John Green

RAeS Greener by Design

RAeS Conference Report

Mitigating the climate impact of non-CO2

Aviation's low-hanging fruit

23 / 24 March 2021

IWACC 7 , UTIAS 21 May 2021

AGENDA

Evolution and objectives of the Greener by Design Contrail Avoidance Group

How we came to be,

what we have achieved and

what we aim to achieve

Conference Programme

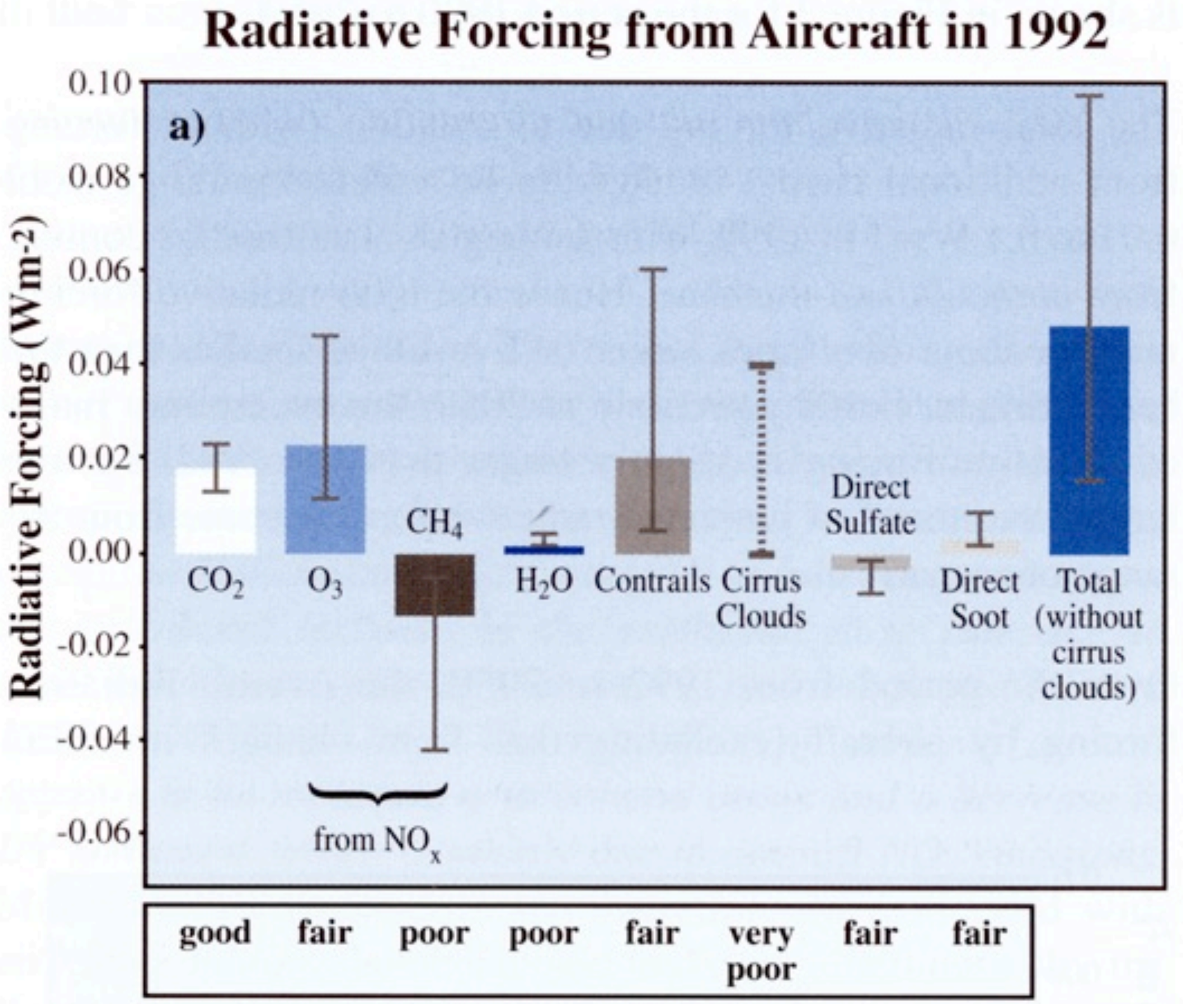
- The Science Base
  - Overview
  - NOx
  - Contrail forecasting and observation
- Mitigation possibilities
  - Emissions reduction
  - Novel fuels
  - Contrail avoidance
  - Impact on fuel burn
  - Regulation and governance
  - Way forward

