COPENHAGEN CONTRAILS CONFERENCE
25-26 March 2025 · Scandic Copenhagen

09:40-10:20 Masterclass:

What are contrails, how do they impact the climate, and what can be done to stop them from warming the climate?

Marc Stettler
Professor of Transport and Environment, Imperial College London

IMPERIAL

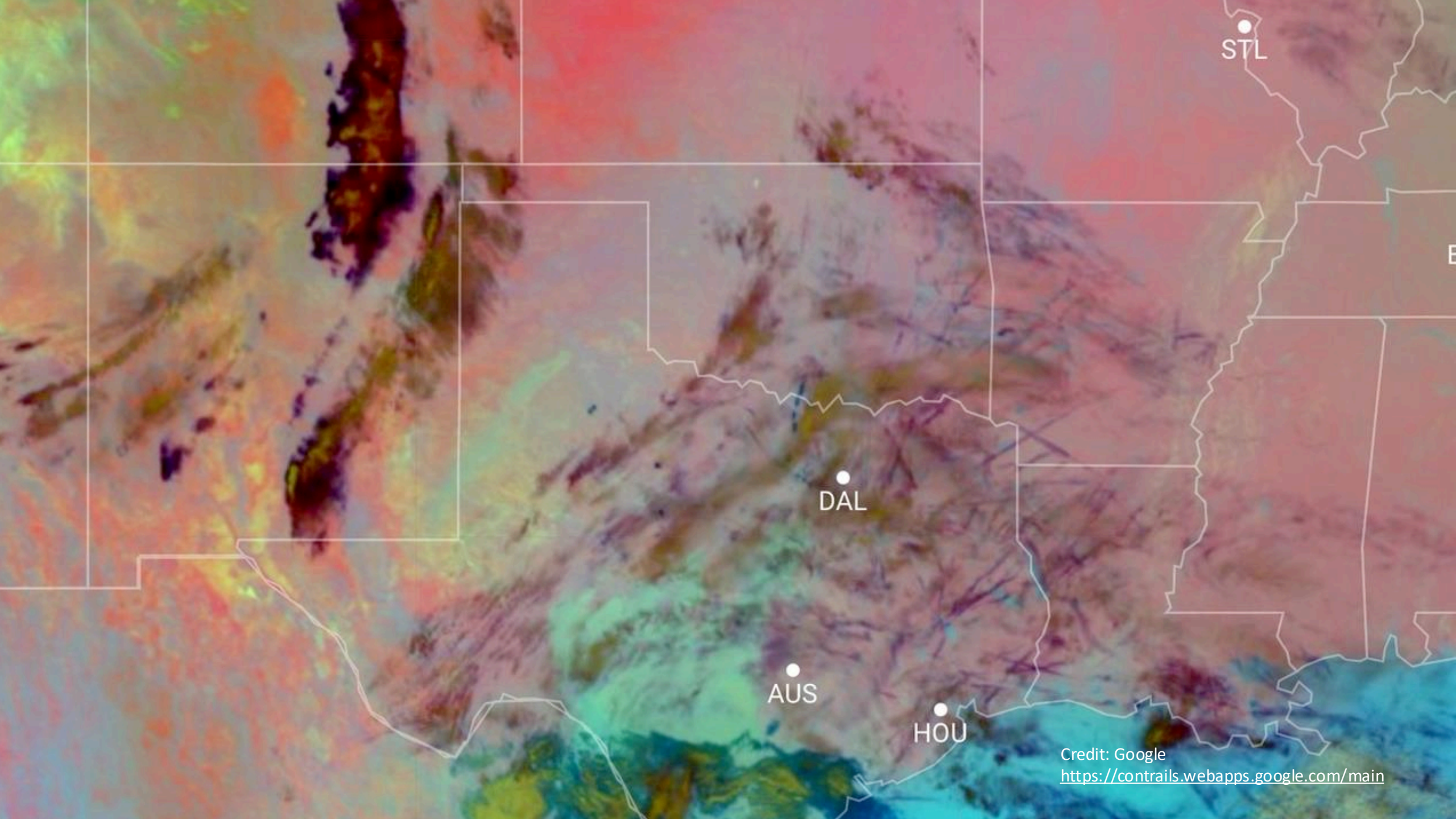
Masterclass:
What are contrails, how do they impact the climate, and what can be done to stop them from warming the climate?

Marc Stettler

Copenhagen Contrail Conference

25th March 2025

Credit: Ed Gryspeerdt
https://amt.copernicus.org/articles/18/37/2025/


STL
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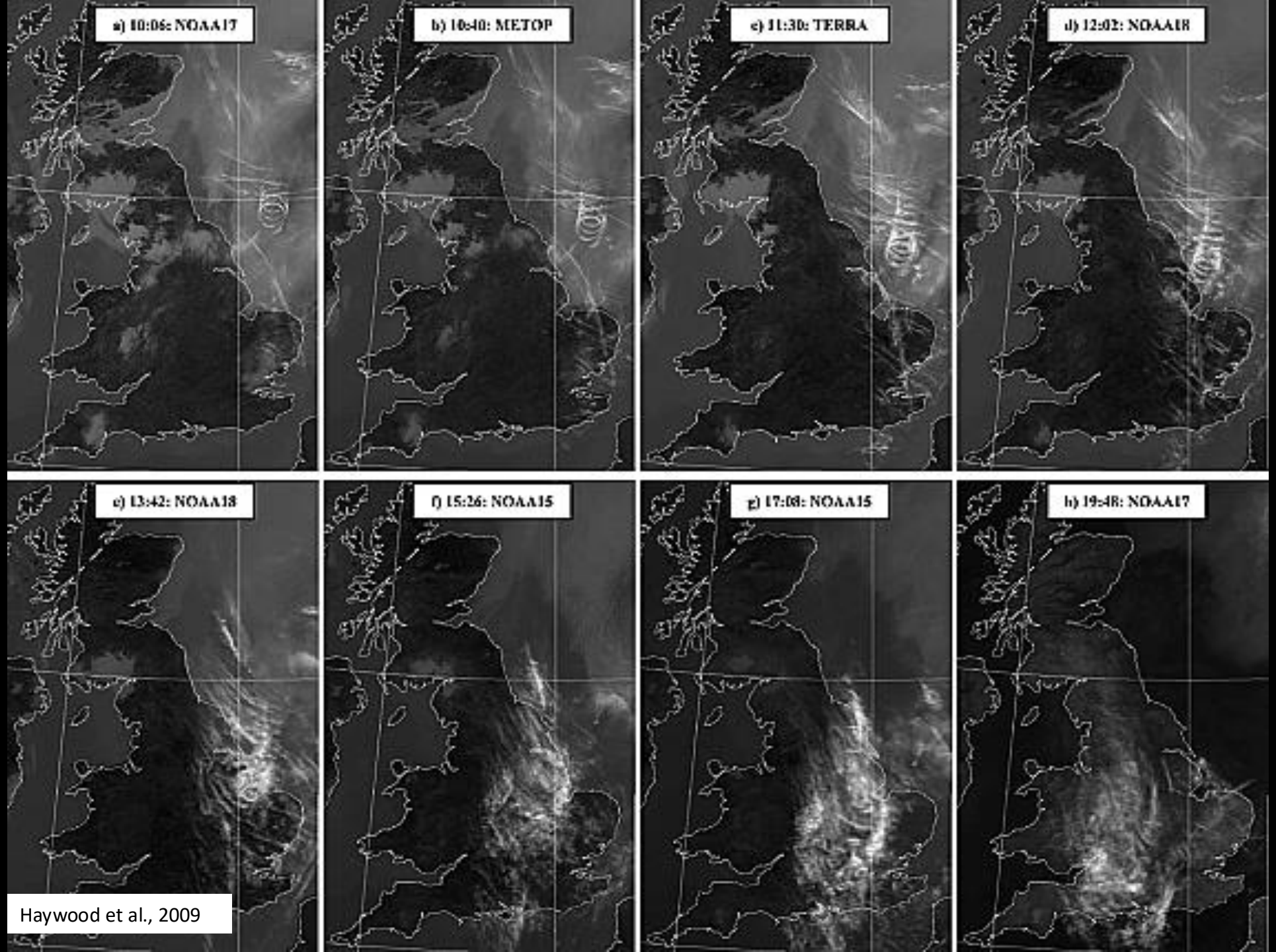
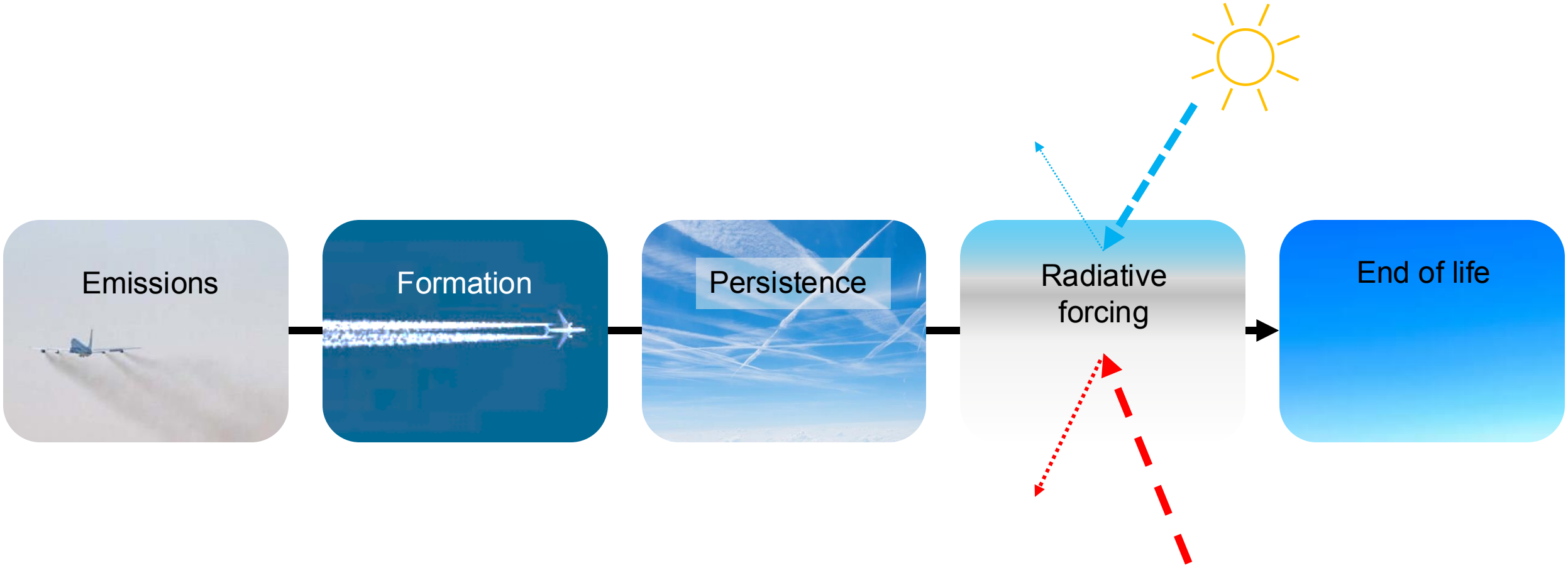
Credit: Google
https://contrails.webapps.google.com/main

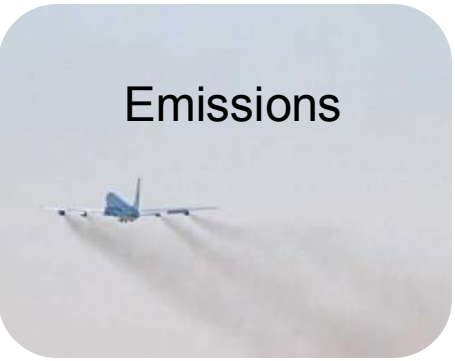


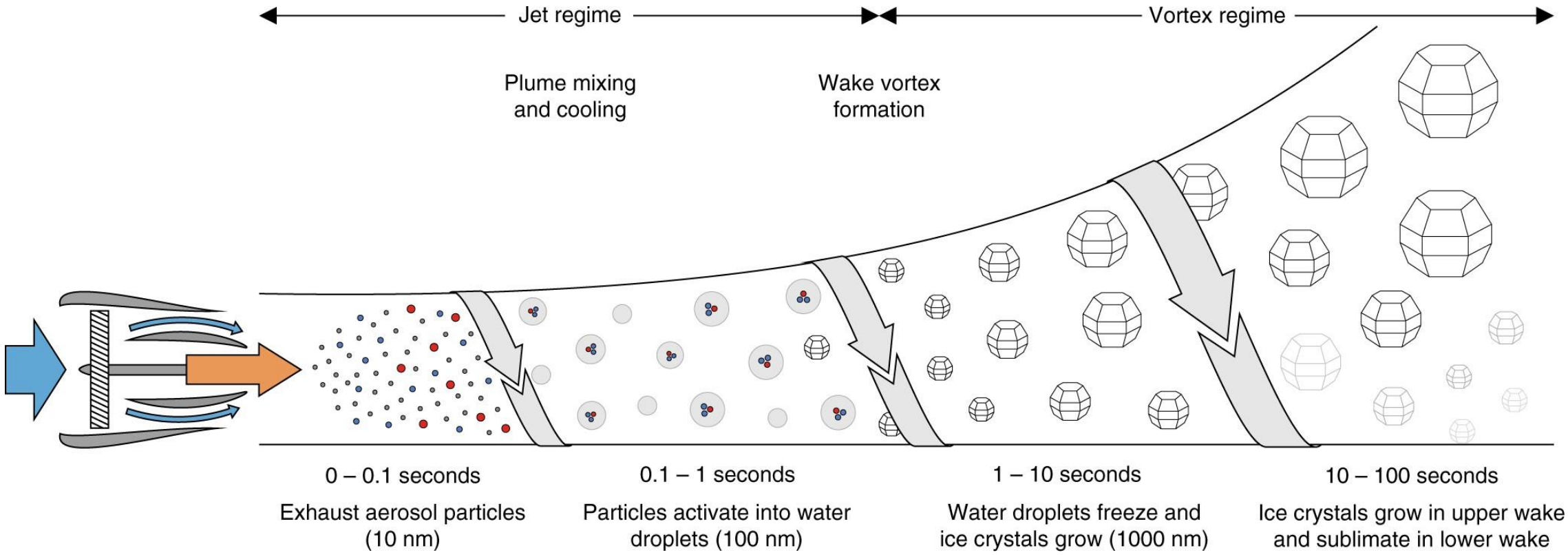
Haywood et al., 2009


Emissions
Formation
Persistence
Radiative forcing
End of life

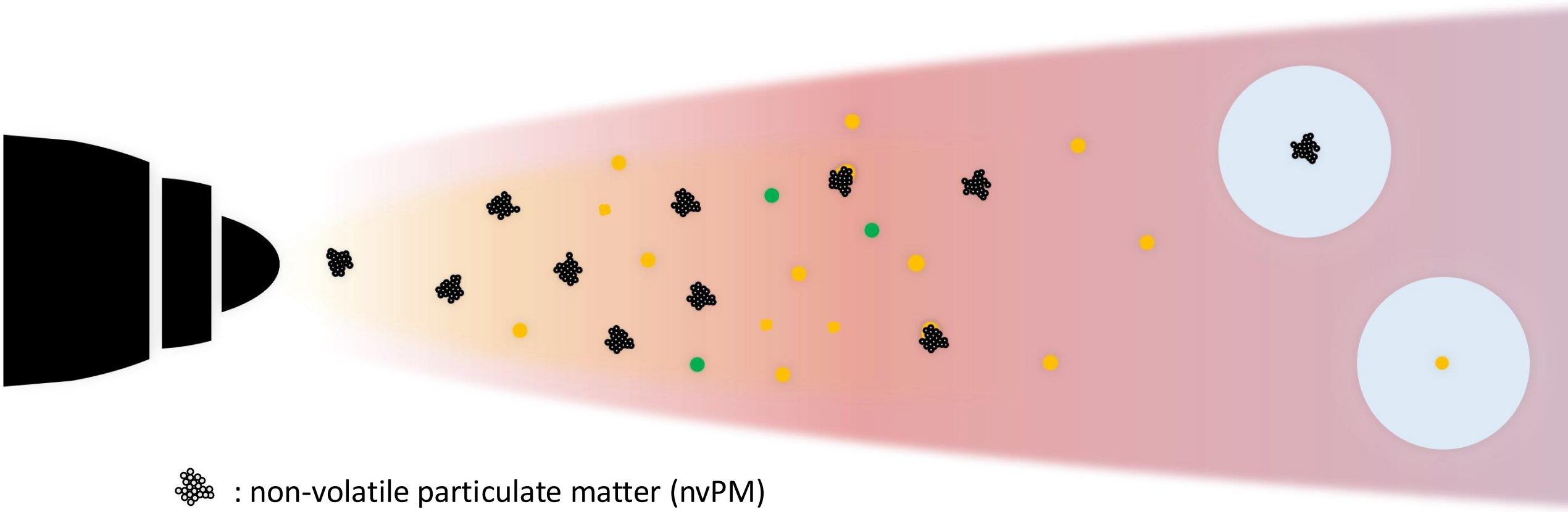
Emissions

Contrails ice particles form on particles emitted by engines





Kärcher, 2018



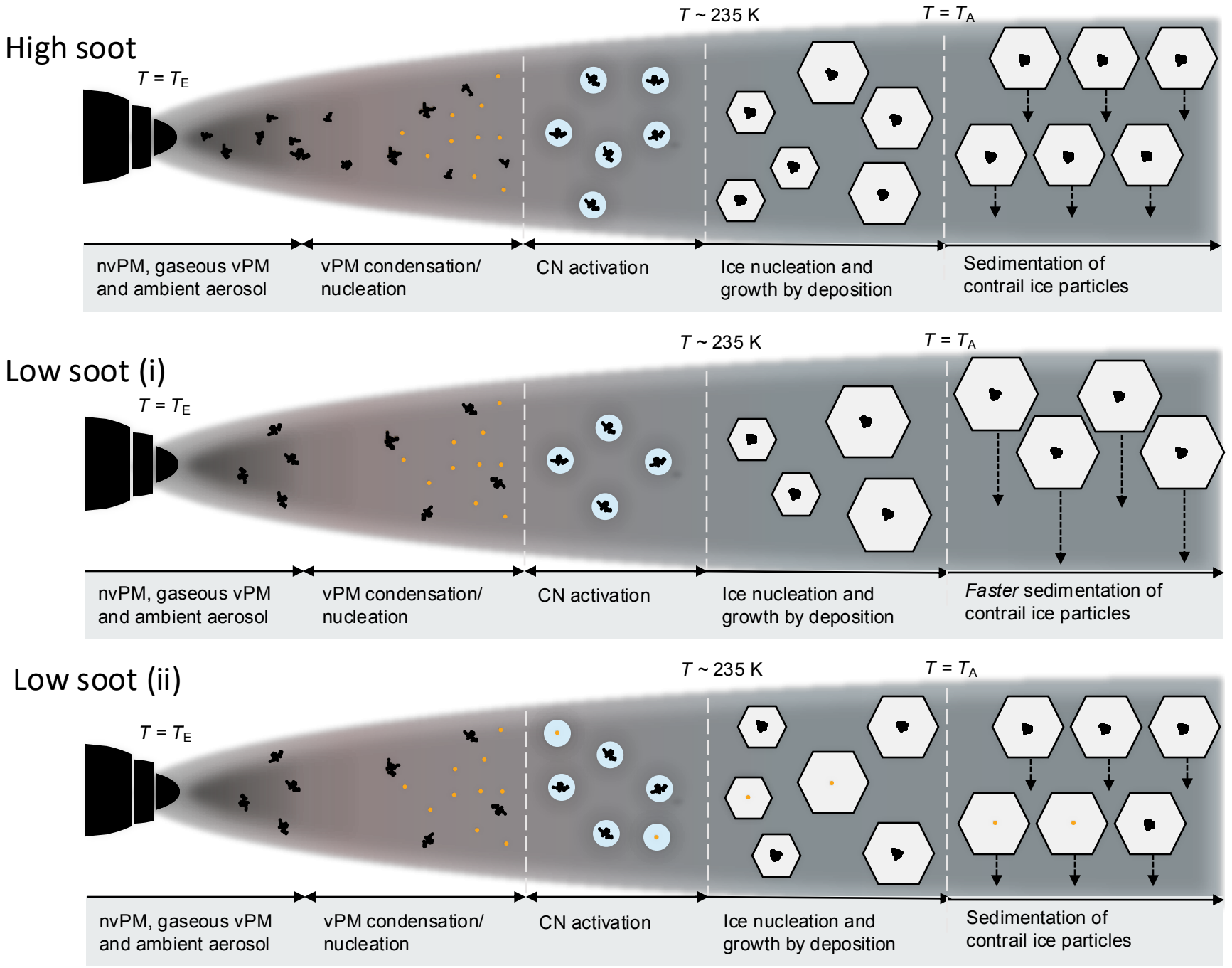
: non-volatile particulate matter (nvPM)

: volatile particulate matter (vPM)

: nvPM with condensed vPM coating

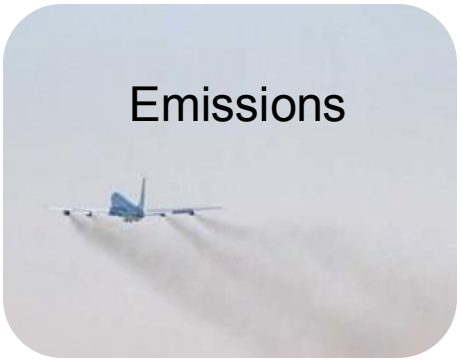
: ambient aerosols

Not to scale


High soot
T = T_E
T ~ 235 K
T = T_A
nvPM, gaseous vPM and ambient aerosol
vPM condensation/ nucleation
CN activation
Ice nucleation and growth by deposition
Sedimentation of contrail ice particles
Low soot (i)
T = T_E
T ~ 235 K
T = T_A
nvPM, gaseous vPM and ambient aerosol
vPM condensation/ nucleation
CN activation
Ice nucleation and growth by deposition
Faster sedimentation of contrail ice particles
Low soot (ii)
T = T_E
T ~ 235 K
T = T_A
nvPM, gaseous vPM and ambient aerosol
vPM condensation/ nucleation
CN activation
Ice nucleation and growth by deposition
Sedimentation of contrail ice particles

Emissions

Key takeaways



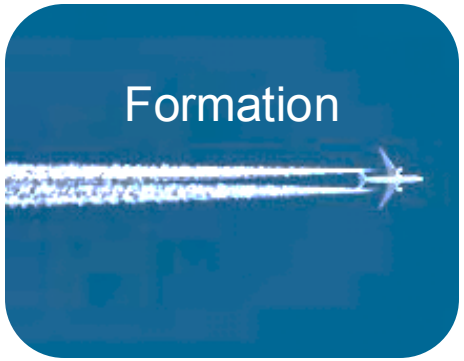
1. Engine particle emissions modify the properties and lifetimes of contrails. Fuels and technology can reduce emissions.

