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Research Workshop: Climate Change and the Role of Air Traffic Control, 22 – 23 September 2021, Vilnius, Lithuania

Setting the scene: climate change and its impact on air traffic control

David S Lee, Manchester Metropolitan University, UK

Key concepts addressed

- Aviation's impacts on climate
- Key concepts:
    - The pervasive and long-lasting impact of CO_2
    - 'Radiative forcing' and 'Effective radiative forcing'
    - The relative role of non-CO_2 impacts to total aviation impacts
- Potentials for ATM climate impact reduction

Global[1] aviation and climate – vital statistics[2]

- ~1,000 Million Tonnes of CO_2 in 2018 (based on IEA/IATA data)
- 2.4% of 2018 global annual emissions of CO_2 from fossil fuel combustion, cement manufacturing and land use change (based on above and Global Carbon Budget project)
- 32.6 billion tonnes of cumulative CO_2 since 1940, ~50% of which in the last 20 years
- CO_2 is the principal greenhouse gas emitted by aviation but there are important non-CO_2 effects that cause additional warming
- The metric used to assess present-day impacts is called 'Effective Radiative Forcing' (ERF), where positive = warming
- Non-CO_2 impacts presently represent around 66% of the net ERF; cumulative CO_2 emissions represents around 34% of the net ERF
- The major forcings from global aviation come from contrail cirrus clouds, CO_2 and the 'net NO_x' effect, with minor contributions from water vapour, soot and sulfur aerosol-radiation interactions
- The non-CO_2 effects contribute 8 times more than CO_2 to the uncertainties of net global aviation ERF in 2018
- Together, aviation impacts on forcing are 3.5% of total anthropogenic forcing

[1]note that sectoral climate impacts are based on global (international + domestic)

