be available, with different *forecast* contrail probabilities. Verification of *actual* climate gain of flying one, rather than another, would be challenging
- Metrics for calculating CO_2-equivalence are a policy-maker choice that must be matched to policy goals. Global-mean values are not appropriate for assessing the climate impact of individual flights
- The Technology Readiness Level for climate mitigation via contrail avoidance is in the "exploratory" phase (TRL≈2). It can be demonstrated in a "perfect model" environment; we are well short of doing so in the real world.