2. Total particle emissions matter, including both non-volatile and volatile PM. Volatile PM is not routinely measured, let alone regulated. Sulphur content of fuels likely important.

So what? Engine emissions of total particles need to be considered. Sustainable aviation fuels will **not** eliminate contrails.

Formation

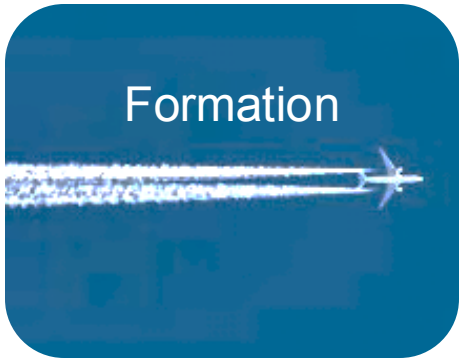
Contrails form when the jet plume is supersaturated

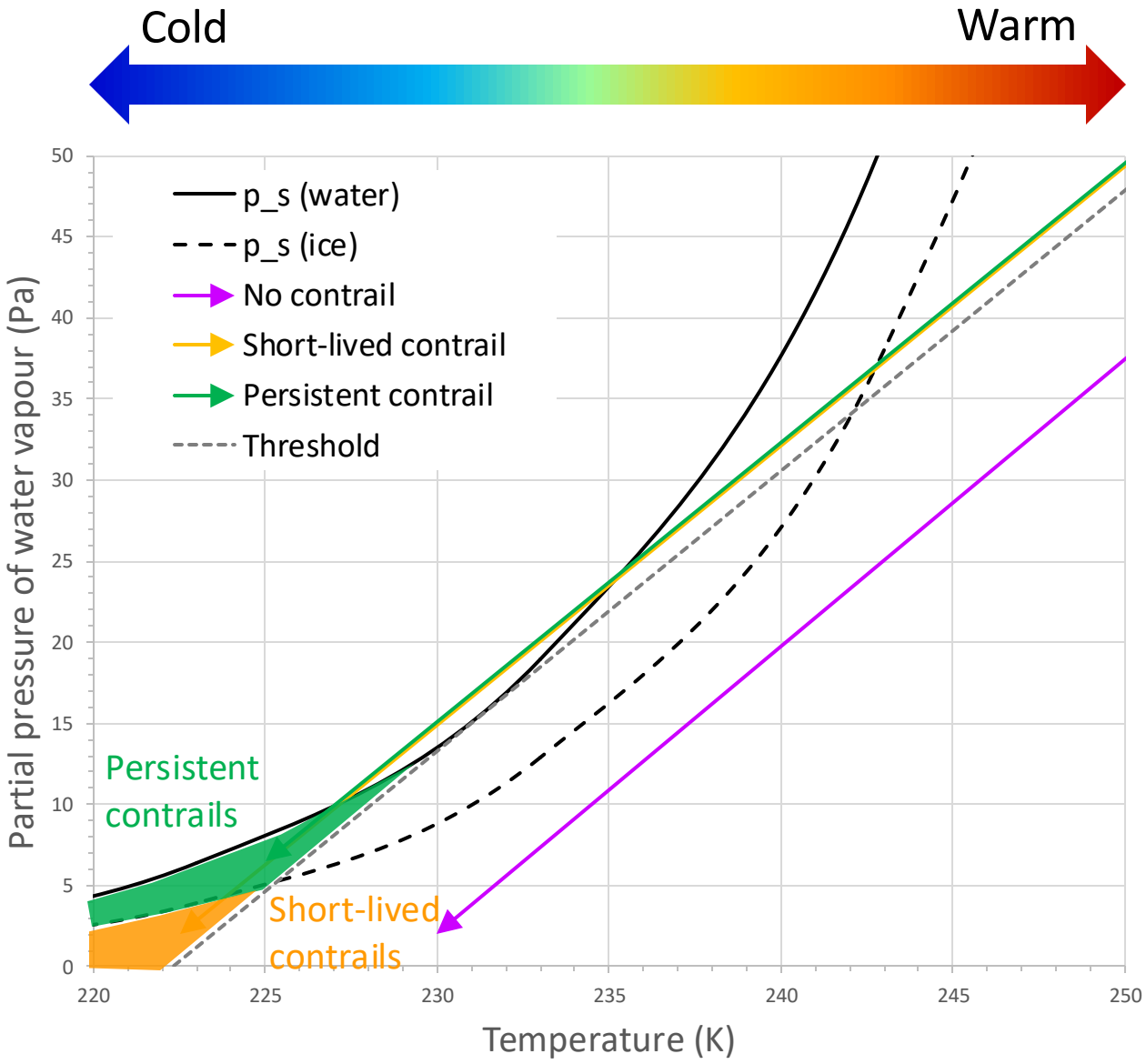


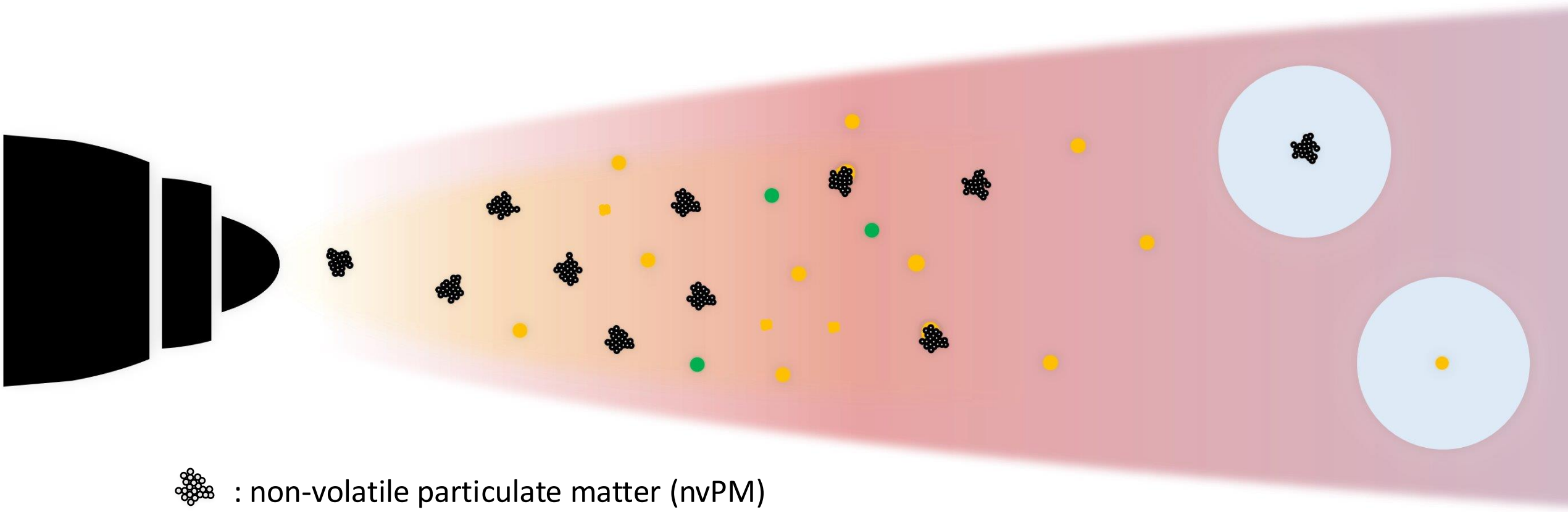
Formation

Contrails form when the jet plume is supersaturated

"Schmidt-Appelman criterion"







: non-volatile particulate matter (nvPM)

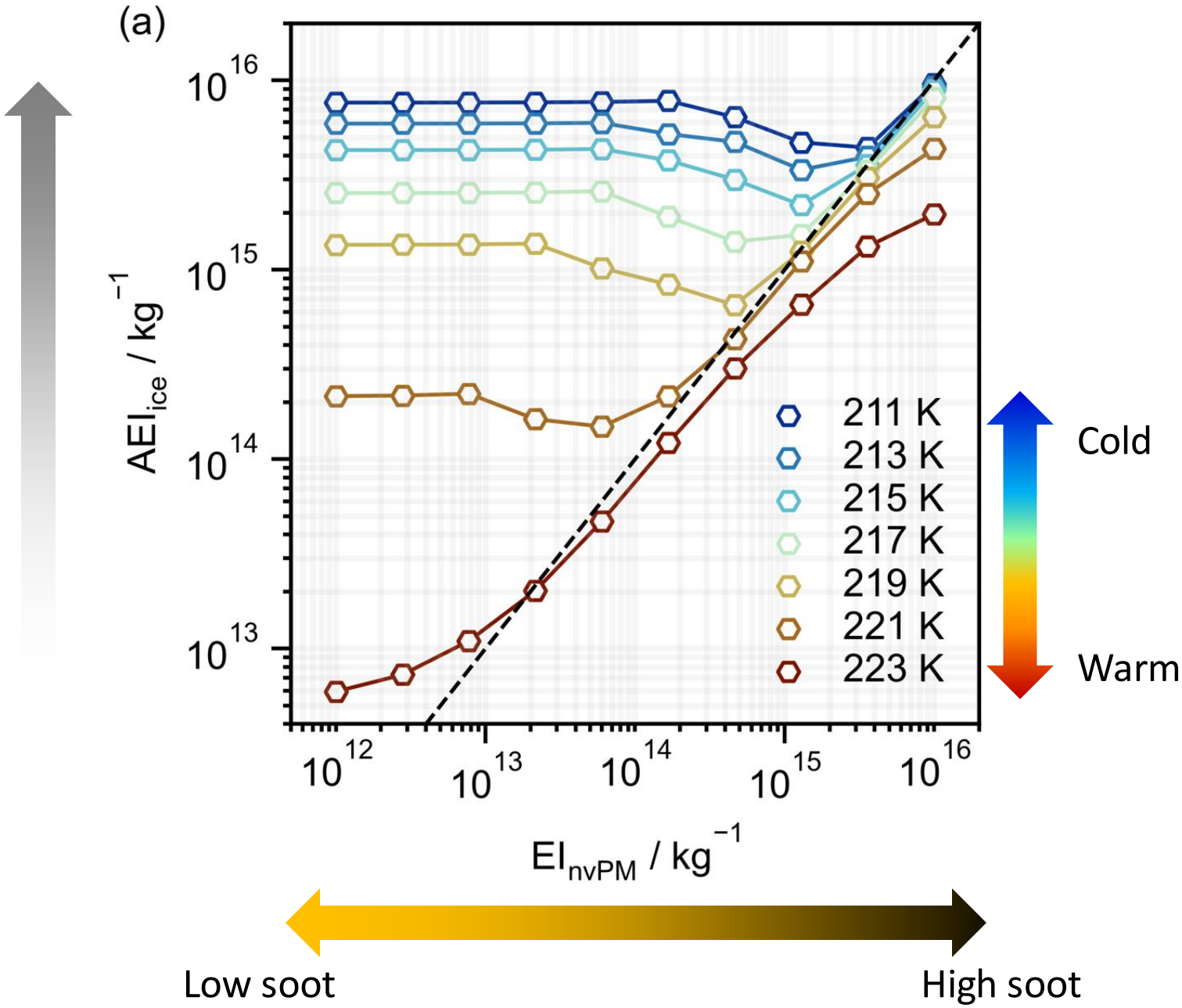
: volatile particulate matter (vPM)

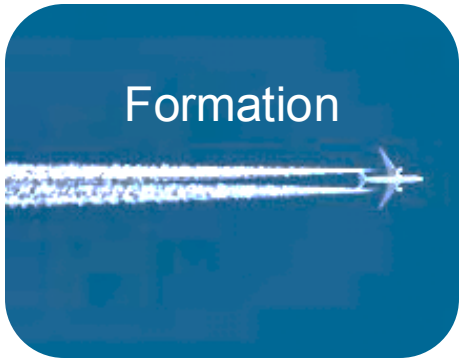
: nvPM with condensed vPM coating

: ambient aerosols

Not to scale

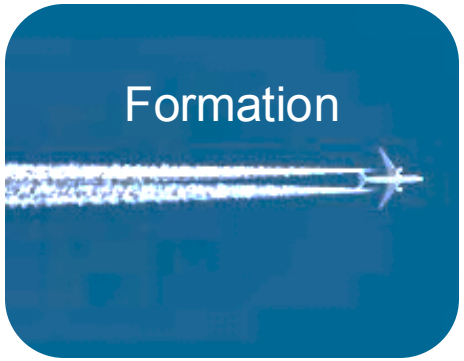
More contrail ice particles





Ponsonby et al., forthcoming

Formation
Key takeaways



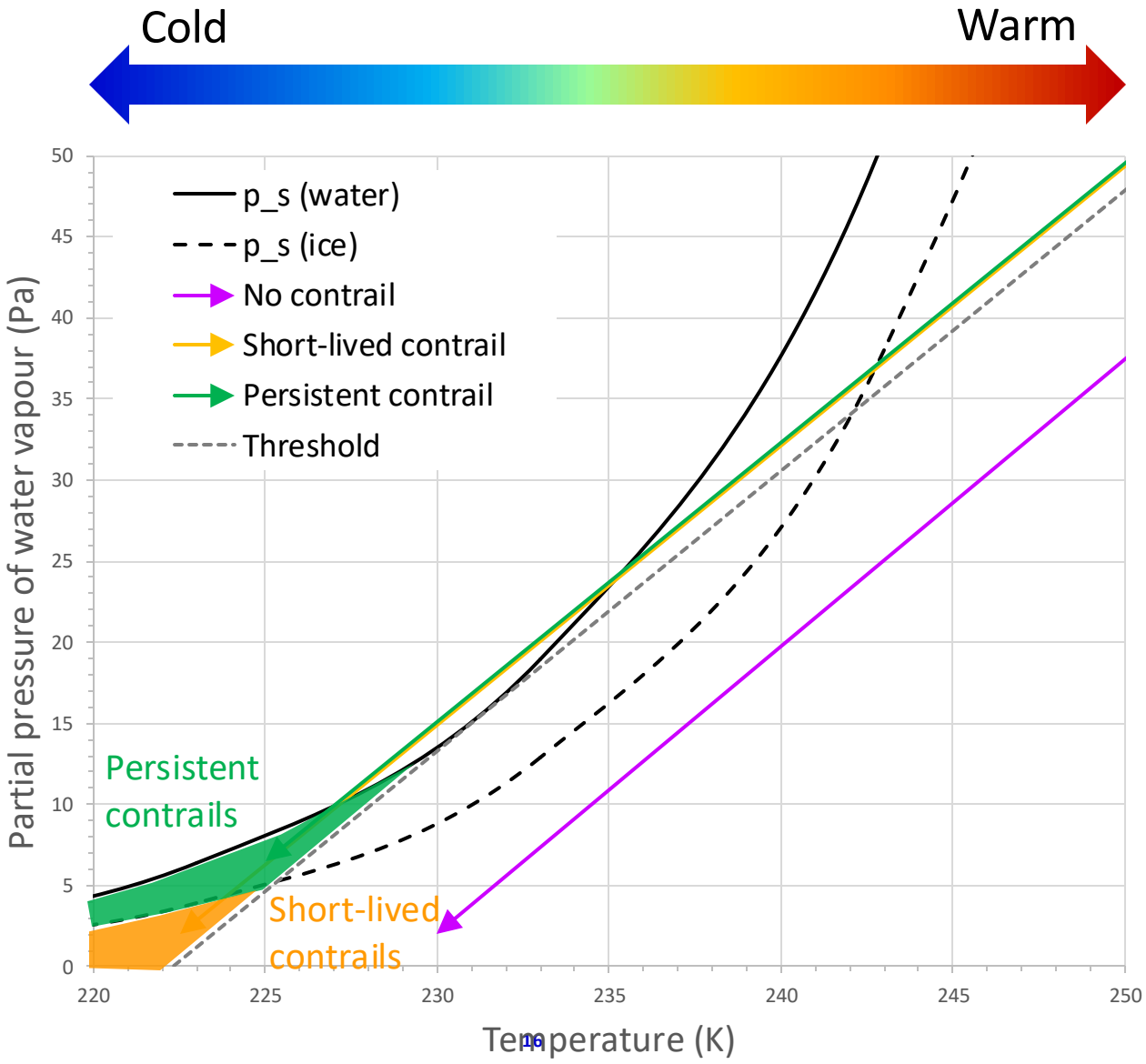
1. Contrail formation requires the jet exhaust to become supersaturated (i.e. >100% humidity).

2. The colder and more humid the plume, the more of the emitted particles will form contrail ice particles.

So what? Not all flights form contrails. Even fewer form “persistent” contrails lasting longer than a few mins.