[2]statistics/data from Lee et al. (2020), *Atmospheric Environment*

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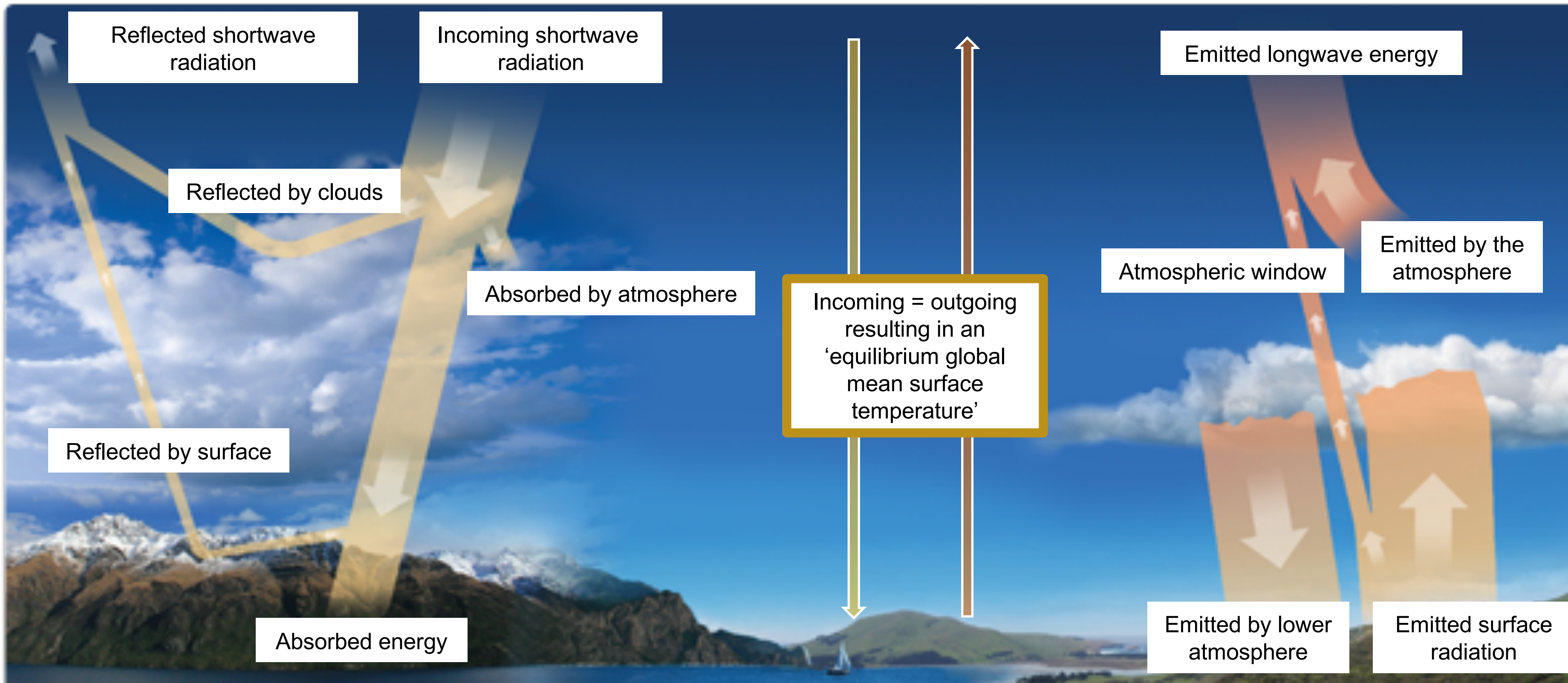
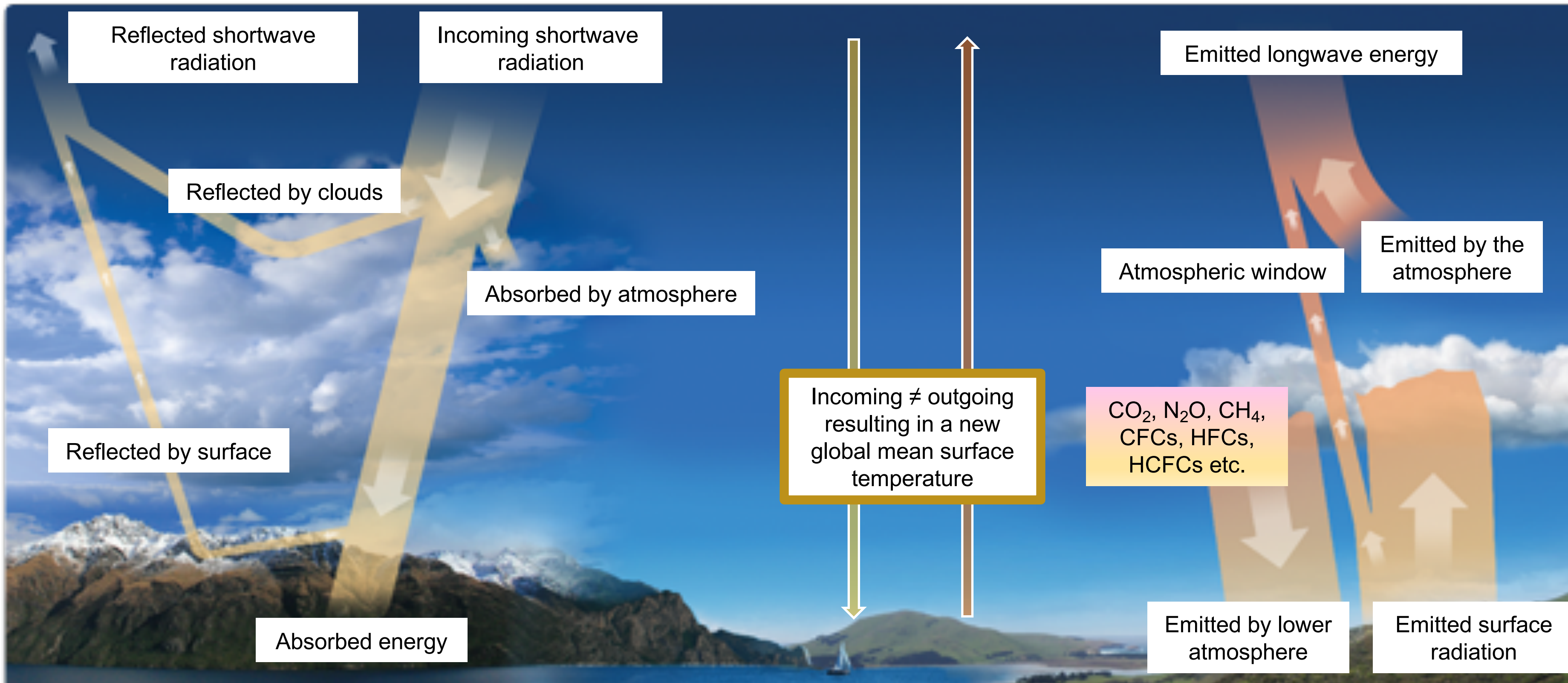
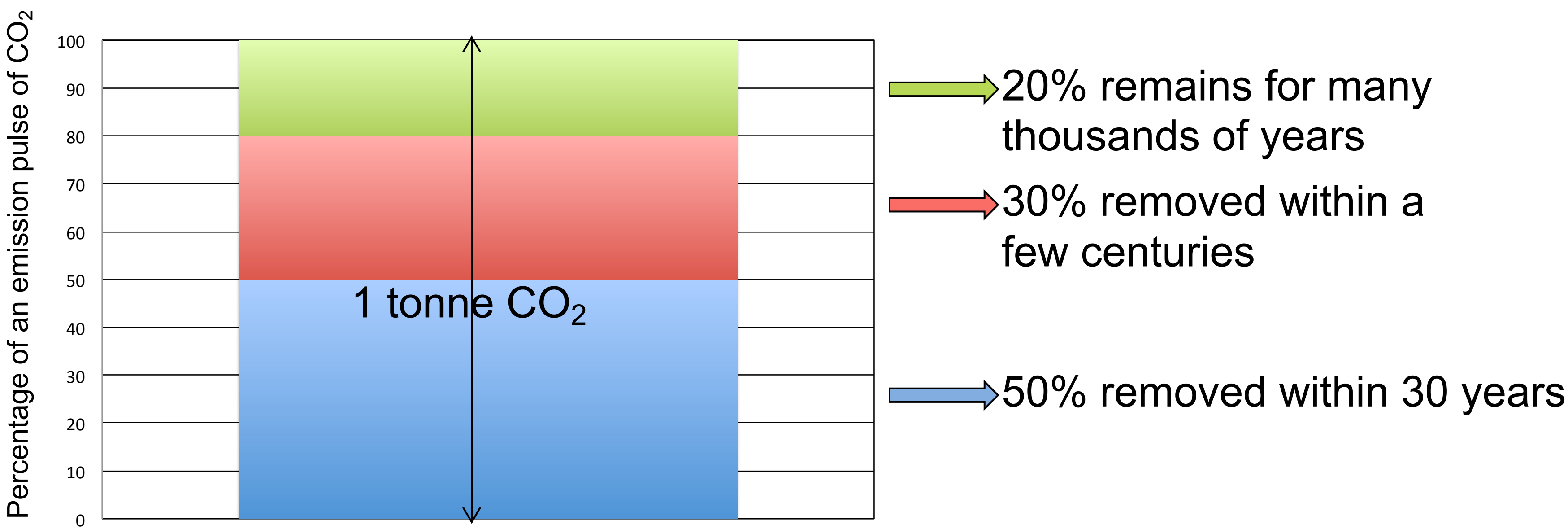
The natural radiation balance of the atmosphere