In the beginning, 1999

IPCC Report on Aviation and the Global Atmosphere published

In the same year the UK air travel community decided to launch Air Travel – Greener by Design

Non-CO2 RF put at 1.7 times that of CO2, with contrails the biggest single contributor



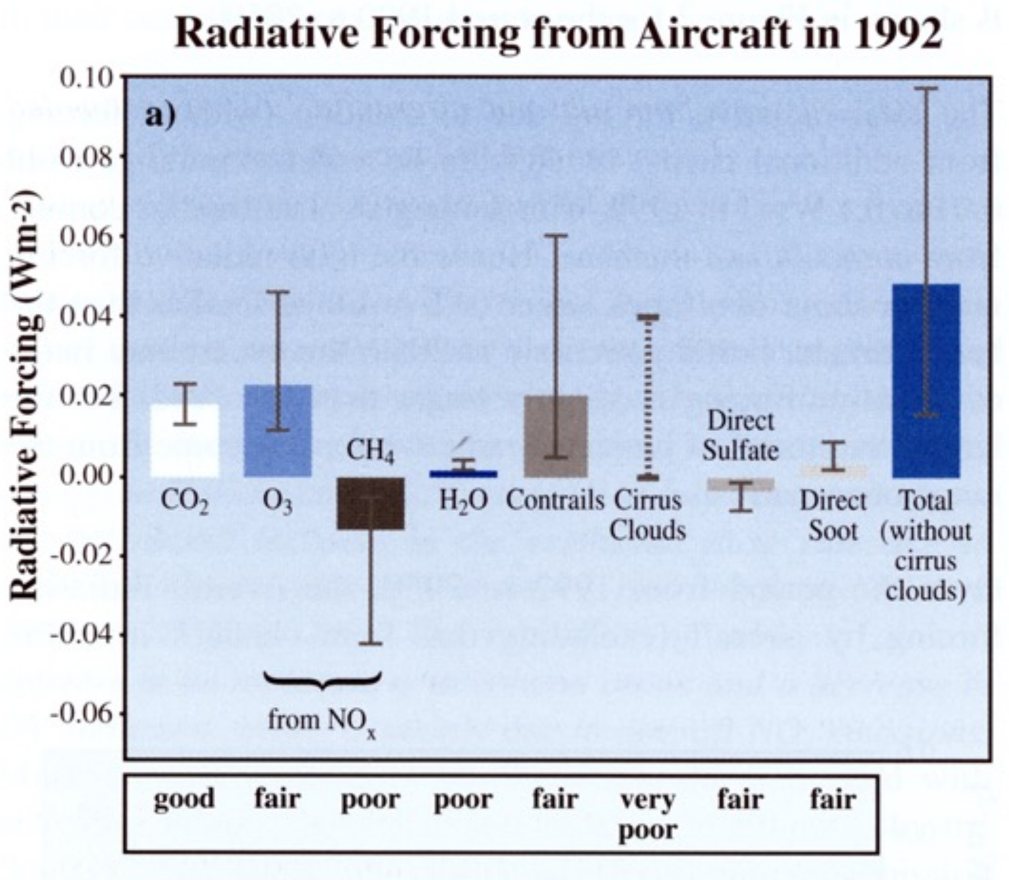
Greener by DESIGN

GBD milestone, July 2001

- First reports of sub groups published
- Report by Technology Sub Group (84 pp) covers noise, LAQ and climate change, with priority given to climate change
- Emphasis on configurations and technology to reduce fuel burn.
- Effect of engine OPR on fuel burn, NOx and total RF discussed
- No recommendation on contrail reduction