Persistence

Ice-supersaturation is required for contrails to persist

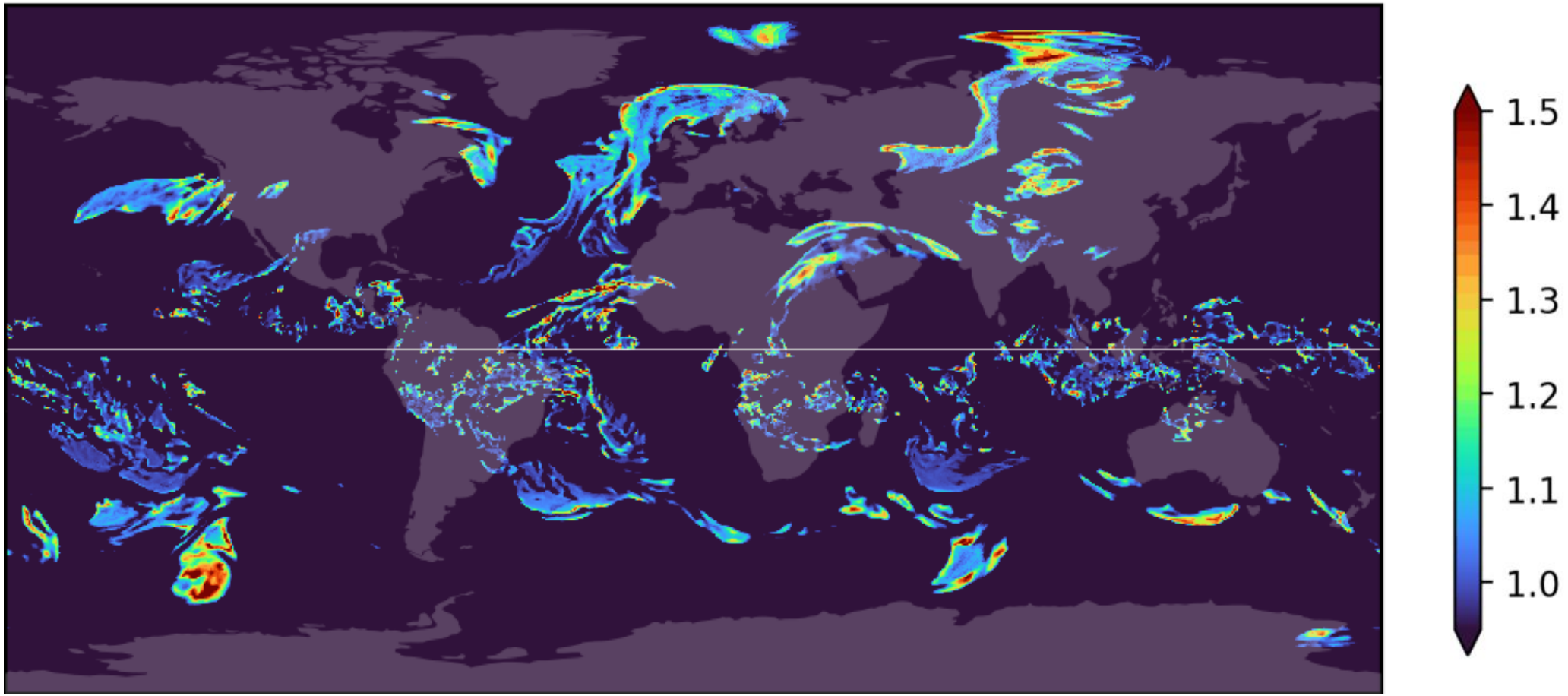


Persistence

Ice-supersaturated regions (ISSRs) are dynamic

FL360, 2020-01-01 00:00:00 (UTC)

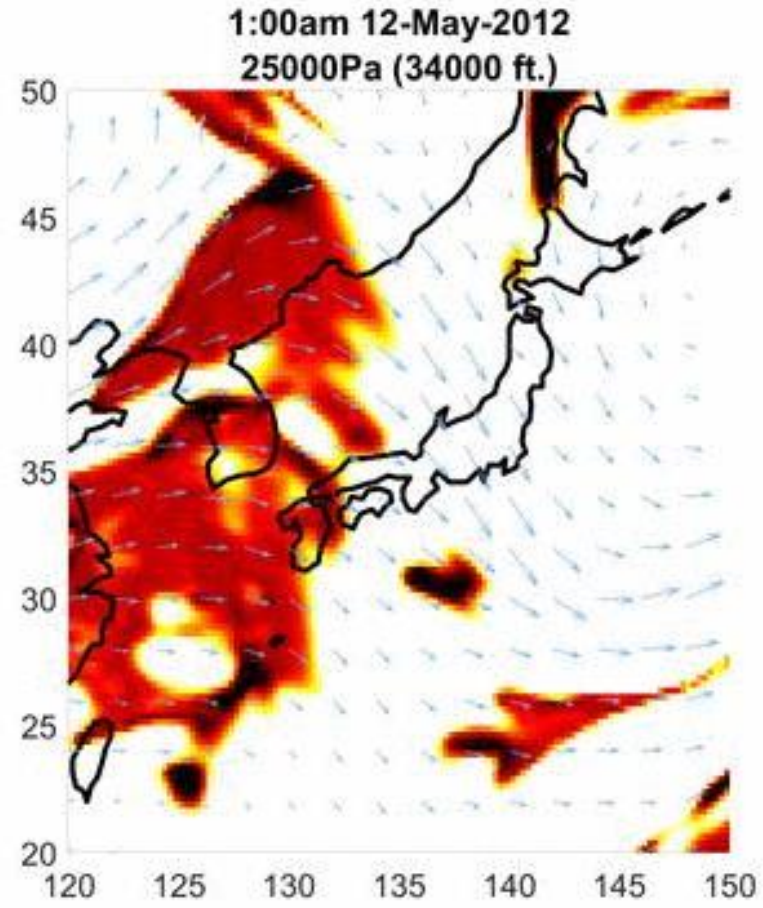
(b) Global correction (9.11 % coverage)



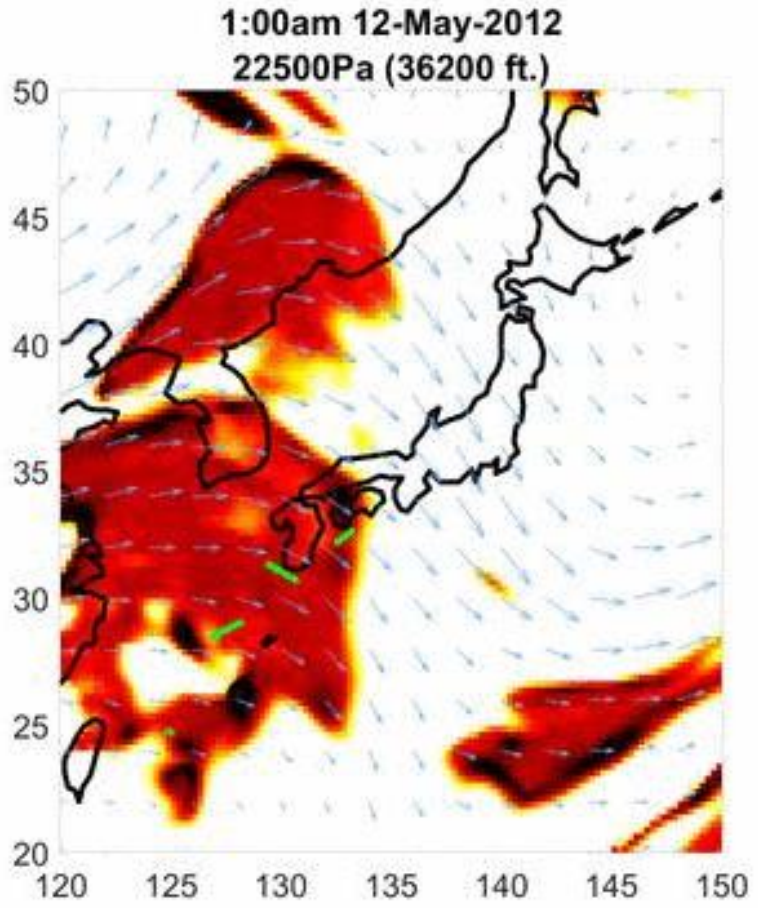
Teoh et al., 2024

Persistence
ISSRs vary by flight level

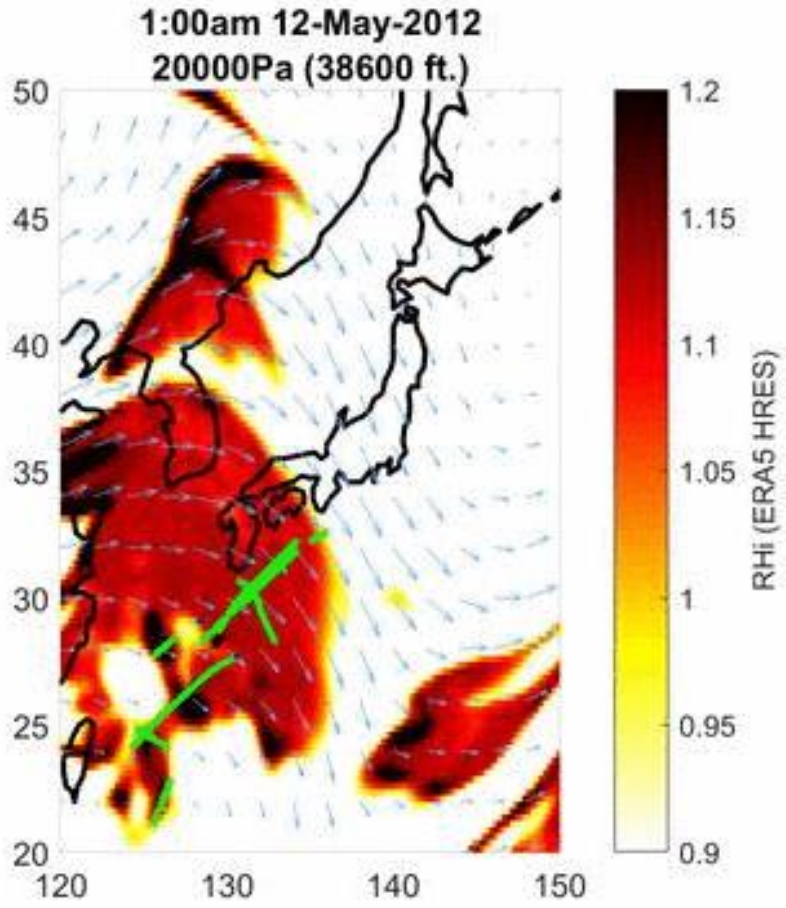
Short-lived contrails → Contrail lifetime > 1 h



FL 340



FL 360

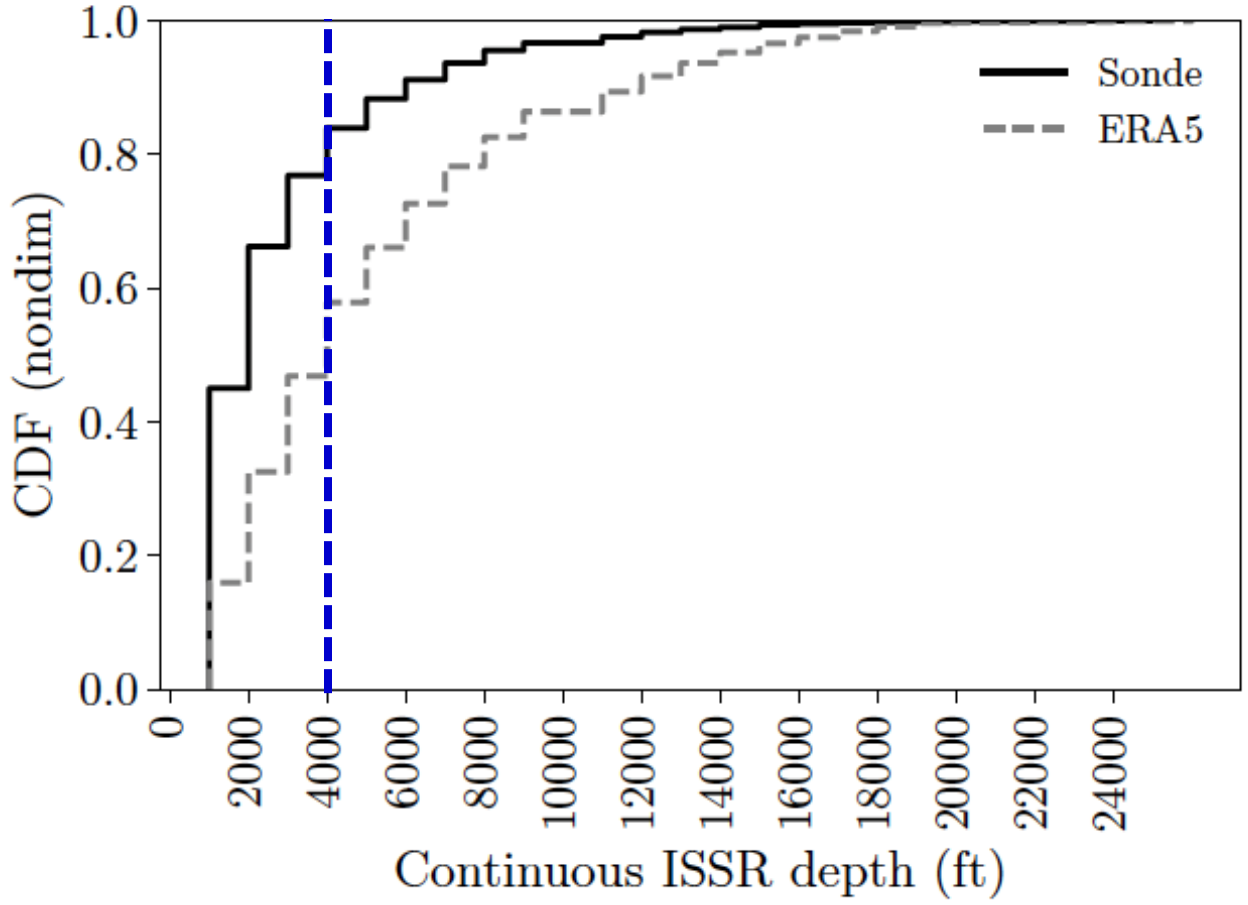


FL 390

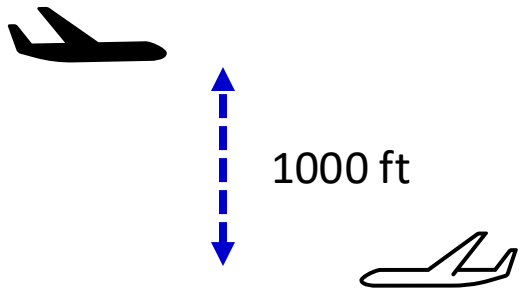
Teoh et al., 2020

Persistence

ISSRs are thin relative to the range of cruise altitudes

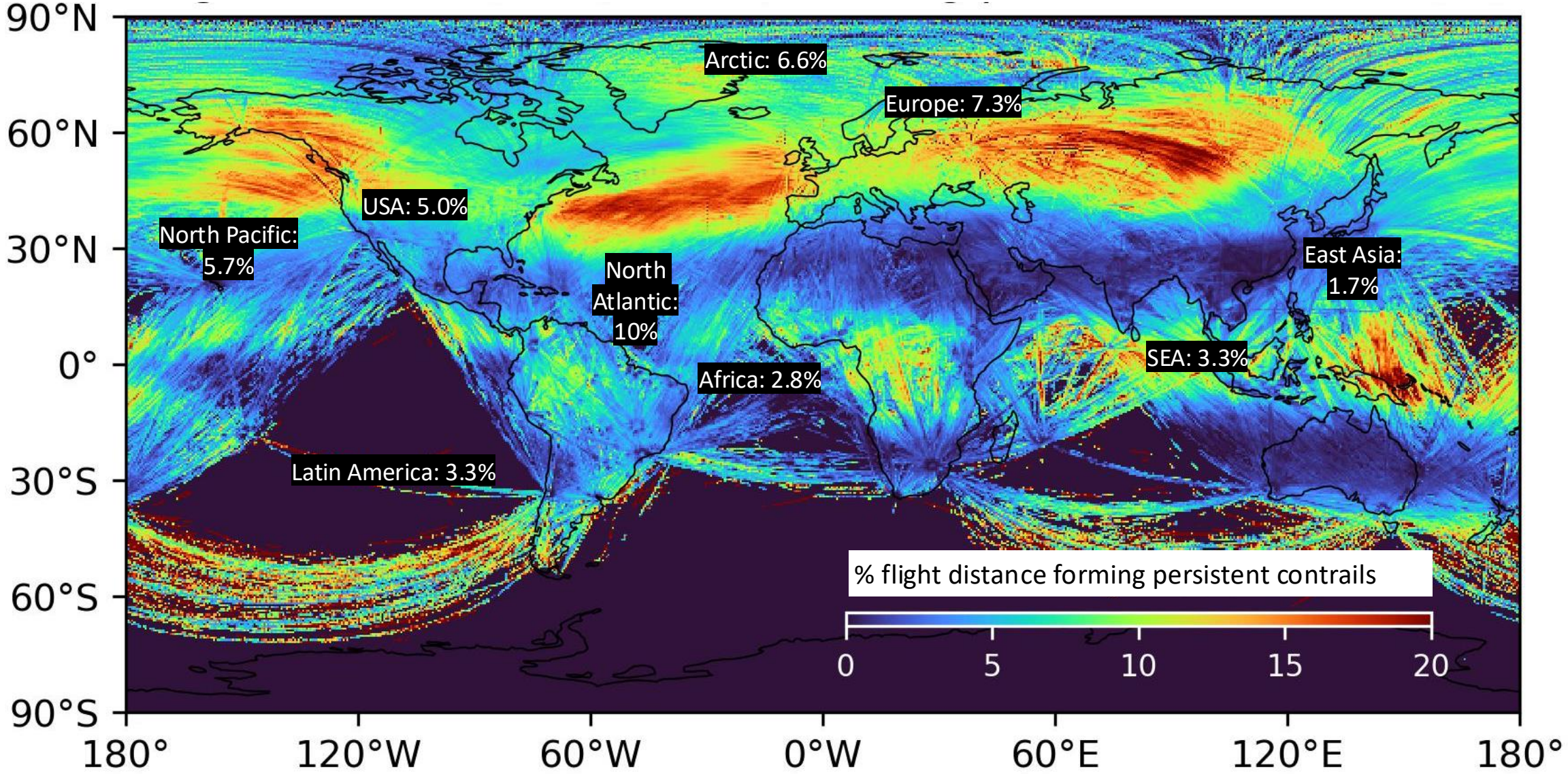


c.f. Reduced Vertical Separation Minima (RVSM) = 1000 ft



Persistence

Globally, ~5% of flight distance flown forms persistent contrails.



Teoh et al., 2024

Persistence
Key takeaways

1. Contrail persistence requires the ambient atmosphere to be supersaturated with respect to ice.

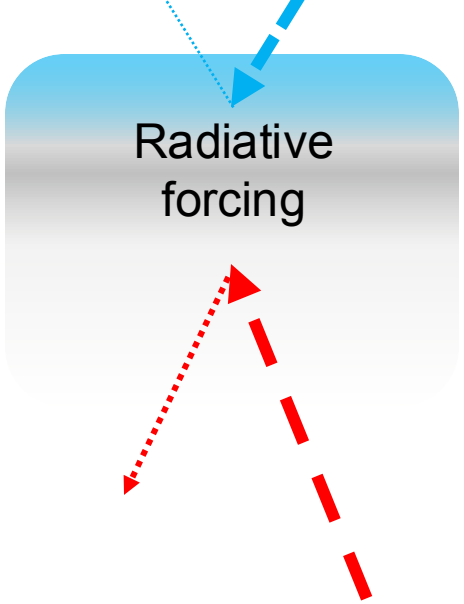
2. Ice-supersaturated regions are dynamic and typically <4,000 ft deep.

3. Globally, ~5% of flight distance forms persistent contrails, some regions are worse than others.

So what? Persistent contrails could be avoided by minor changes to flight altitude **if** forecasts of ISSRs are sufficiently accurate

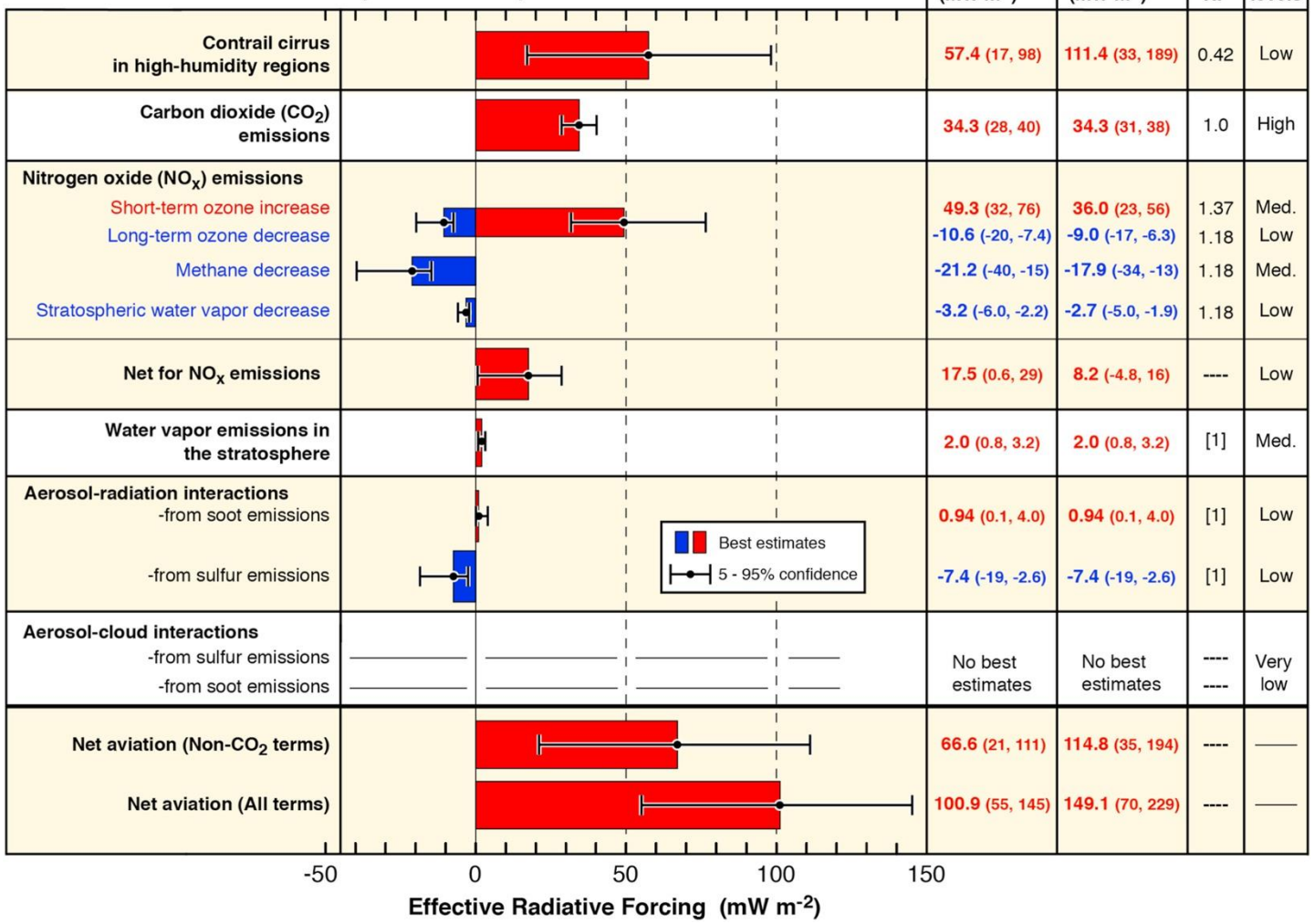
Radiative forcing

"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."