The perturbed radiation balance of the atmosphere ‘radiative forcing’ (see annex 1)



Why is CO_2 so important? An explanation



Source: IPCC WG1, 2007, Chapter 7

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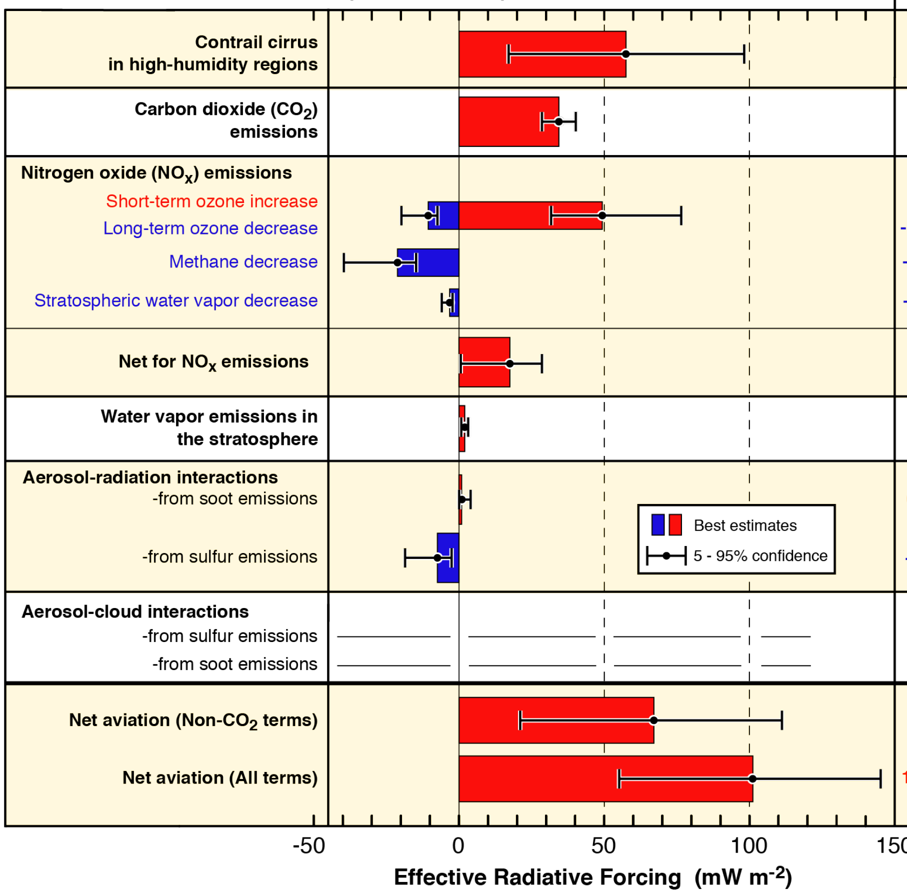
Global Aviation Effective Radiative Forcing (ERF) Terms (1940 to 2018)