Presentation to CASI and Aero J paper, 2003

- Persistent contrails can be avoided by flying above, below or around ice-saturated regions: this will increase fuel burn and CO2 emissions
- Further advances in atmospheric science, air traffic management and meteorology are needed before such a strategy can be justified or adopted
- Nevertheless, if we allow for some significant contribution from cirrus, reducing persistent contrails might prove to be the single most powerful means of reducing the impact of aviation on climate, even though it would increase CO2 emissions
- Perhaps in 20 years' time improvements in ATM and met may make such a strategy feasible



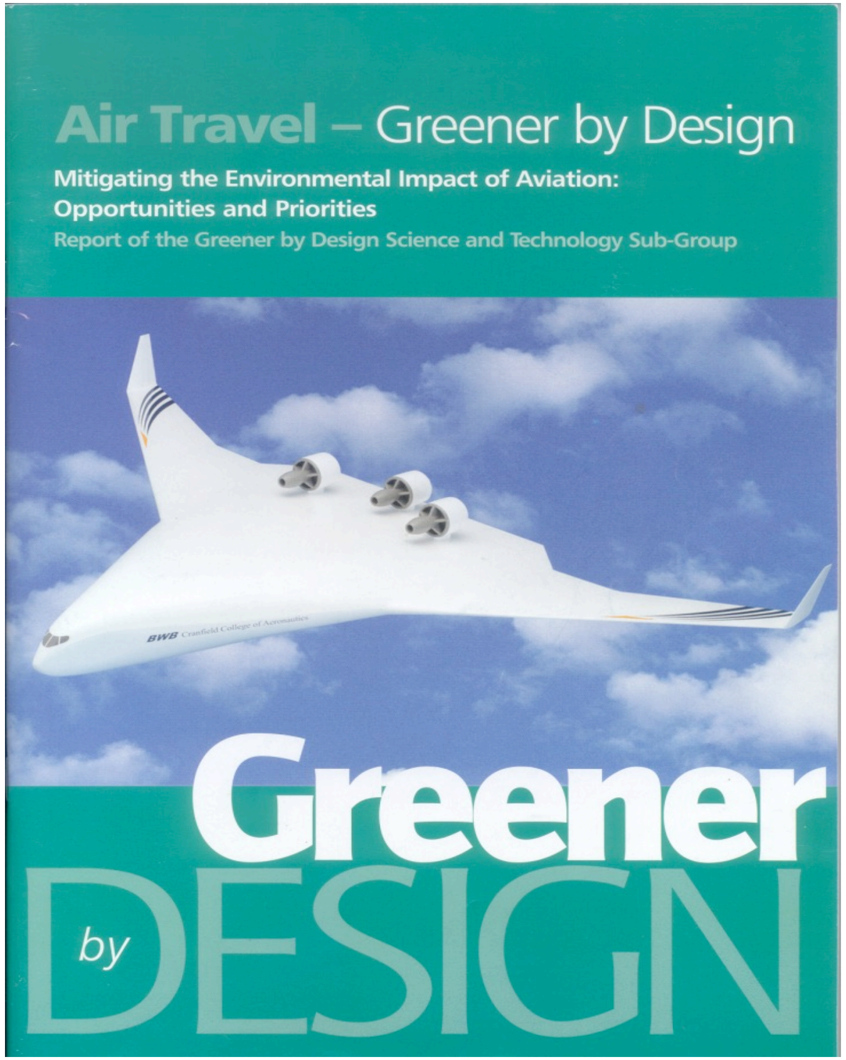
A recommendation, July 2005

Study proposed of “the practicalities and difficulties of adapting the European air-traffic control system to enable contrail formation to be reduced by denial of critical flight levels and by re-routing.”