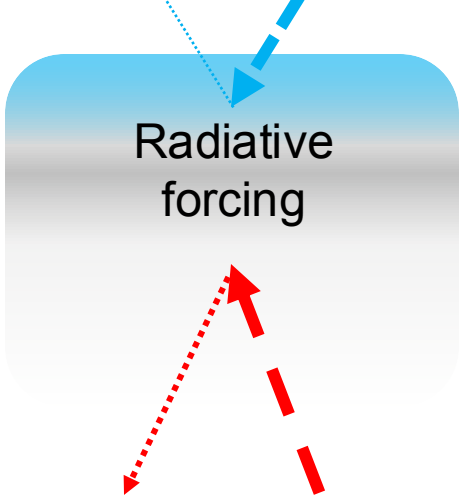
Global Aviation Effective Radiative Forcing (ERF) Terms
(1940 to 2018)

	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

Radiative forcing
The impact pathway



Emissions

Atmospheric concentra-tions

Radiative forcing (RF)

The perturbation of the planetary energy balance by a climate change mechanism.

Climate change

Temperature, precipitation, sea-level, etc.

Impacts

Agriculture, ecosystems, energy production, social effects

Damages

Welfare loss, economic costs

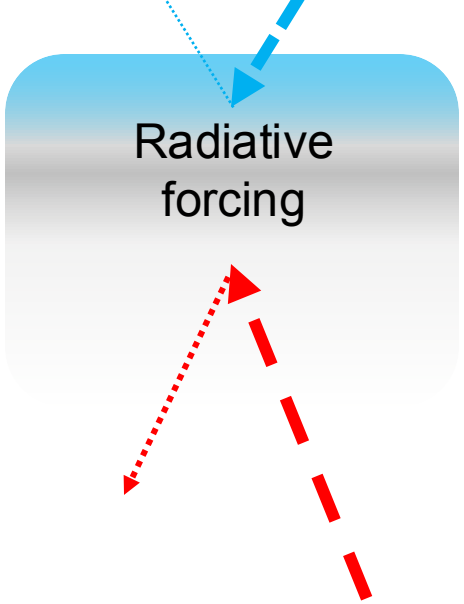
Increasing relevance

Increasing uncertainty

Fuglestvedt et al., 2003

Radiative forcing

Contrails account for ~50% of aviation ERF



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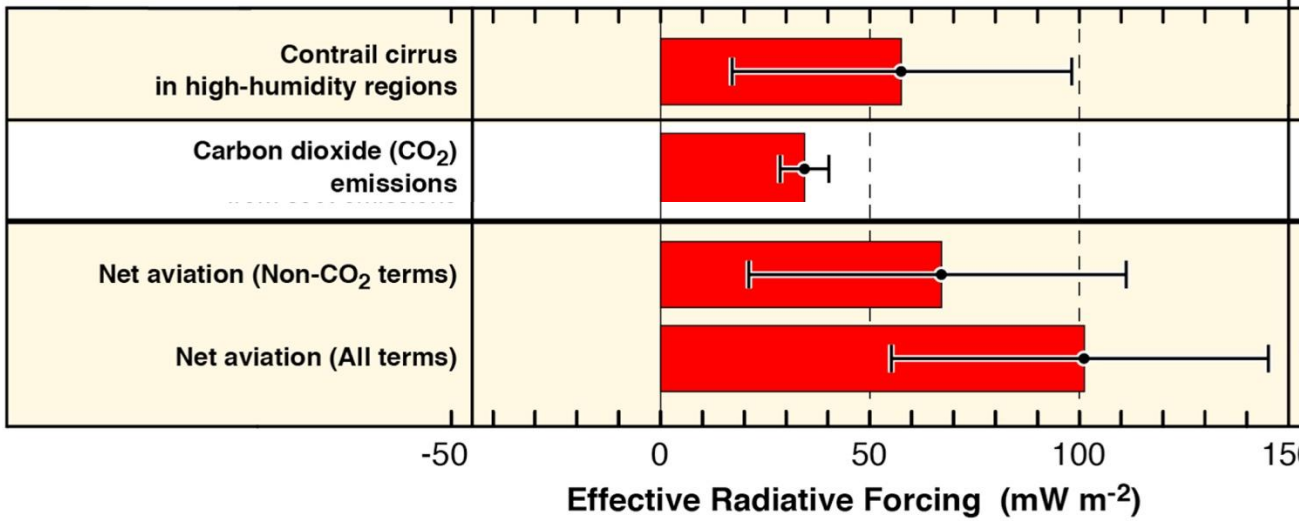

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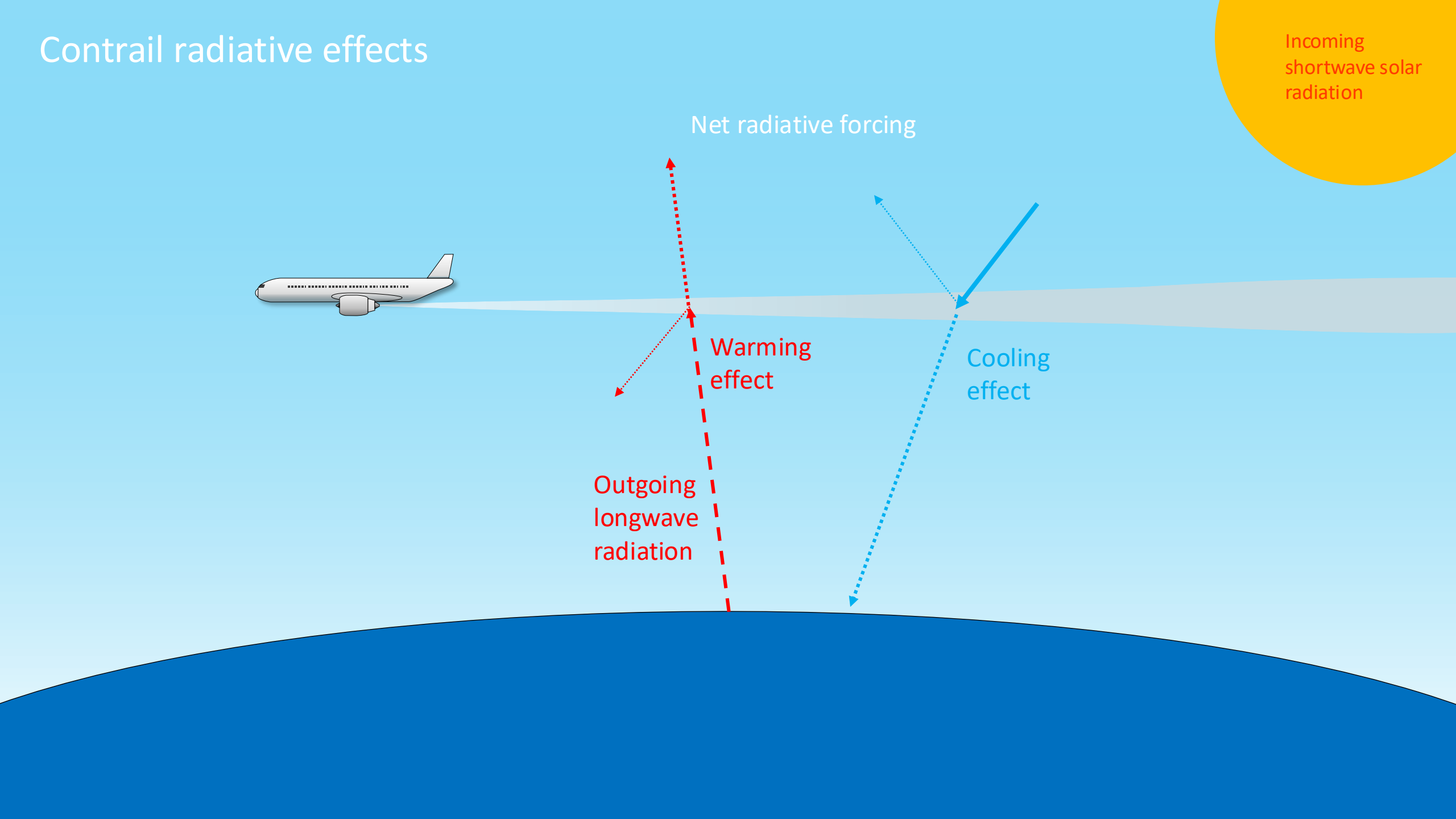
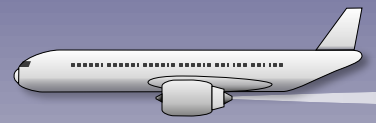
Lee et al., 2021

Contrail radiative effects



Contrail radiative effects



Net radiative forcing

Warming effect

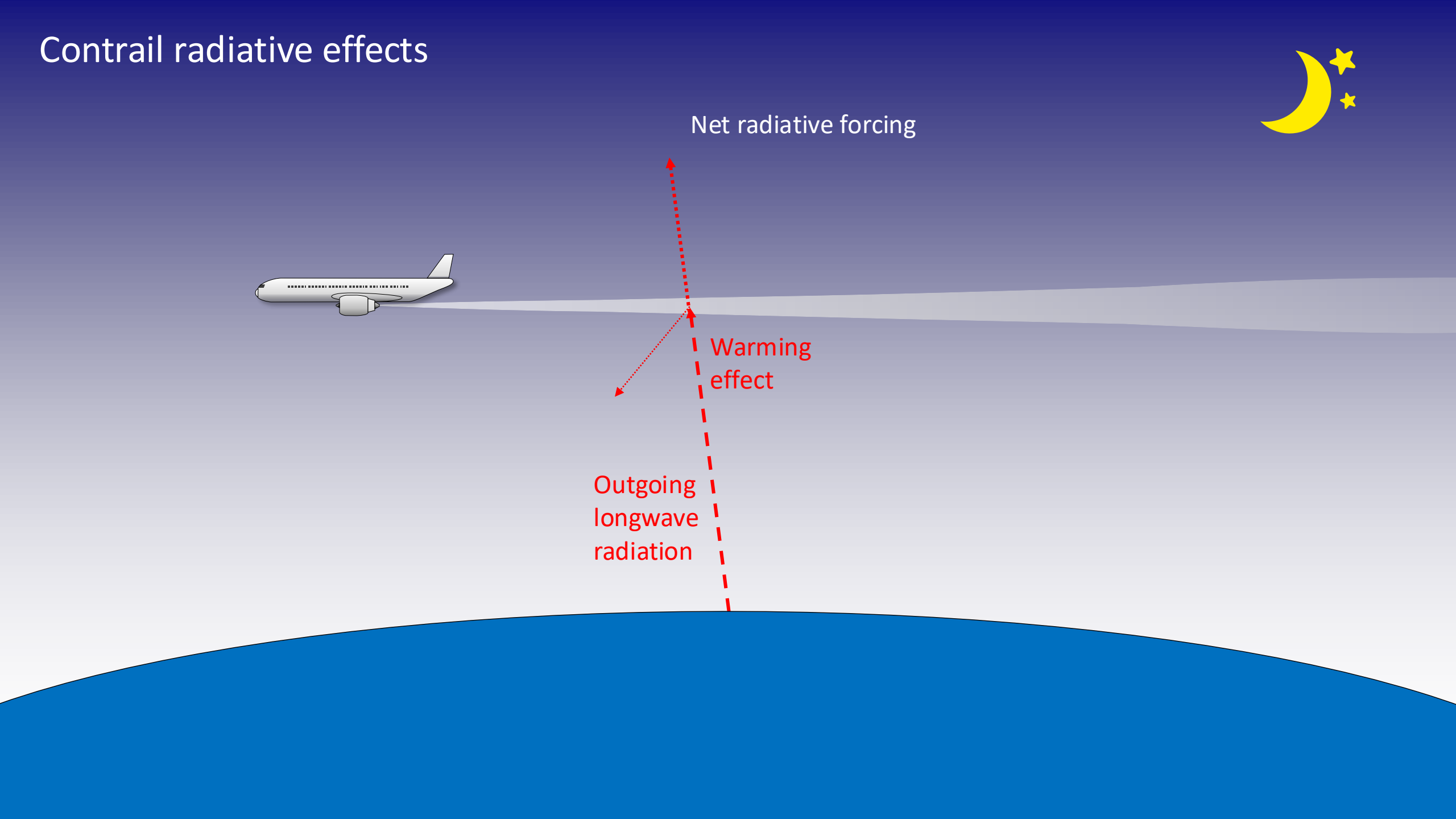
Outgoing longwave radiation

Total CO_2 ERF ≈ 35 mW/m^2
Contrails ERF ≈ 57 mW/ m^2
Total non-CO_2 ERF ≈ 66 mW/m^2
Total aviation ERF ≈ 100 mW/m^2

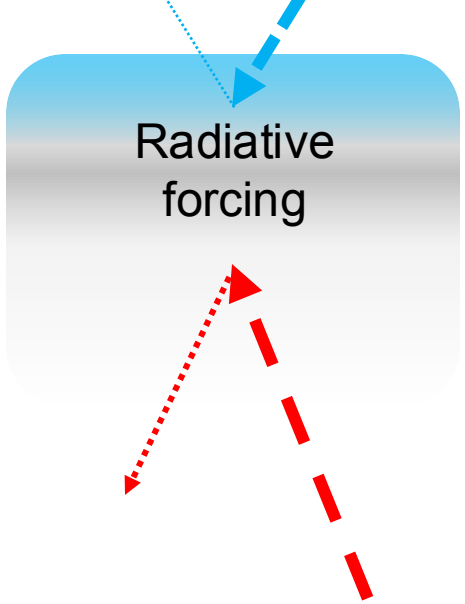
Total anthropogenic radiative forcing ≈ 3000 mW/m^2
Aviation contribution to radiative forcing ≈ 3.5%

Contrails account for 1-2% of all ERF

Contrail radiative effects



Radiative forcing
Tips for interpreting ERF



Carbon dioxide

- CO_2 remains in the atmosphere for centuries, it accumulates.
- The CO_2 ERF term represents the cumulative effect from 1940-2018.
- If we stopped flying tomorrow, the ERF from aviation CO_2 would decline over centuries, it would **not** go to zero and the heating effect would continue.

Contrails

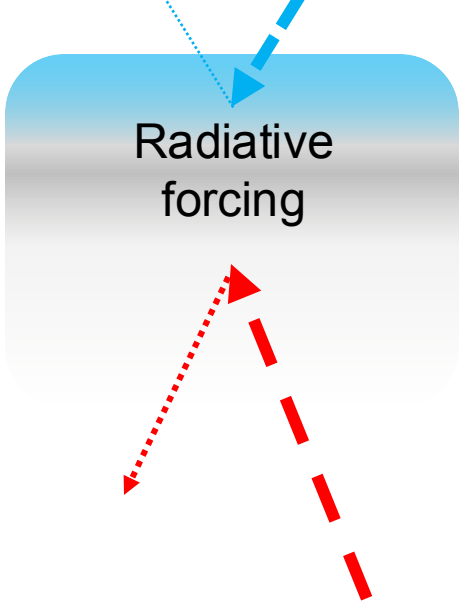
- Contrails last a few hours.
- The contrails ERF term represents the average effect of contrails in 2018.
- If we stopped flying tomorrow (or stopped producing contrails), the ERF from contrails would go to zero within hours and the heating effect would decay quickly.

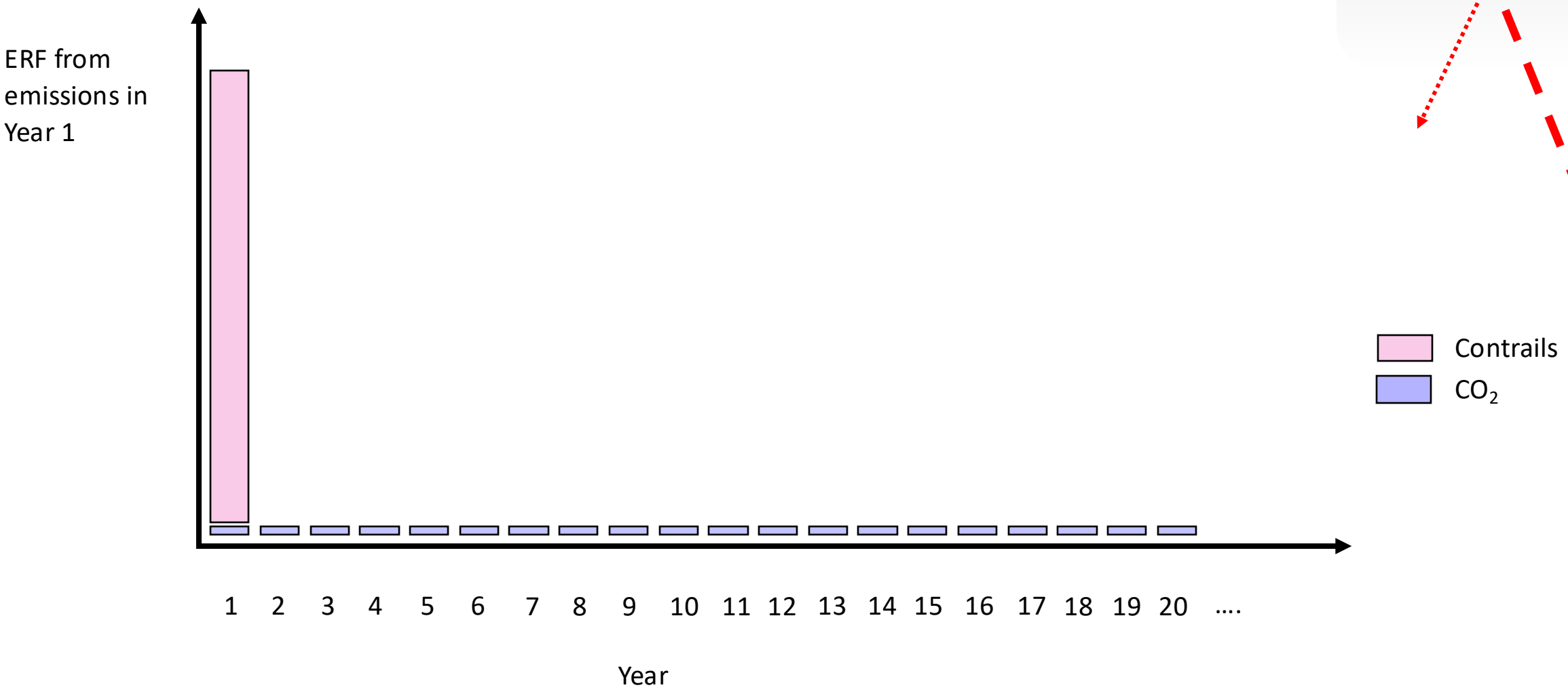
ERF looks **backwards** from the past to the present-day.