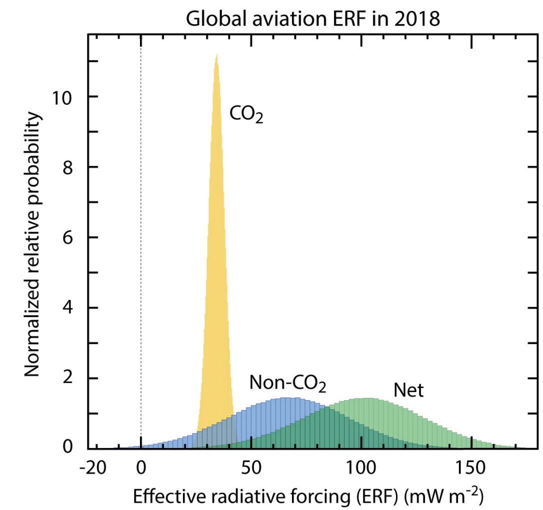
Term	ERF (mW m^{-2})	RF (mW m^{-2})	ERF/RF	Conf. levels
Contrail cirrus in high-humidity regions	57.4 (17, 98)	111.4 (33, 189)	0.42	Low
Carbon dioxide (CO_2) emissions	34.3 (28, 40)	34.3 (31, 38)	1.0	High
Short-term ozone increase	49.3 (32, 76)	36.0 (23, 56)	1.37	Med.
Long-term ozone decrease	-10.6 (-20, -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
Aerosol-radiation interactions -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
Aerosol-cloud interactions -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)	----	——

Source: Lee et al. (2020) *Atmospheric Environment*

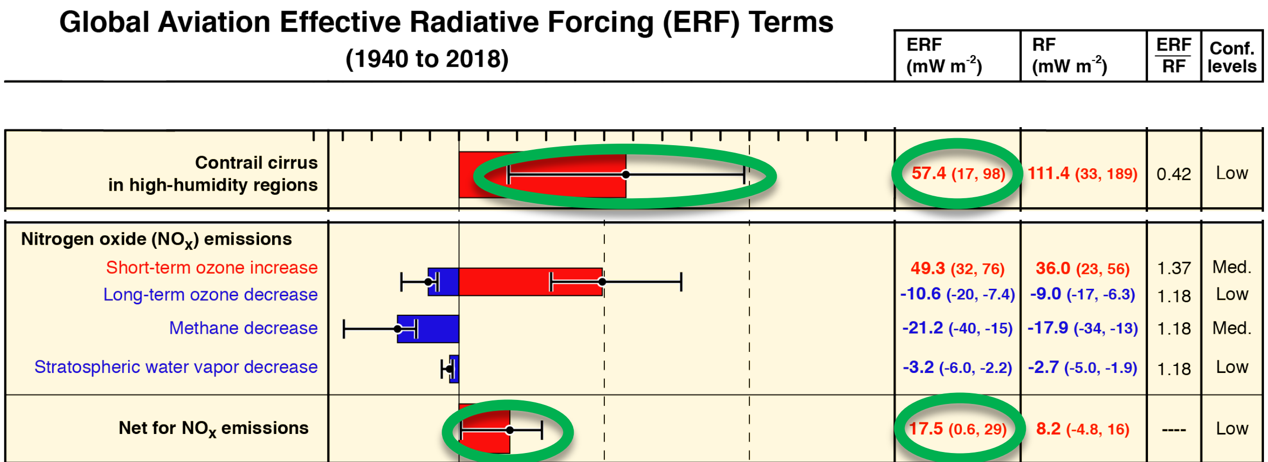
So, what are we certain/uncertain about?

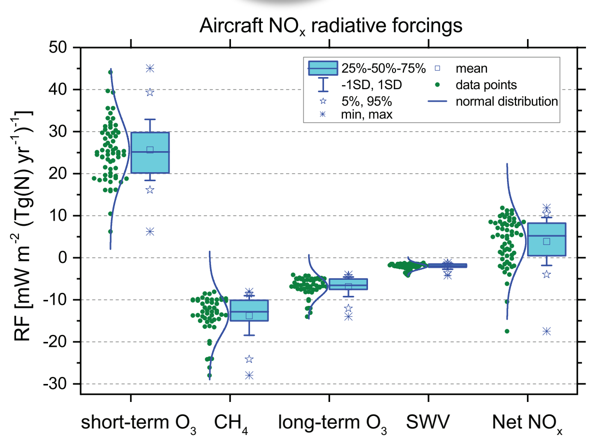
- We have a 'high' confidence level in the CO_2 forcing term
- We have 'low confidence' in the net NO_x and contrail cirrus terms
- We have 'very low confidence' in the aerosol-cloud interactions
- This assessment uses an IPCC methodology

Medium *High agreement* *Limited evidence*	***High*** *High agreement* *Medium evidence*	***Very High*** *High agreement* *Robust evidence*
Low *Medium agreement* *Limited evidence*	***Medium*** *Medium agreement* *Medium evidence*	***High*** *Medium agreement* *Robust evidence*
Very Low *Low agreement* *Limited evidence*	***Low*** *Low agreement* *Medium evidence*	***Medium*** *Low agreement* *Robust evidence*



Source: Lee et al. (2020) *Atmospheric Environment*





Nature of uncertainties

Contrail cirrus

- largely expert judgement
- limited simulations
- three models

Net NO_x

- Statistical
- Large number of (different) model simulations

N.B. evaluations and uncertainties relate to present-day conditions; the latter would be larger for unknown future states of the background atmosphere

Source: Lee et al. (2020) *Atmospheric Environment*

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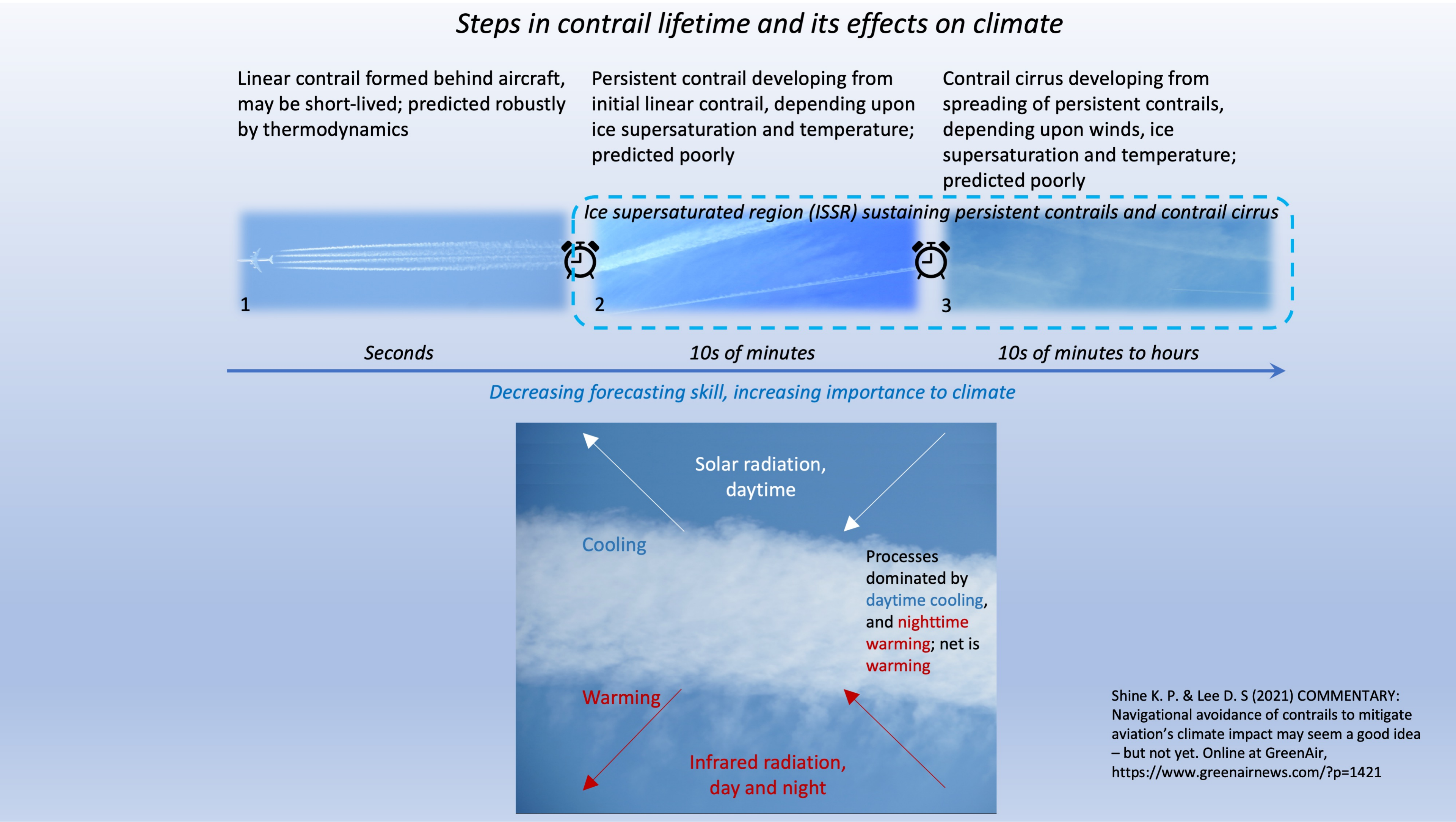
Reducing impacts via ATM