Looking **forwards**, the climate impact of aviation contrails in 2018 is comparable to CO_2 but the relative magnitude depends on the climate metric used…

Radiative forcing

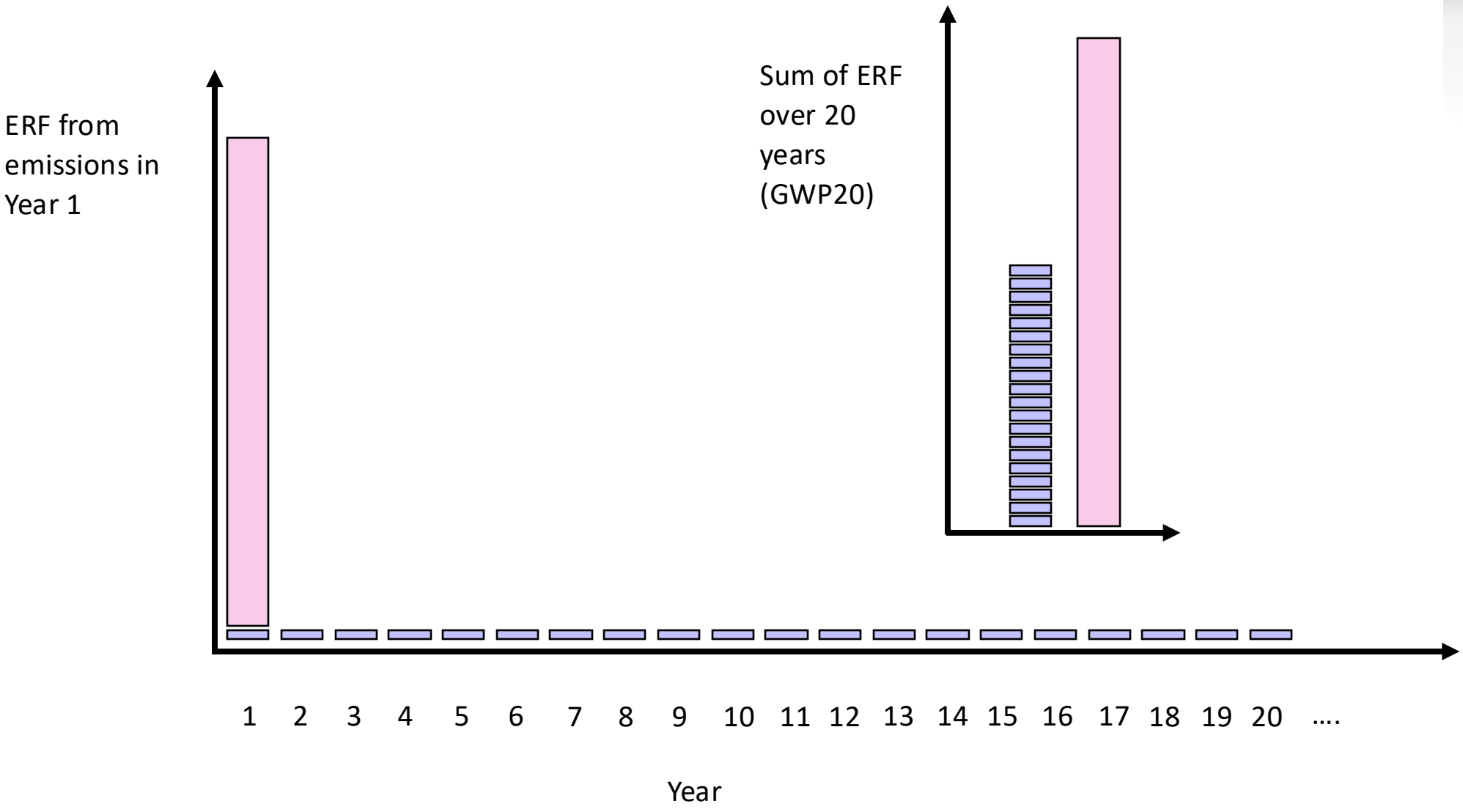
Response to a pulse of aviation activity in one year

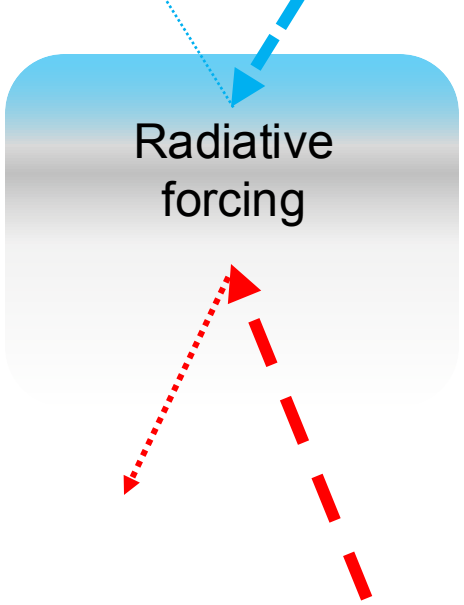




Radiative forcing

Response to a pulse of aviation activity in one year



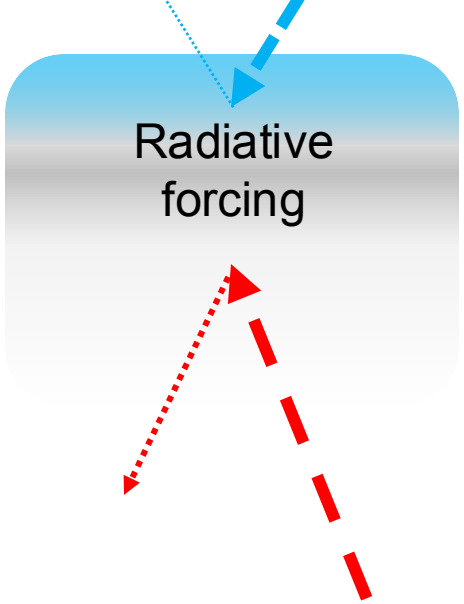


Contrails

CO_2

Radiative forcing

Response to a pulse of aviation activity in one year



ERF from emissions in Year 1

Temperature response in 20 years (GTP20)

Contrails

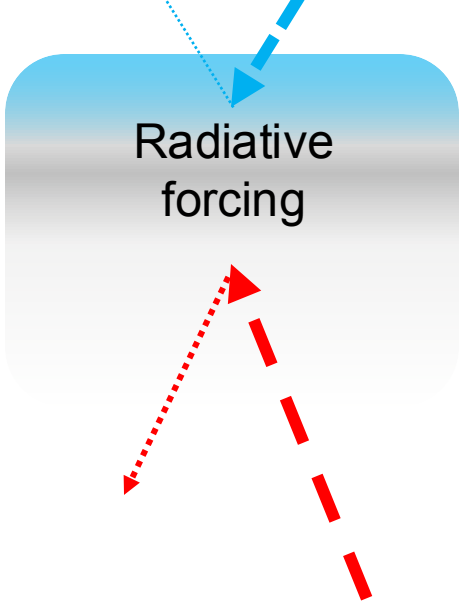
CO_2

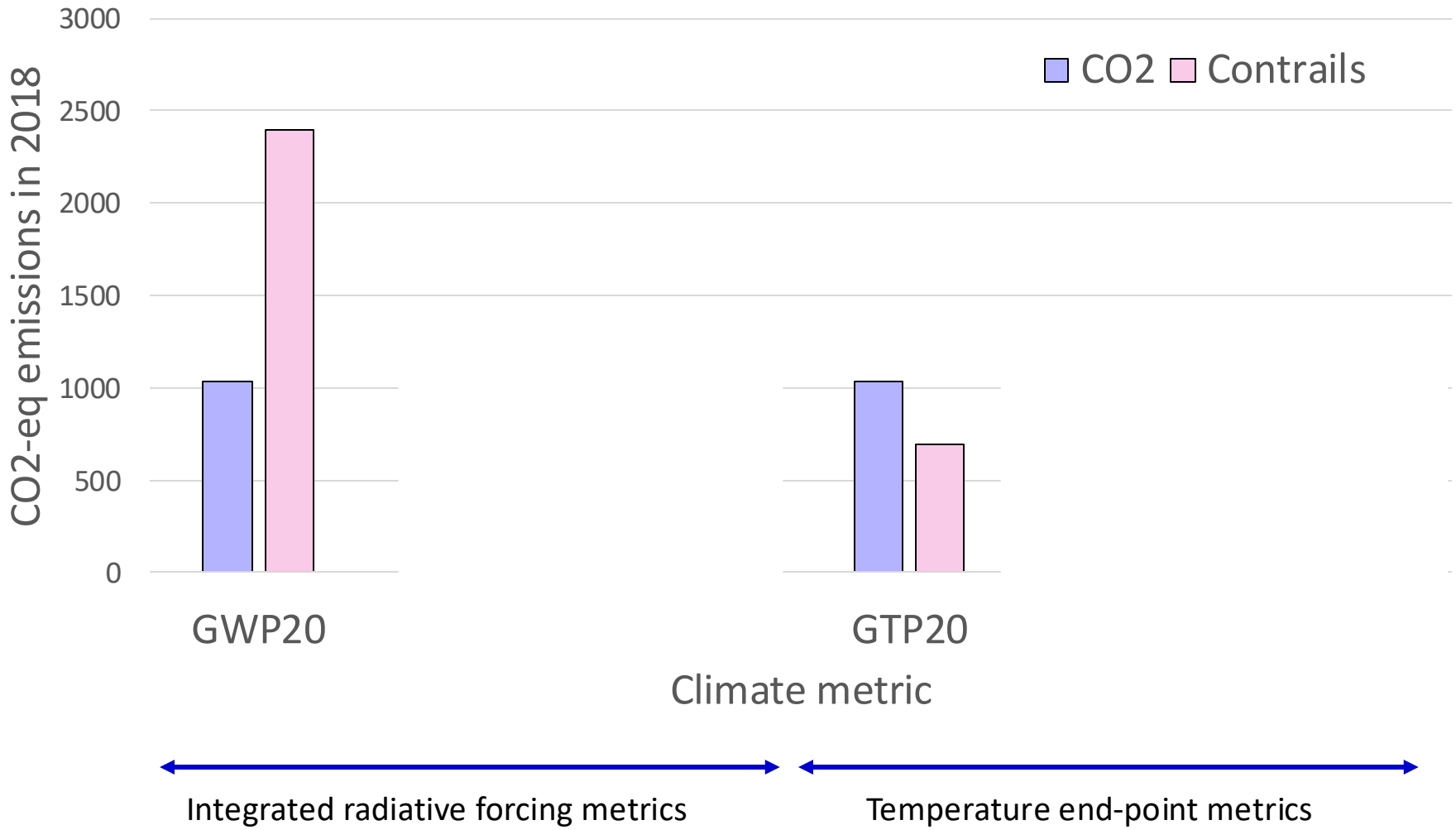
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 ….

Year

Radiative forcing

Metrics are used to compare different GHGs on the same basis

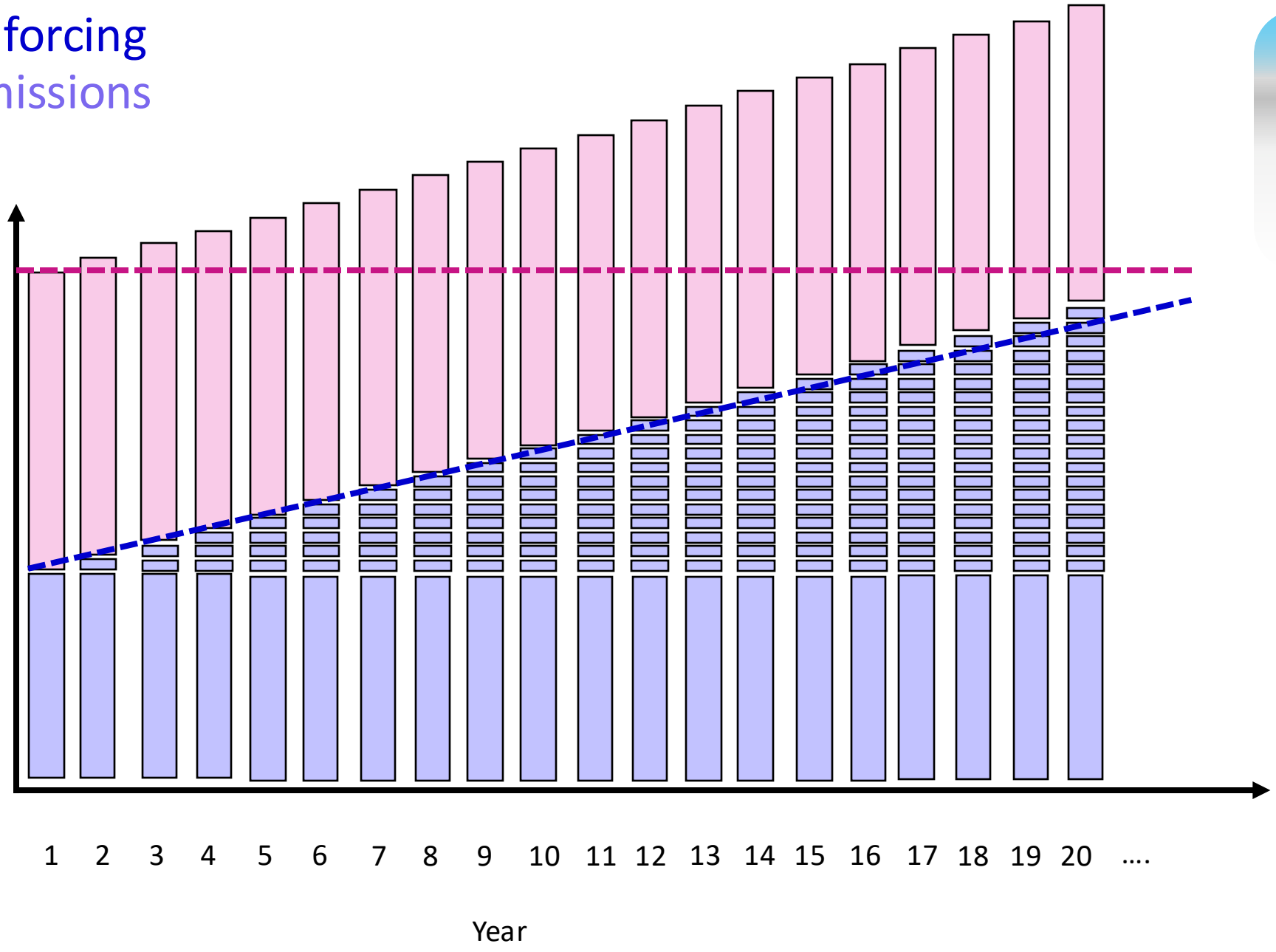


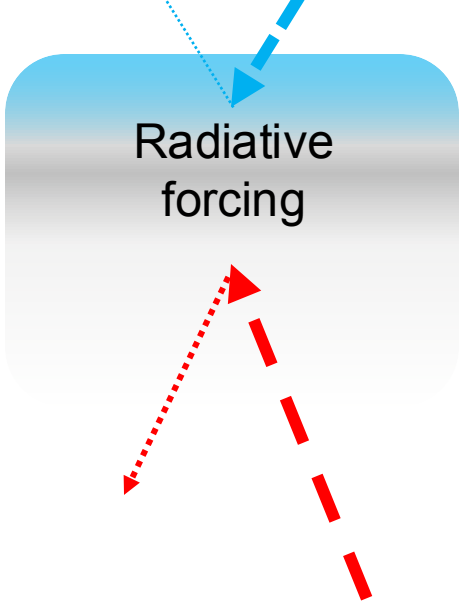


Lee et al., 2021

Radiative forcing
Future emissions

ERF from emissions in Year 1



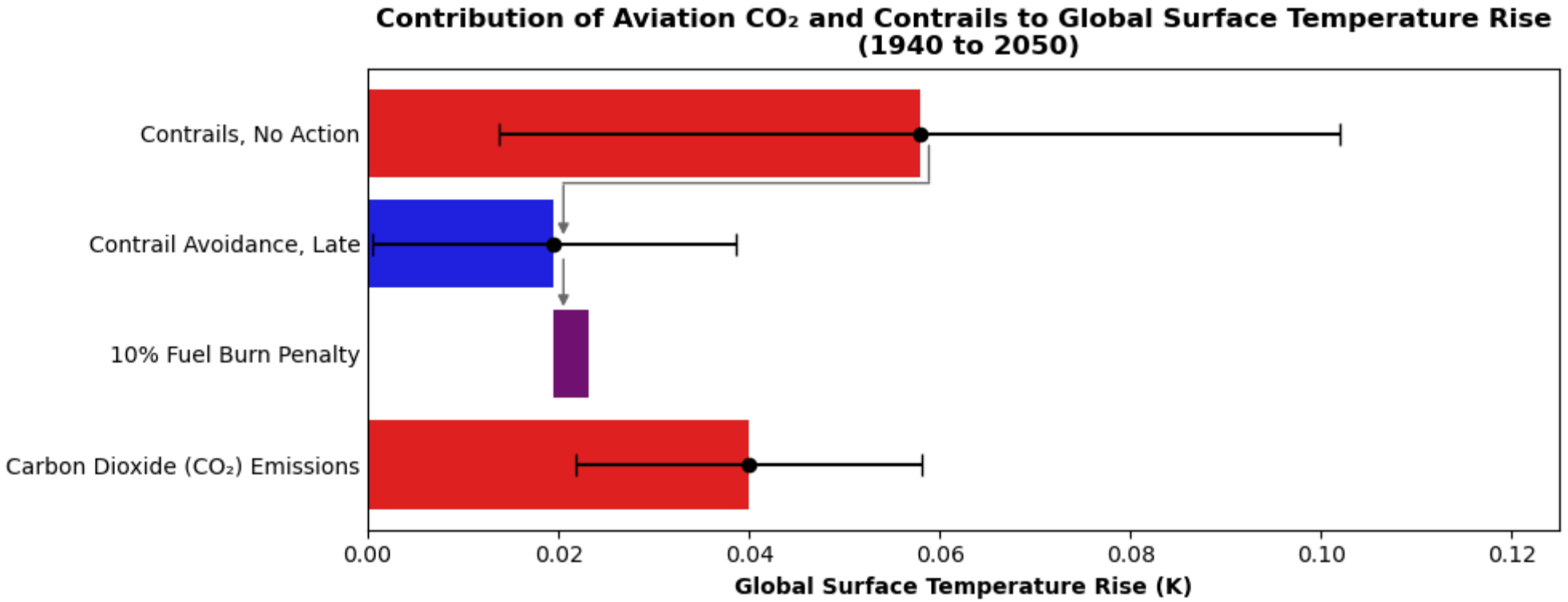


Contrails

CO_2

Temperature rise due to aviation in 2050

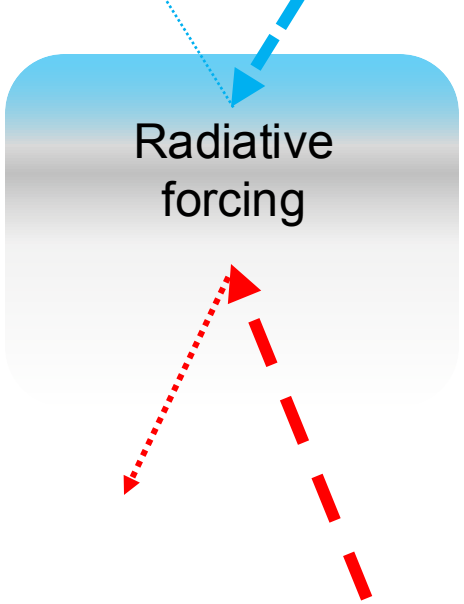
Contrails account for ~60% of temperature rise in 2050



Preliminary, please do not cite or quote

Smith et al., forthcoming

Radiative forcing
Key takeaways



1. Aviation accounts for ~3.5% of human-induced ERF

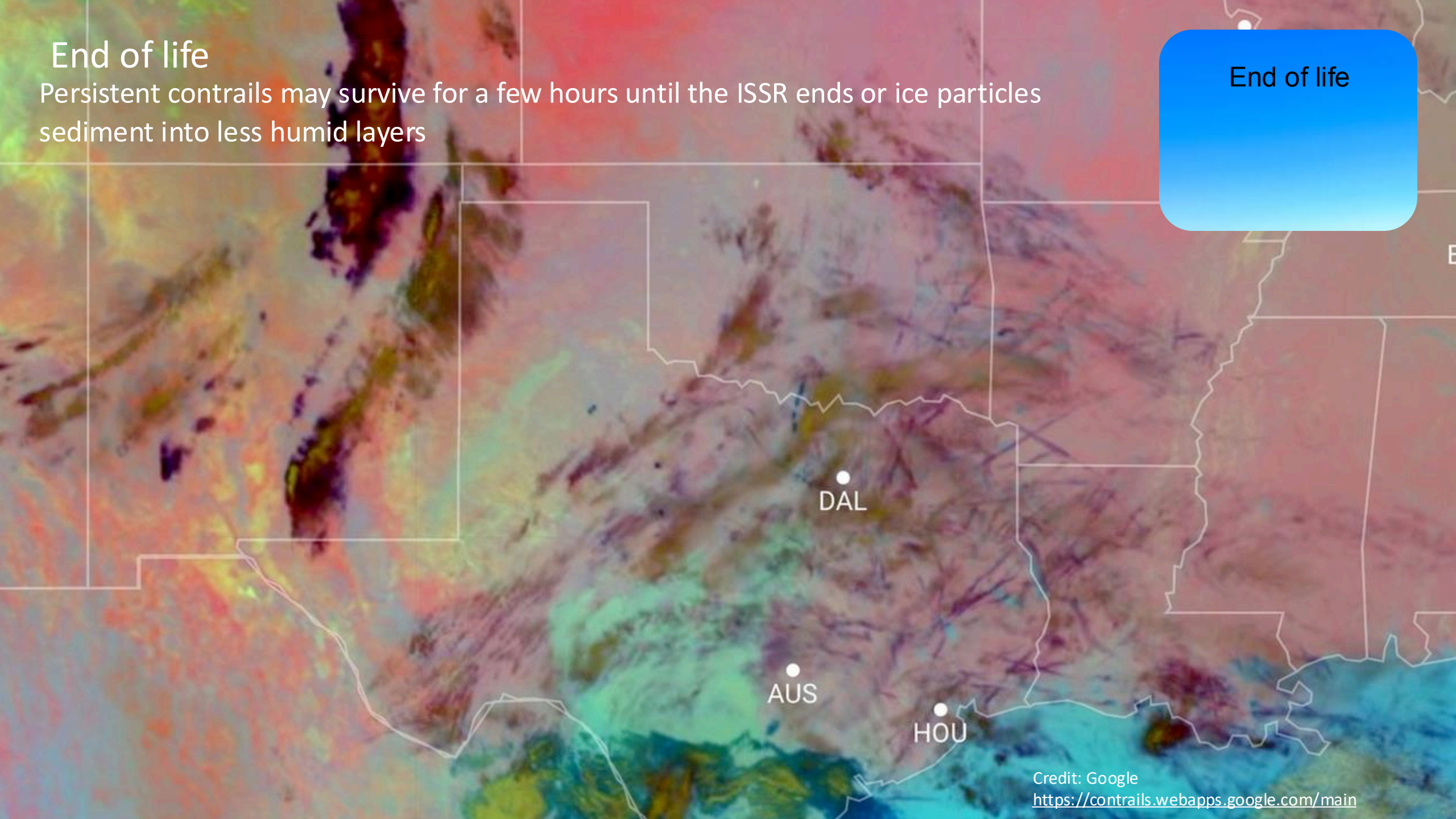
2. Contrails account for ~1/2 of aviation's total ERF

3. To quantify the impact of a flight today (or mitigation action), we must consider the CO_2 and non-CO_2 impacts into the future, and choose a time-horizon

So what? There can be trade-offs between different climate forcers, e.g. CO_2 versus contrails; the relative importance will depend on the quantity of 'emission' and the metric.