- NO_x impacts, contrail cirrus (avoidance) – this is not straightforward, since:
  - The sensitivity of the atmosphere is dependent on region and other emissions
  - There are tradeoffs, e.g. flying lower would increase CO_2
  - Comparing impacts (one increased, one decreased) depends on the emission equivalence metric used (e.g. GWP, GTP etc.), and the time horizon over which it is calculated
  - We cannot, at present, predict *persistent* contrails with sufficient accuracy with meteorological models



Steps in contrail lifetime and its effects on climate
Linear contrail formed behind aircraft, may be short-lived; predicted robustly by thermodynamics
Persistent contrail developing from initial linear contrail, depending upon ice supersaturation and temperature; predicted poorly
Contrail cirrus developing from spreading of persistent contrails, depending upon winds, ice supersaturation and temperature; predicted poorly
Ice supersaturated region (ISSR) sustaining persistent contrails and contrail cirrus
1
2
3
Seconds
10s of minutes
10s of minutes to hours
Decreasing forecasting skill, increasing importance to climate
Solar radiation, daytime
Cooling
Processes dominated by daytime cooling, and nighttime warming; net is warming
Warming
Infrared radiation, day and night
Shine K. P. & Lee D. S (2021) COMMENTARY: Navigational avoidance of contrails to mitigate aviation's climate impact may seem a good idea – but not yet. Online at GreenAir, https://www.greenairnews.com/?p=1421

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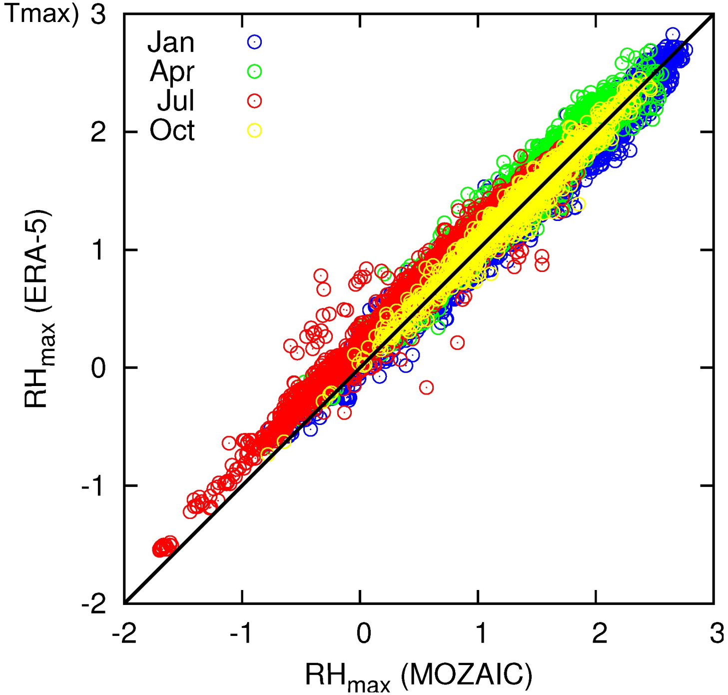
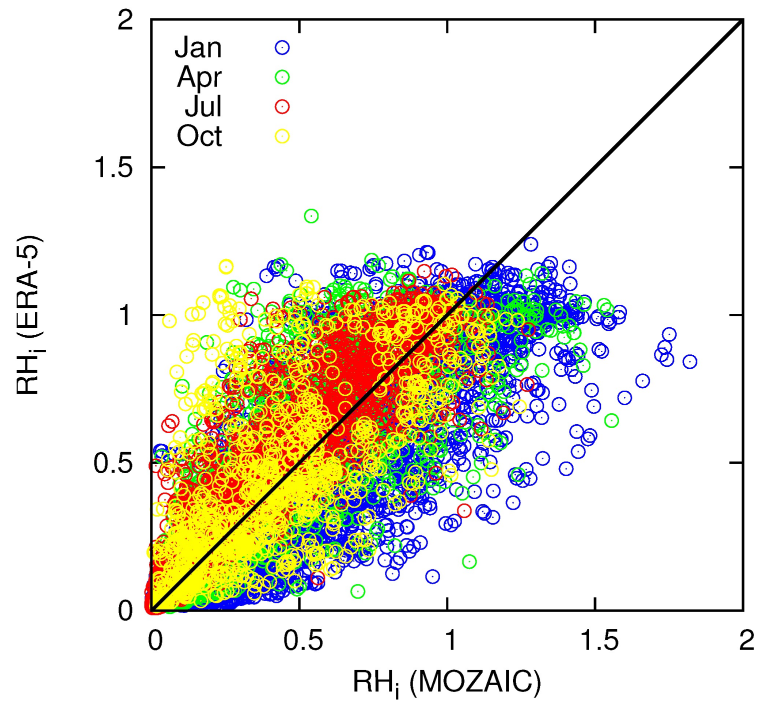
Meteorological model forecast skill – a critical limitation

Comparison of contrail formation conditions expressed as relative humidity in the exhaust plume in the moment when the temperature reaches Tmax, for MOZAIC (x-axis) and the corresponding ERA-5 data (y-axis). Contrails are possible when RHmax≥1. Negative RHmax signifies conditions warmer than the maximum temperature where contrails are possible (that is, the plume does not get as cold as Tmax)

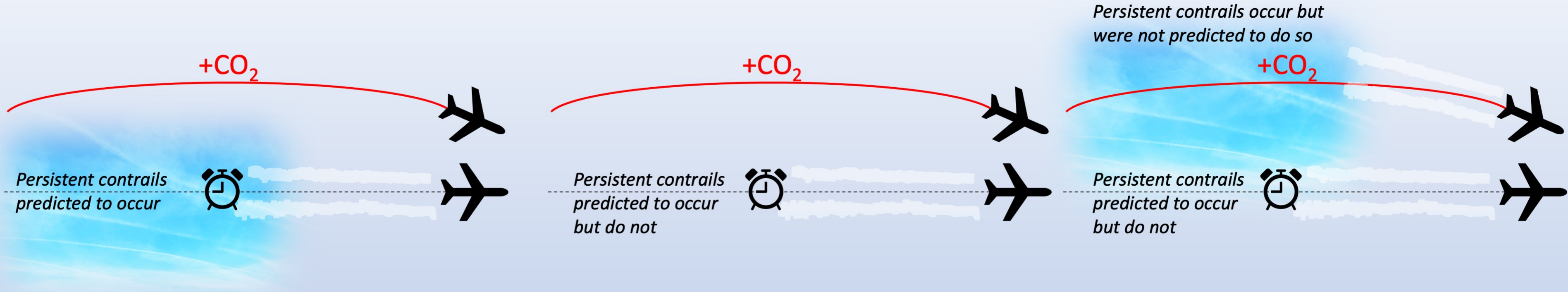


Comparison of relative humidity with respect to ice for MOZAIC (x-axis) and the corresponding ERA-5 data (y-axis). Colours are as in Figure 1. Contrails are persistent when RHi≥1.



Source: Gierens et al. (2020) *Aerospace*

Potential outcomes of navigational avoidance of persistent contrails



1. Successful re-route (but only if extra fuel use is justified to avoid contrail)[1]. Persistent contrail conditions occur where predicted, spreading into contrail cirrus.

[1]Assuming it can be verified that persistent contrail conditions would have occurred, as predicted, on original route

2a. Failed re-route (illustrated). Persistent contrail conditions do not occur (on original route) where predicted.
2b. Failed re-route (not illustrated). Persistent contrails occur on *both* the original and the re-route.

Bad outcome: extra CO_2

3. Failed re-route. Persistent contrail conditions predicted to occur on original route but actually occur instead on the re-route.