End of life

Persistent contrails may survive for a few hours until the ISSR ends or ice particles sediment into less humid layers



Credit: Google
https://contrails.webapps.google.com/main

So what?

Not all contrails are created equal

1. Engine emissions of total particles need to be considered, sustainable aviation fuels will not eliminate contrails.

2. Not all flights form contrails. Even fewer form “persistent” contrails (~5%) lasting longer than a few mins.

3. Persistent contrails could be avoided by minor changes to flight altitude **if** forecasts of ISSRs are sufficiently accurate.

4. There can be trade-offs between different climate forcers, e.g. CO_2 versus contrails; the relative importance will depend on the quantity of ‘emission’ and the metric.

→ *We need to quickly find out if contrail avoidance is feasible and to what extent.*

What can we do about contrails?

Sustainable aviation fuels

Caiazzo et al. (2017) [USA]

*Increase in contrail occurrence and the lower albedo of contrails forming in the biofuel case outweigh the cooling effect of optical depth reduction,… leads to a **higher average net radiative forcing** of between 0% and +18%*

Teoh et al. (2022) [N. Atlantic]

*Fleetwide adoption of 100% SAF increases contrail occurrence (+5%), but lower non-volatile particle emissions (−52%) **reduces the annual mean contrail net radiative forcing** (−44%)… targeting 1% SAF at a 50% blend ratio to ~2% of flights responsible for the most highly warming contrails reduces $EF_{contrail}$ by ~10%*

Märkl et al. (2024) [Global]

*Global mean radiative forcing estimate for the 100 % SAF run is 53 mW m^{-2} for the year 2018… a **decrease in the contrail cirrus radiative forcing of 26%**.*

Engine technology

Burkhardt et al. (2018) [Global]

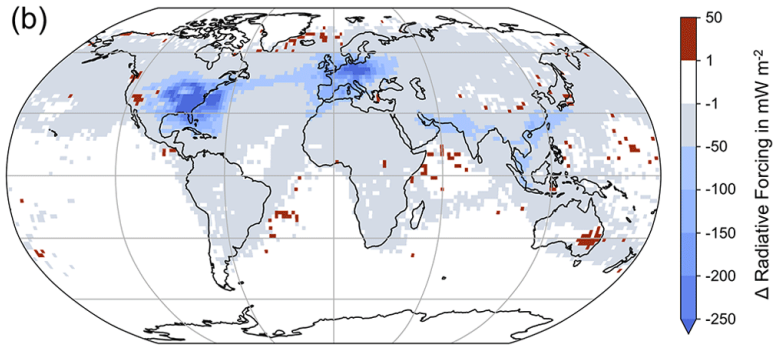
*Contrail cirrus lifetimes and coverage are strongly reduced leading to significant reductions in contrail cirrus radiative forcing… A reduction in the initial ice crystal number of 80% leads to a **decrease in contrail cirrus radiative forcing** by 50%*

Teoh et al. (2020) [Japan]

*Widespread use of new engine combustor technology, which reduces particle emissions, could achieve a 70% **reduction in the contrail EF***

Teoh et al. (2024) [Global]

*Reducing soot particle emissions by a factor of 10 **reduces** global contrail RF by ~80%*



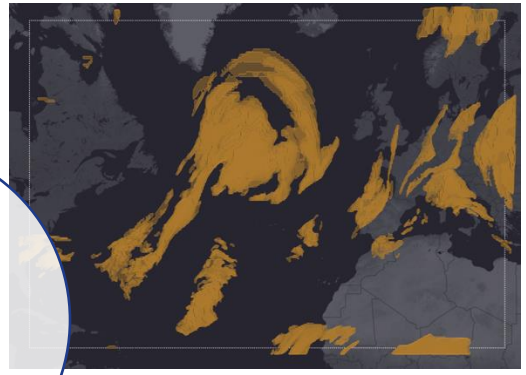
Märkl et al., 2024

Not all contrails are created equal

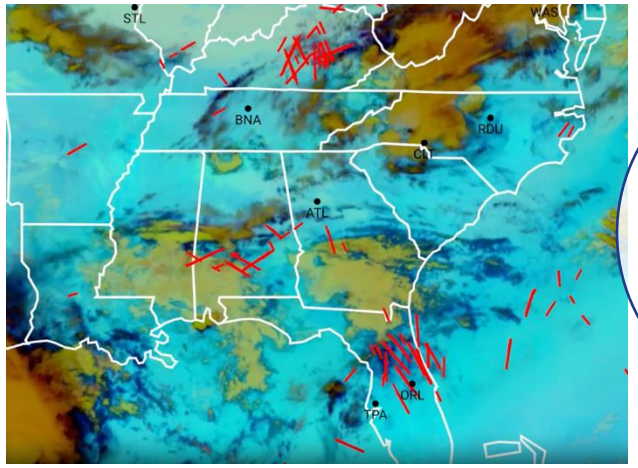
Meteorology, engine emissions, albedo, diurnal / seasonal cycles – all significantly affect radiative forcing

Continuously improved

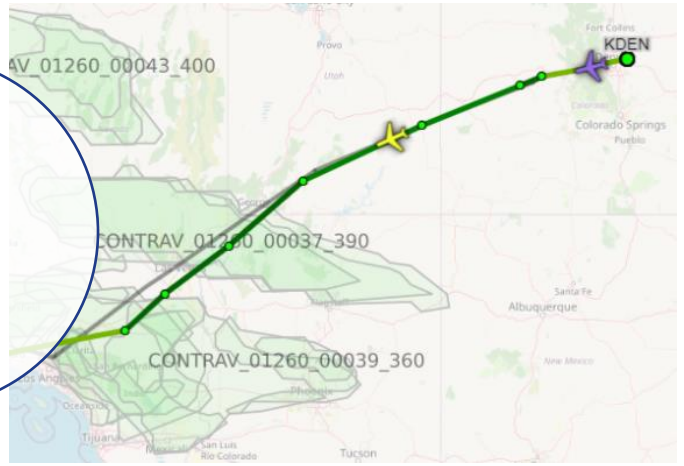
Observations assimilated in near-real-time



Contrail forecast

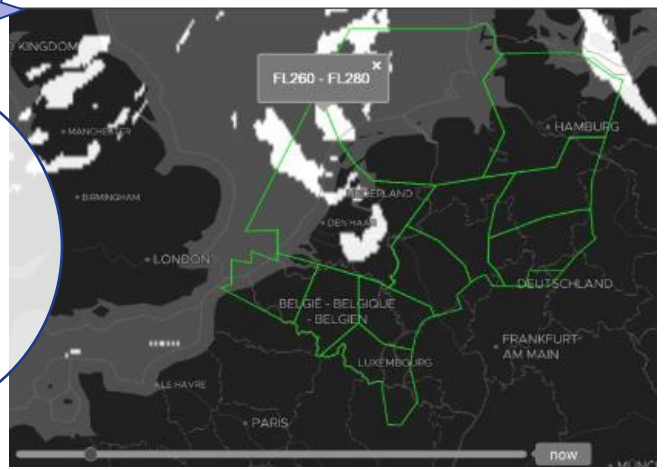


Contrail observations



Flight planning

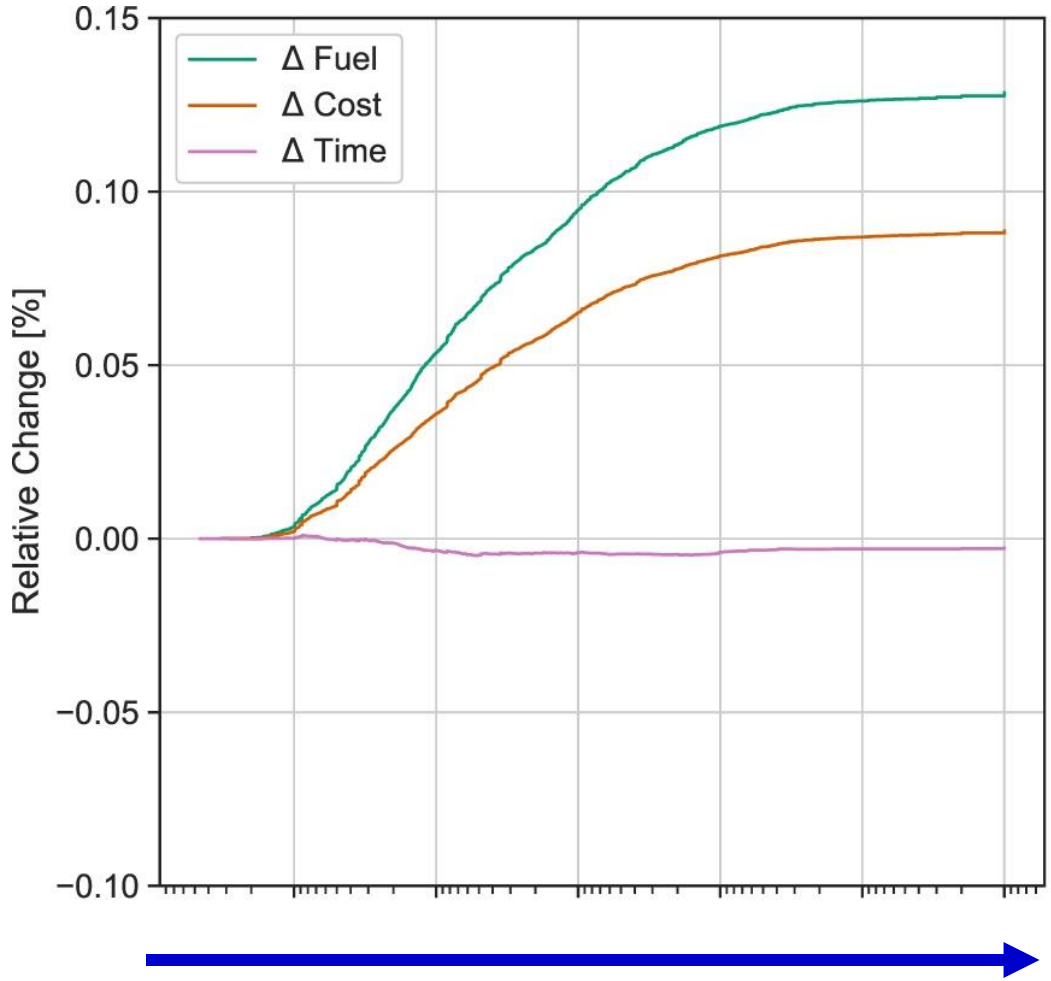
EFB (Cockpit)



ATC

Demonstrate the potential

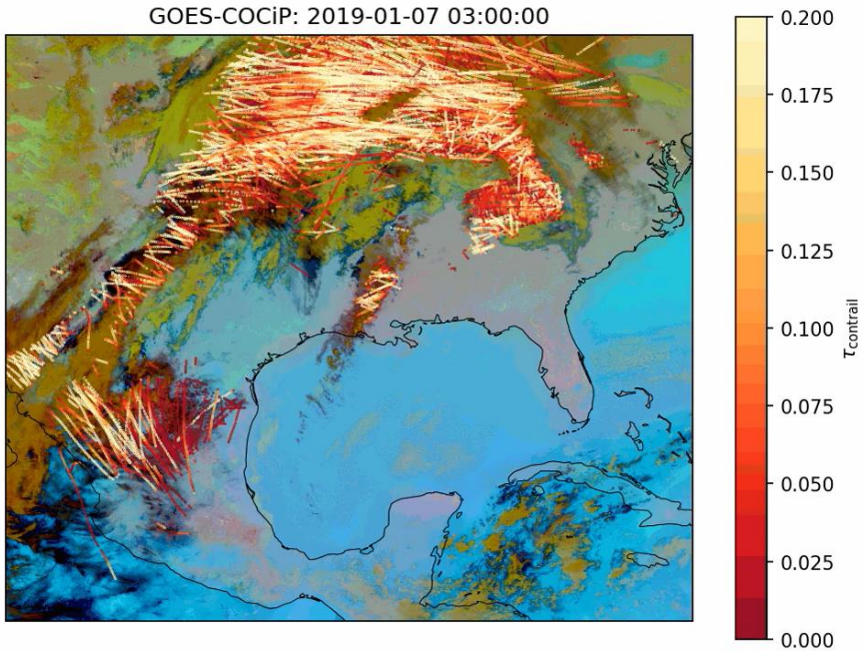
From simulations to real-world demonstrations

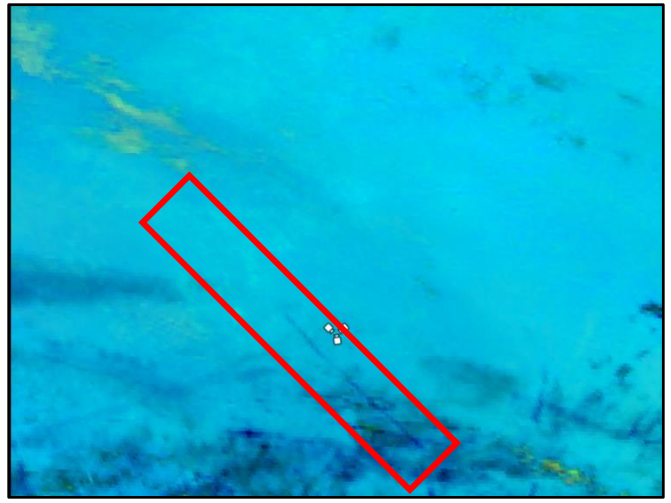


Martin Frias et al., 2024

Evaluation compared to observations

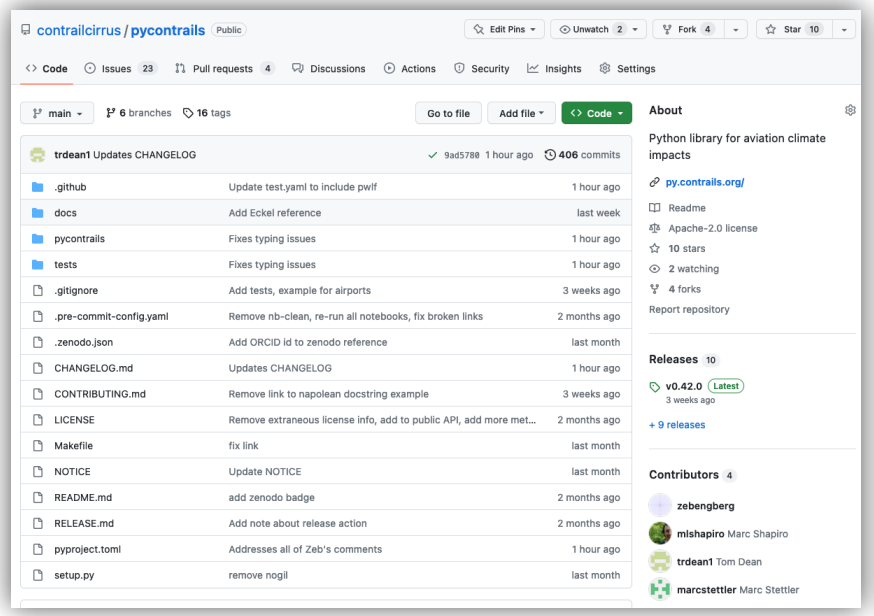
Observations are not perfect, need to combine multiple sources



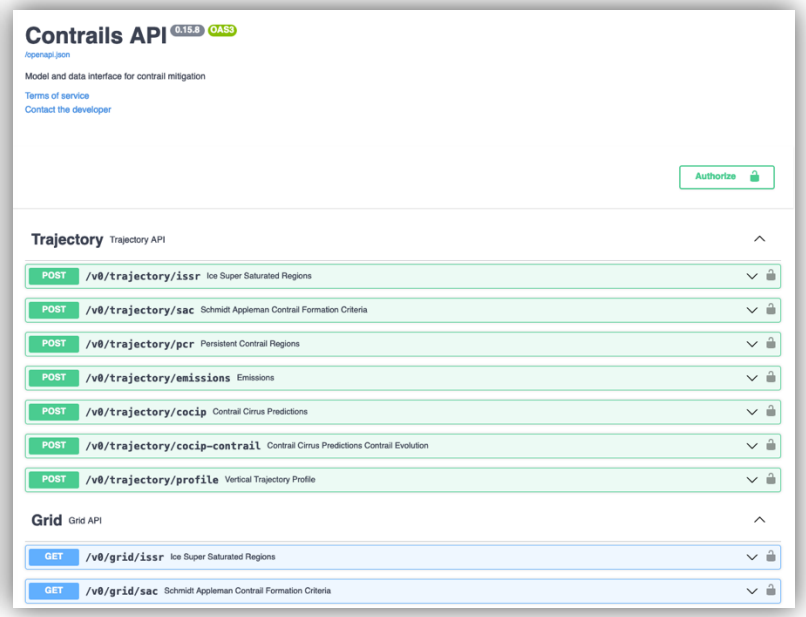


Develop transparent models and interfaces for contrail data

API access to forecast data, verification tools, and historical impact data.



https://py.contrails.org



https://api.contrails.org

https://forecast.contrails.org

We need to talk about Uncertainty.

Uncertainty everywhere all at once

We can take a rational approach to understanding uncertainty. Some are scientific, some are operational.

1. 🤷 Contrail processes are uncertain we don't know if any one contrail will be warming or cooling.
   🙋 Nighttime contrails, if they form and persist are very likely to be warming.

2. 🤷 There is uncertainty in aircraft emissions, especially vPM.
   🙋 Yes! More measurements needed. We can use observations to look for differences in contrails.

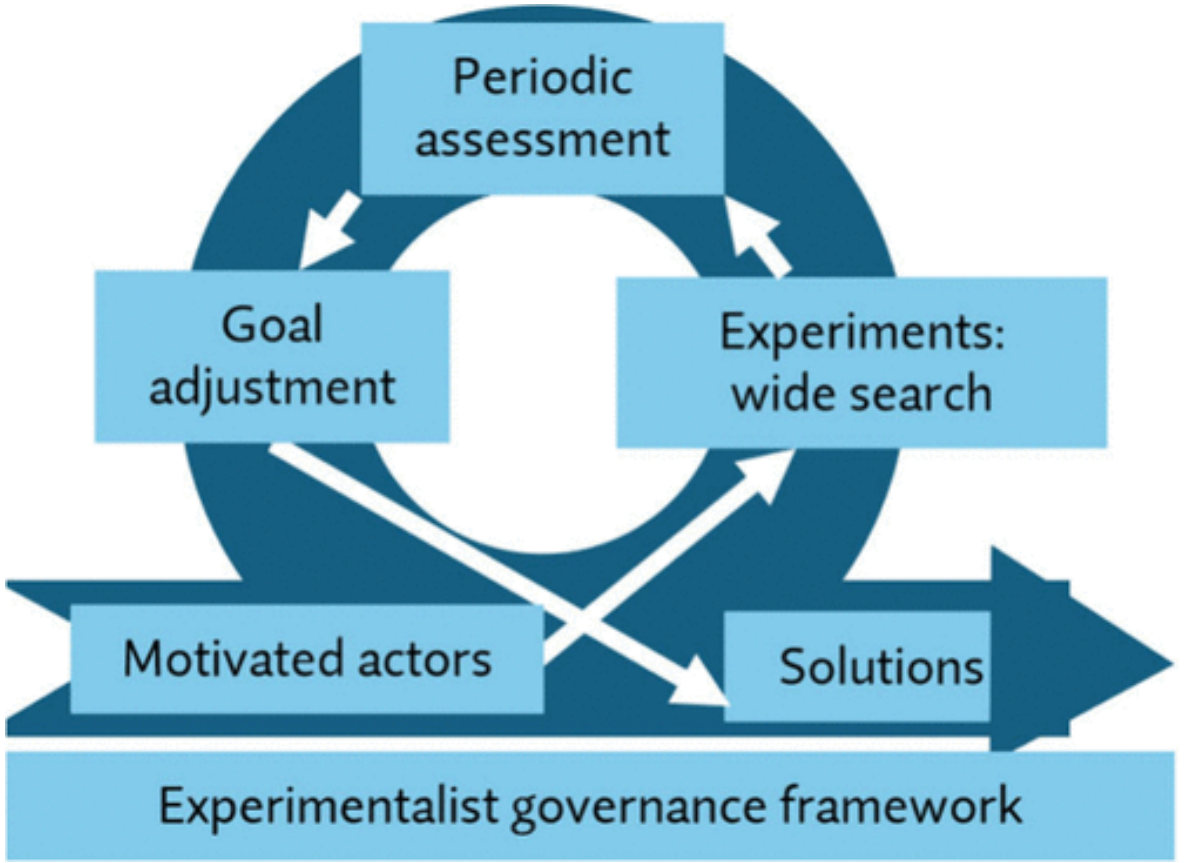
3. 🤷 There is large uncertainty in contrail ERF.
   🙋 Recent studies using different models and observations have estimated contrail ERF within the uncertainty range of Lee et al. 2021.

4. 🤷 Weather forecasts are uncertain and cannot predict ISSRs.
   🙋 All weather forecasts are uncertain, uncertainty can be accounted for and forecasts will improve.

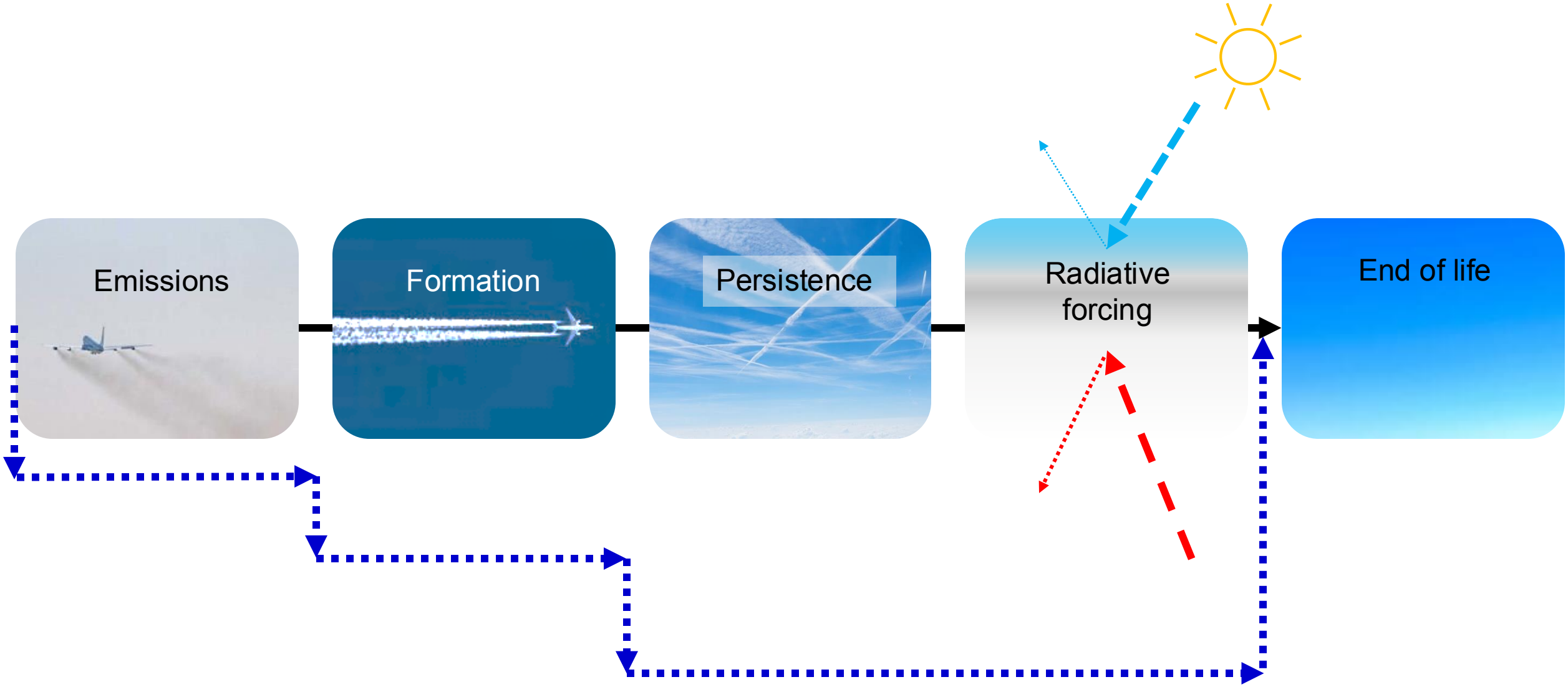
5. 🤷 The fuel penalty associated with avoiding ISSRs is uncertain and may be large.
   🙋 Airline-led simulations and trials suggest it will be small. But this needs to be scaled to entire airspace. Flights aren't fuel optimal today.

Transforming aviation's impact on the climate

Rethinking the research strategy



Kallbekken, Lund and Victor. 2024. ES&T.
https://pubs.acs.org/doi/10.1021/acs.est.4c08470


Emissions
Formation
Persistence
Radiative forcing
End of life

So what?

1. Contrails account for 1-2% of human-caused warming.

2. Not all contrails are created equal – large potential for operational avoidance.

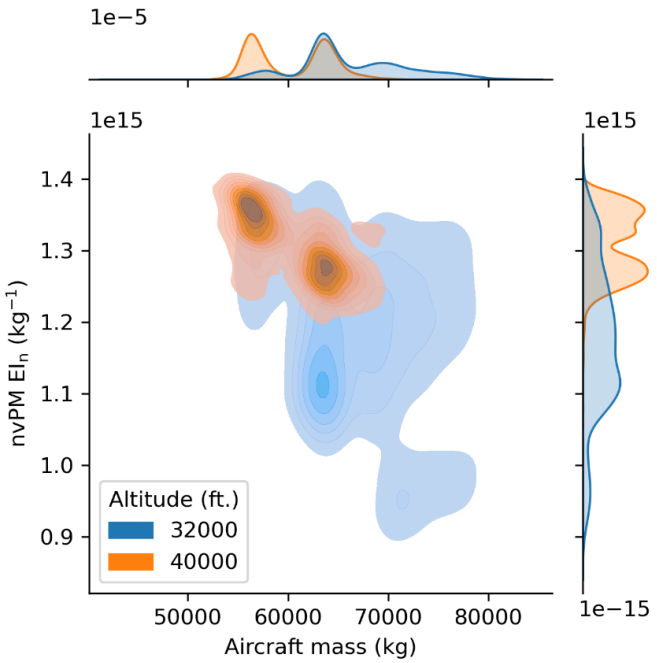
3. We need to work towards real-world demonstrations to tackle complexity and uncertainty head on.

IMPERIAL

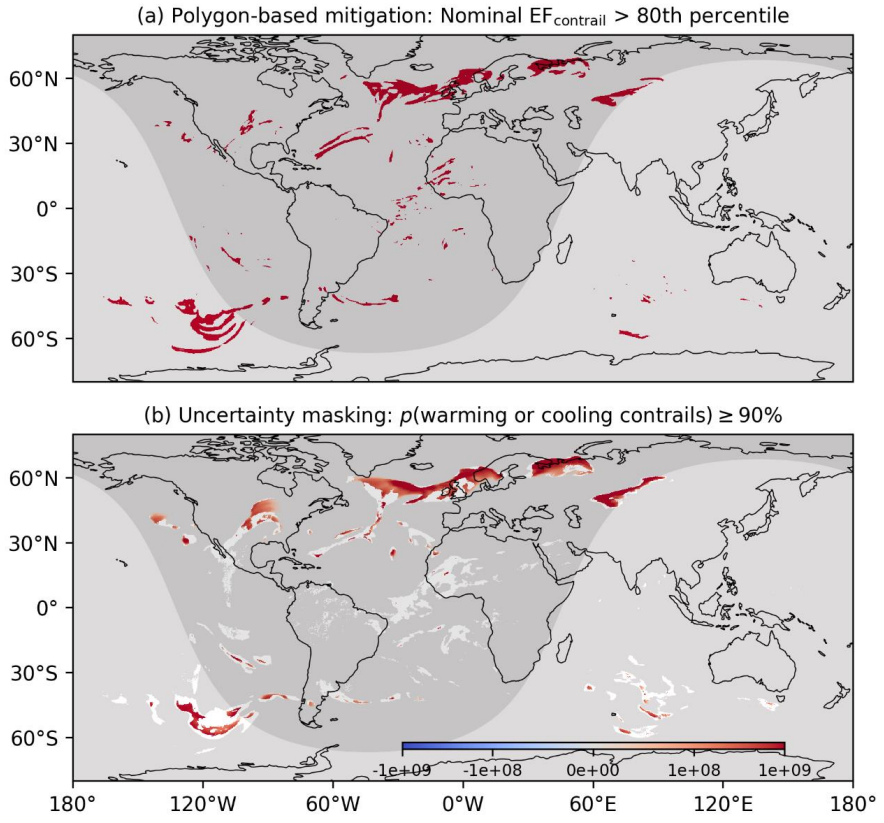
Prototype contrail forecast and implementation

Scaling contrail forecasts

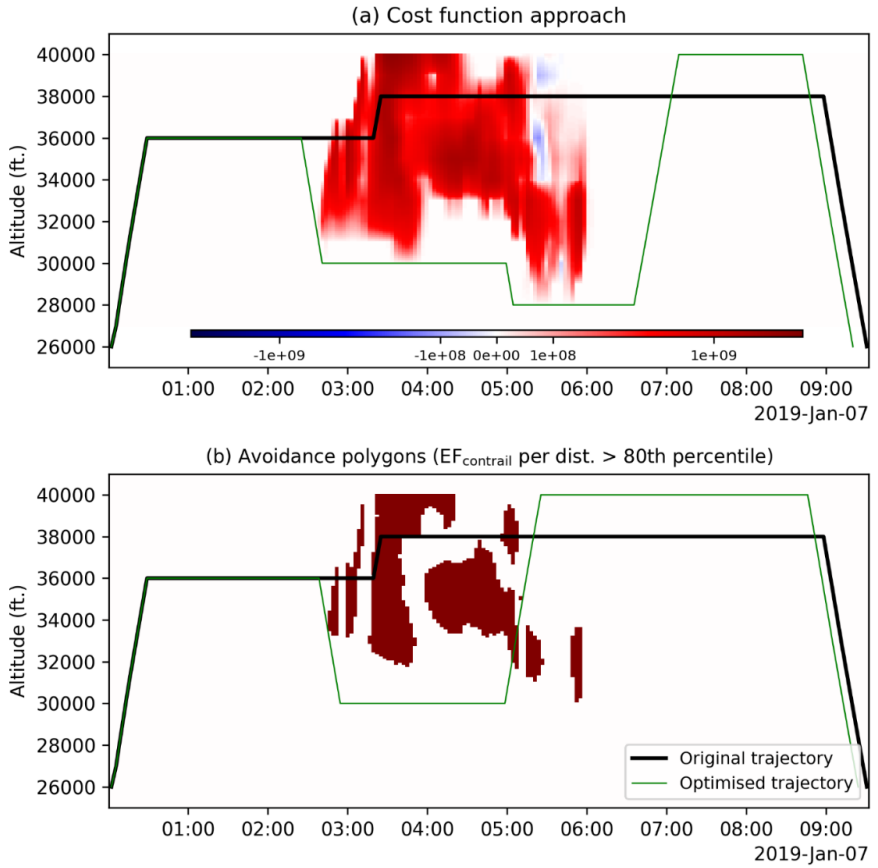
Aircraft classes



Uncertainty masking



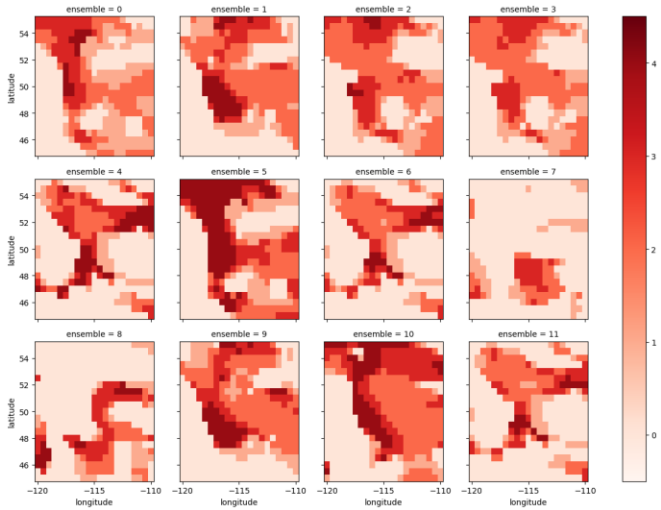
Trajectory optimization



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

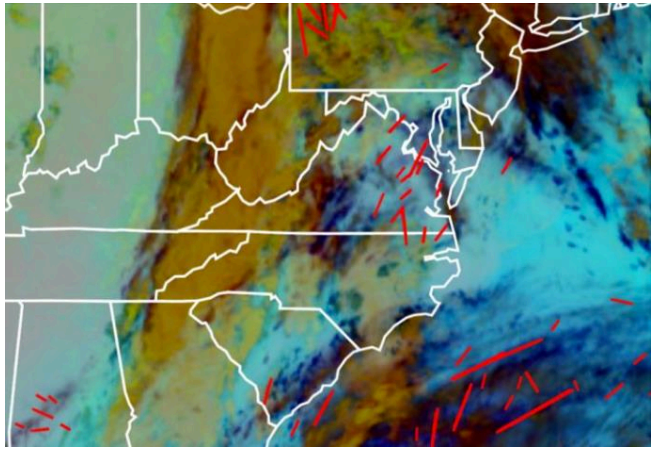
Focus on high-probability high-forcing regions in forecast