Bad outcome: extra CO_2
and persistent contrails still formed

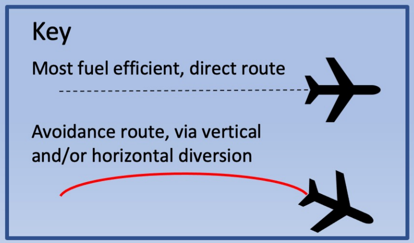


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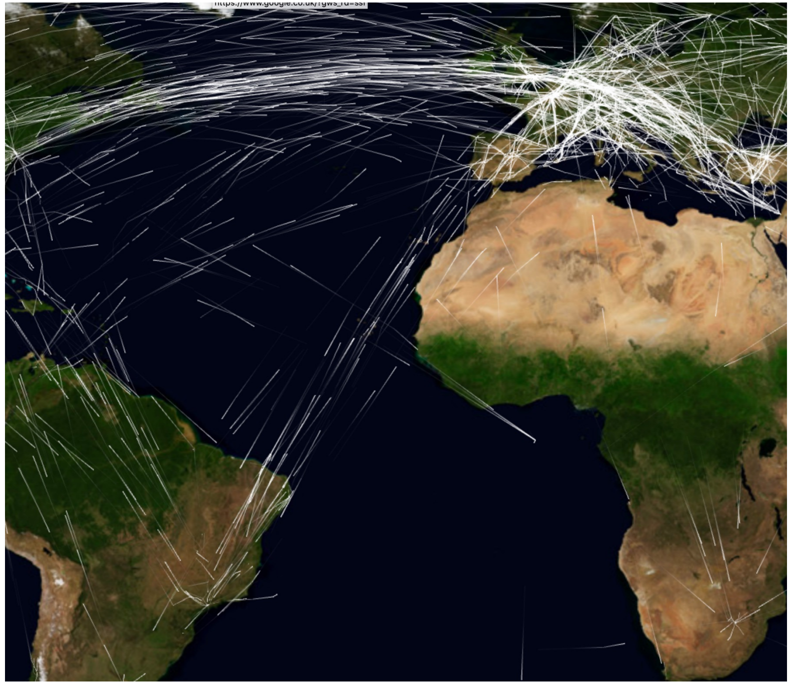
Figure based on an original idea by Dr Emma Klingaman, University of Reading

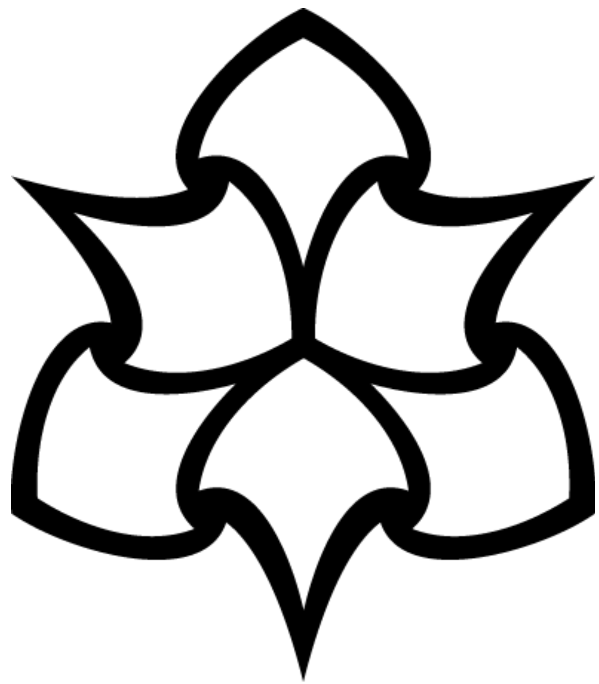
‘Climate optimization’ of flights – a wider look

- Where is this a possibility?
- Over mainland Europe?
- Over NAFC?
- Who has the mandate for this?
- Will re-routing involve extra CO_2?
- How does one calculate whether there is a climate benefit or disbenefit?
- Which ‘climate metric’ (emissions-equivalence), GWP, GTP, ATR, GWP*? And, what time horizon? (they will all give you different answers – they are all ‘correct’ but will suggest difference conclusions as to benefit/disbenefit)



Conclusions

- **Always strive to reduce CO_2 – positive outcome, high confidence**
- Be cautious of actions that reduce ('trade') non-CO_2 effects for increased CO_2
- There is potential for reducing overall aviation climate effects via ATM
- Scientific agreement on 'readiness' of ATM navigational avoidance of climate sensitive areas, and 'how', is low



ANNEX 1: Key concepts

Radiative forcing – the metric of climate change

- 'Radiative Forcing' (RF, in watts per square metre) is the change in the earth-atmosphere energy balance since pre-industrialization and is used to quantify present-day impacts from current and (largely) historical emissions (in the case of long-lived greenhouse gases) as it has an approximately linear relationship with the equilibrium global mean surface temperature change (ΔT_s in Kelvin) since the onset of industrialization.
- $$\Delta T_s = \lambda \; RF$$
- Where λ is the climate sensitivity parameter in K $(Wm^{-2})^{-1}$
- Since IPCC AR5, the scientific community is now using the 'Effective Radiative Forcing' (ERF), since it accounts for fast feedbacks & adjustments from e.g., clouds, aerosols better and has a better relationship with ΔT_s

Key takeaway – the metric that the climate science community use has changed (RF → ERF) in terms of capturing the impact on climate in a more complete manner