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



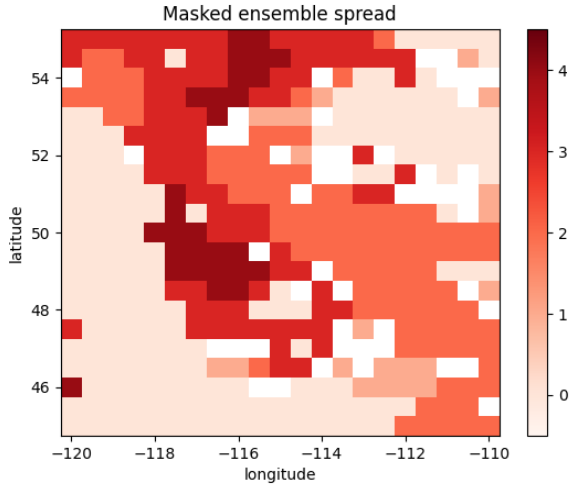
Generate contrail forecast ensembles

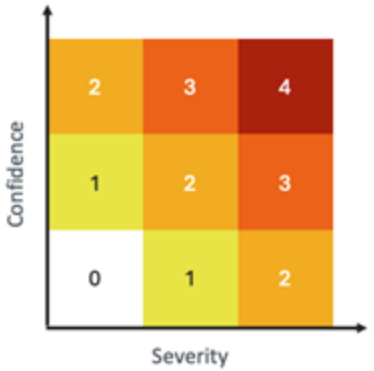
+



Assimilate observation sources

→

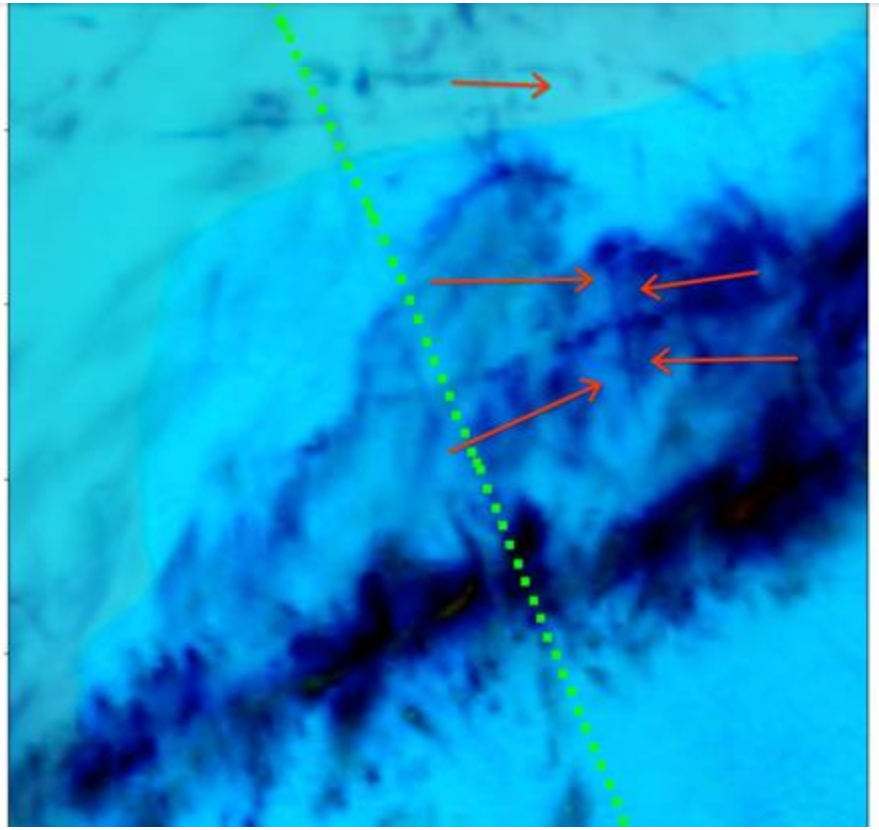


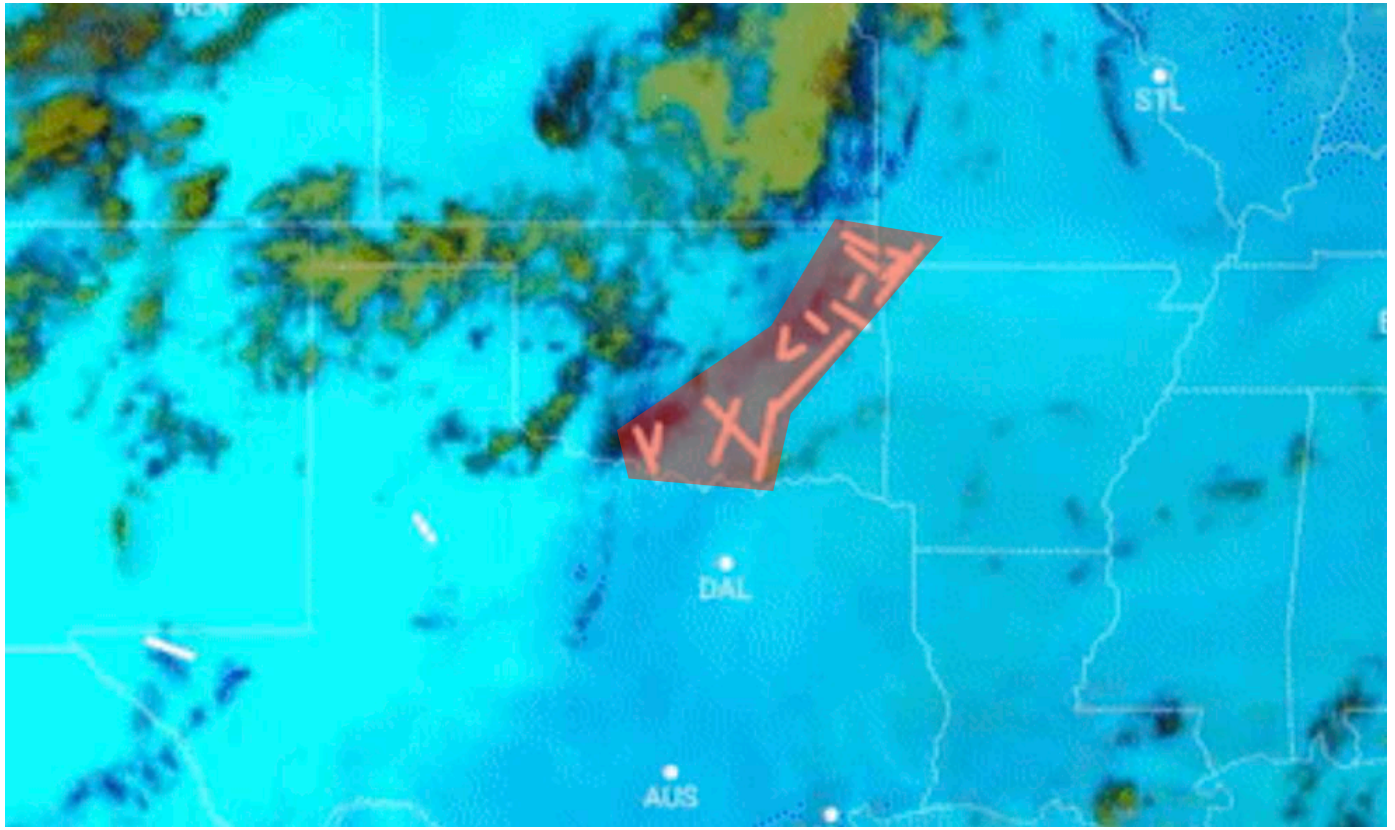


High-probability high impact contrail regions

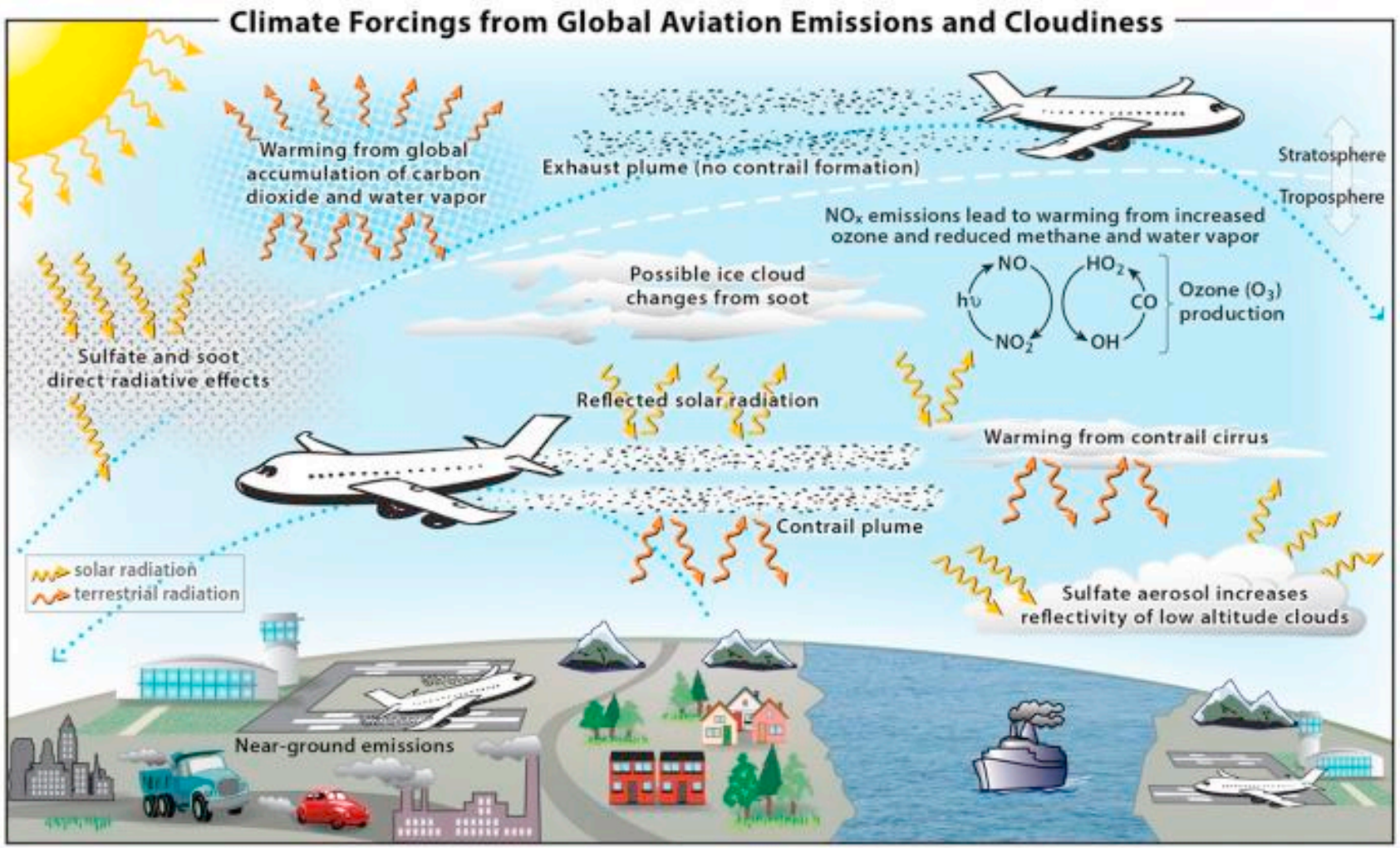
Verify interventions with observational data

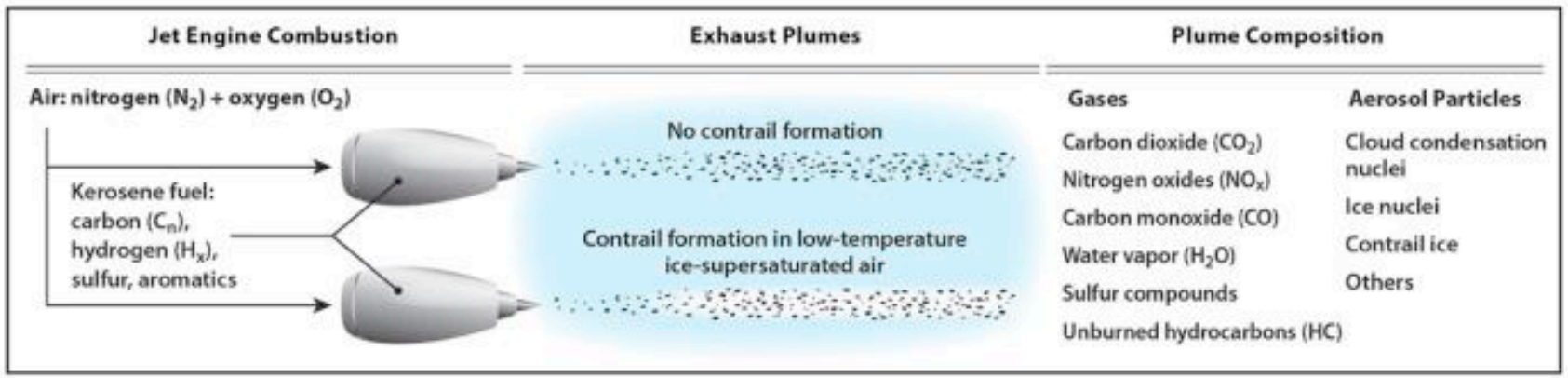
Ensure forecast / nowcast pipelines lead to reduction in contrail formation and contrail outbreaks overall





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



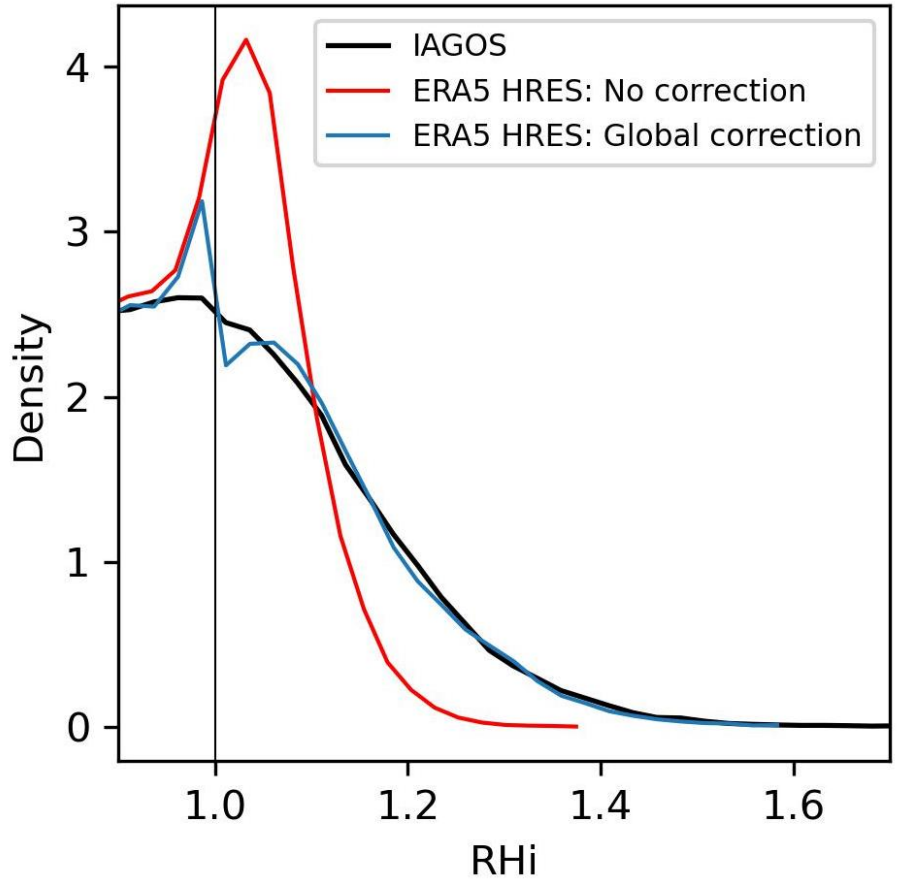


Lee et al., 2021

Persistence

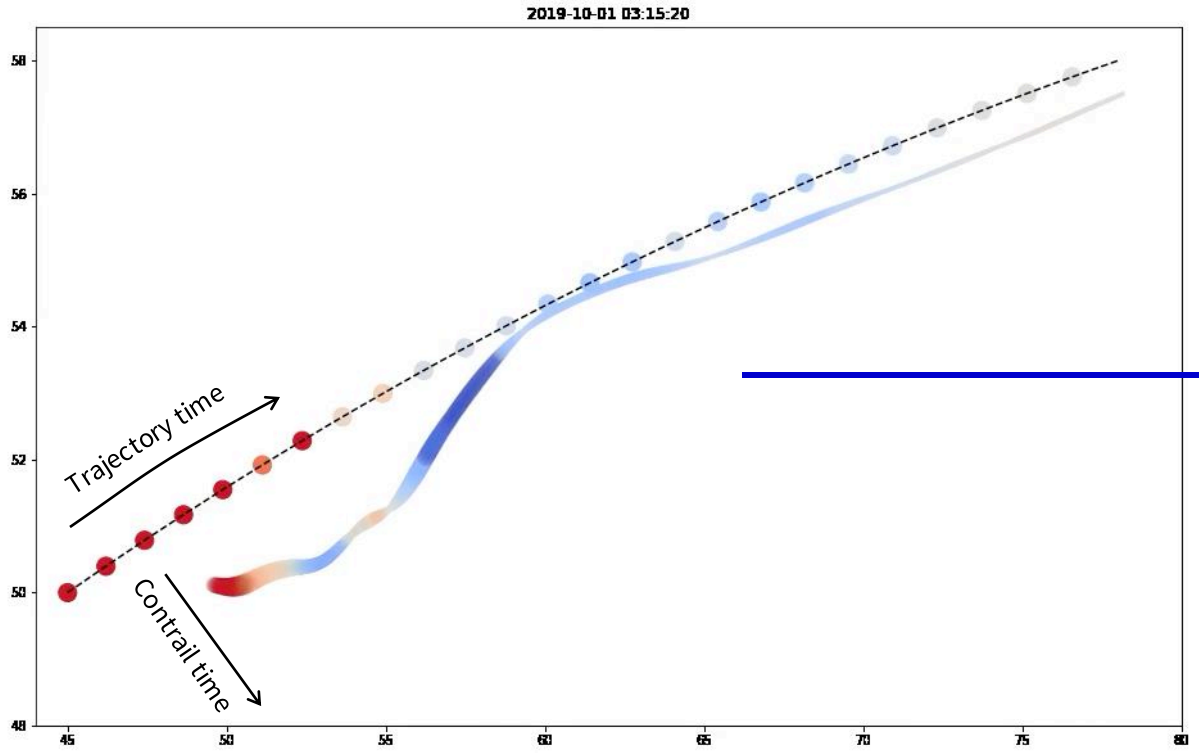
There are limited measurements of humidity at cruise altitudes

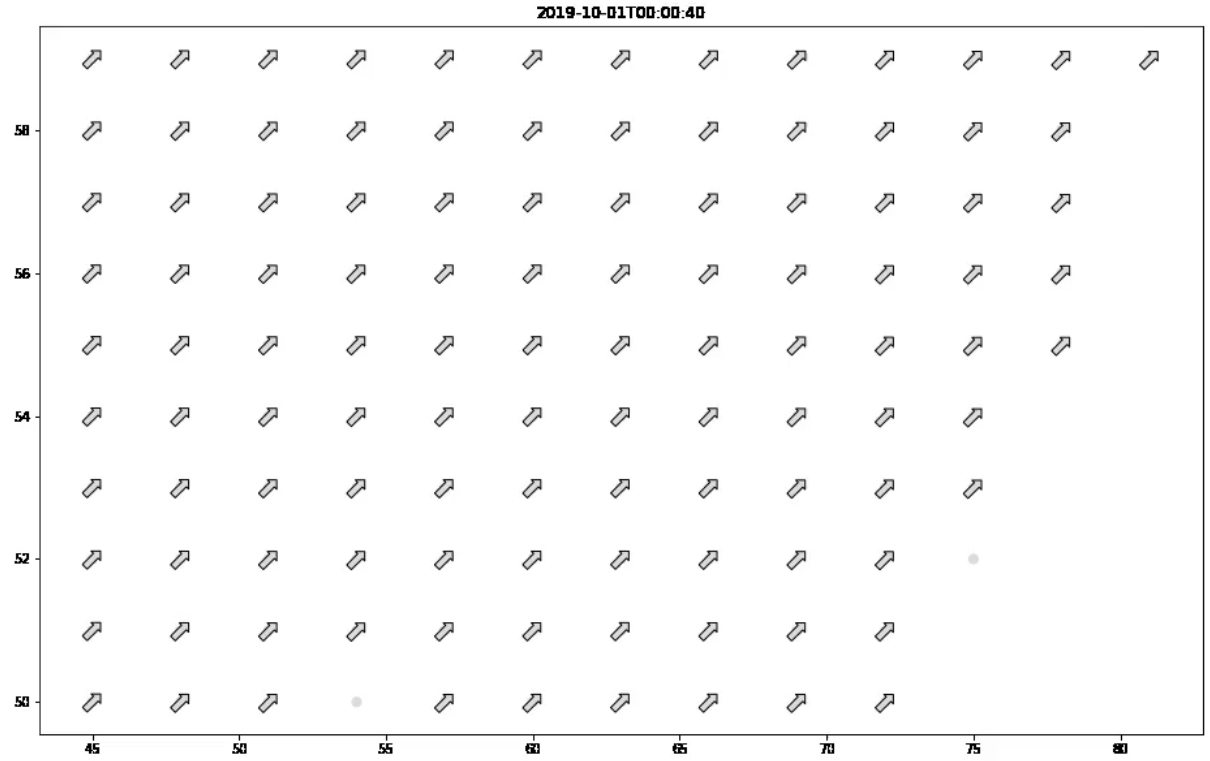
IAGOS
IN-SERVICE AIRCRAFT FOR A GLOBAL OBSERVING SYSTEM



Contrail forecast and implementation

“CoCiP Grid”





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

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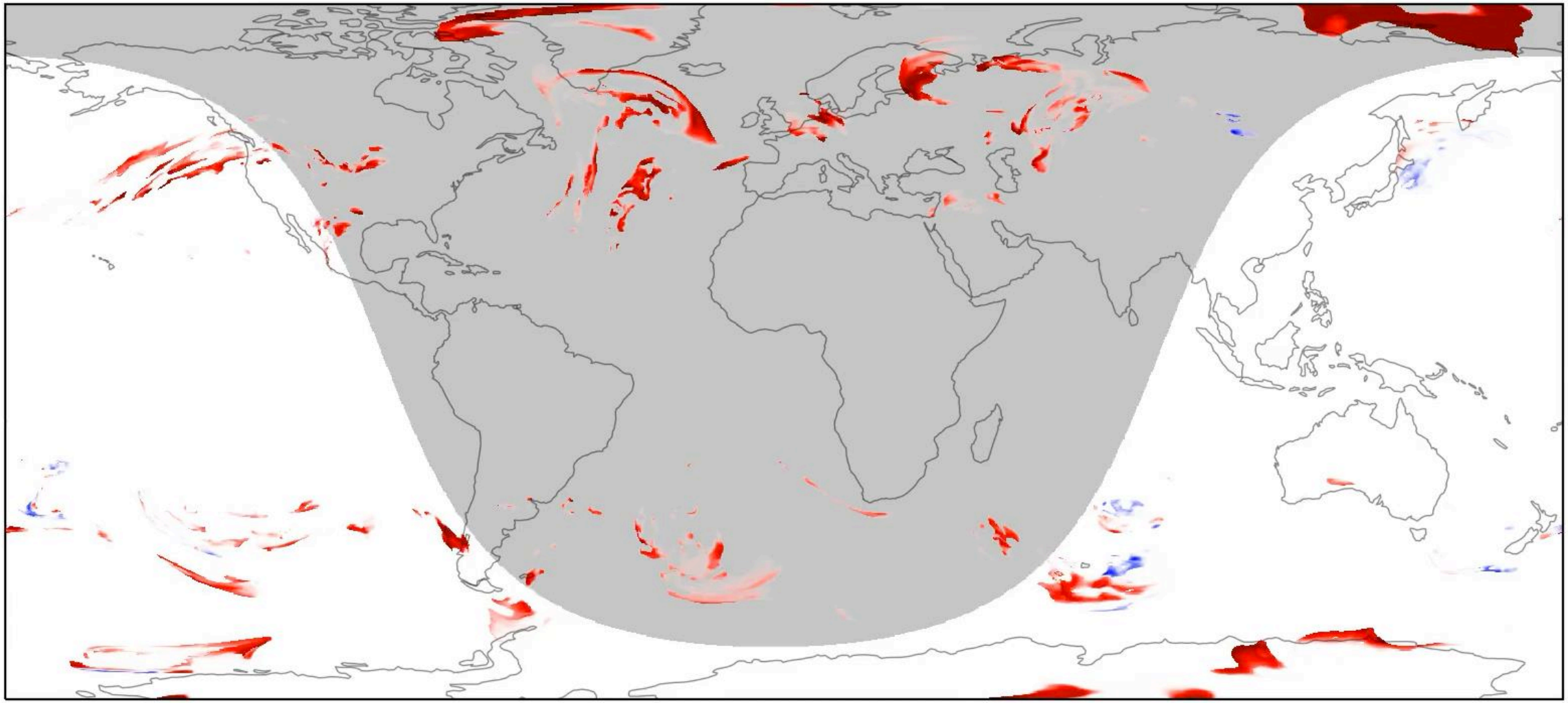

Credit: Global Meteor Network

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