Prompted by research at DLR and Imperial College

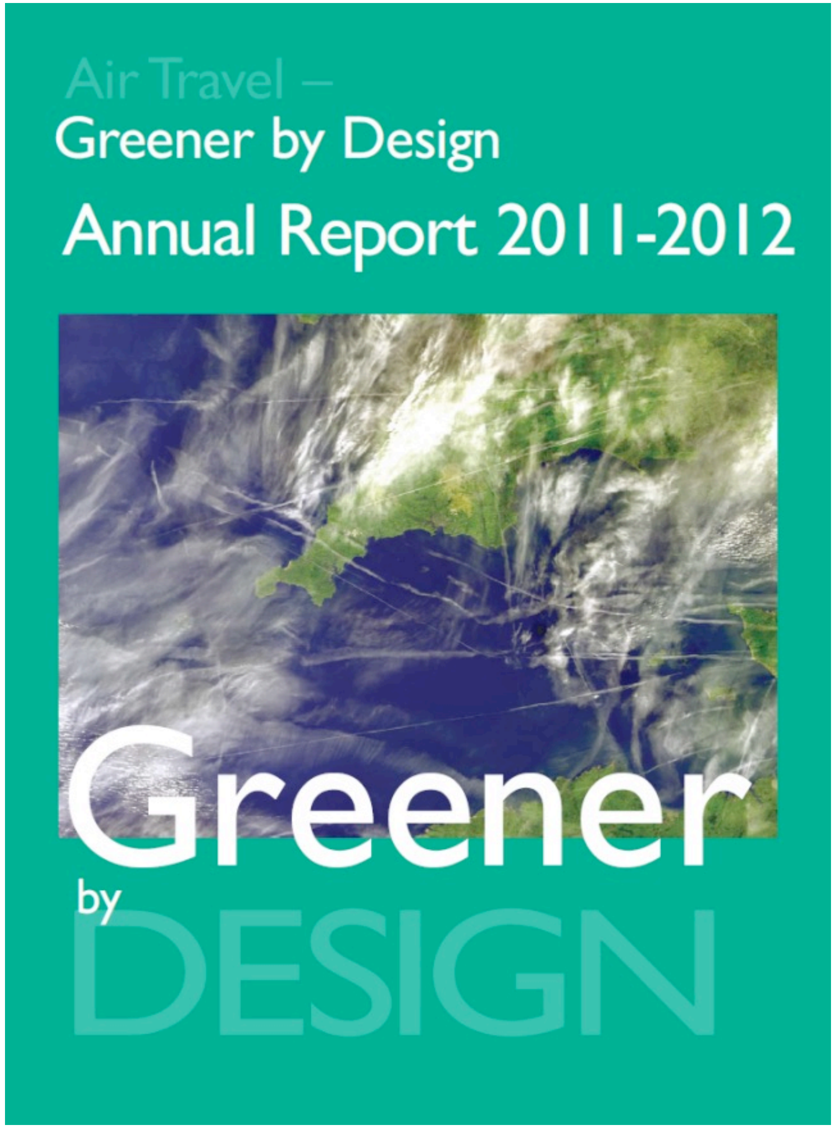
General pushback

- Too difficult
- Too costly for airlines
- Science base not secure enough



COSIC Stakeholder Workshop, June 2011

- COSIC (Contrail Spreading Into Cirrus) project led by Leeds University (Piers Forster) sponsored by NERC
- Workshop held at Royal Society, June 2011, reported in GBD Annual Report 2011-2012
- Met Office study (Haywood) of major forcing event by persistent contrail-cirrus from tanker aircraft circling over the North Sea
- DLR presentation (Ulrike Burkhardt) of prediction of radiative forcing by contrail-cirrus
- The DLR work was the first quantitative treatment of radiative forcing to include contrail-induced cirrus and was generally recognised as a potential game- changer



GBD workshop/conference, October 2015

Round Table Conclusions

- Majority view that science base is now secure enough to support a policy of contrail reduction by “smart flying”
- Aim to begin regionally in the north Atlantic with Europe taking the initiative
- Someone had to start the process and GBD undertook to do so
- This led to an informal meeting at Gatwick Airport of a group of key participants in the workshop and the formation of the Contrail Avoidance Group (CAG)

CAG formative meeting, Gatwick, April 2016

- Founder members
- DLR Institute of Atmospheric Physics
- GBD members of Executive Committee
- NATS
- University of Reading, Dept of Meteorology

- Conclusions
- Science base is now good enough to justify proceeding
- Ultimate aim is to stage a flight demonstration of contrail reduction by ATM in the Shanwick OACC of the north Atlantic
- Paper studies, a ‘virtual demonstration’ needed to make the case for a real one
- Sub-group formed to review broader ethical and governance issues, e.g. geo-engineering

Participants in GBD CAG meetings

	April 06, 2016 Gatwick Airport	April 20, 2017 University of Reading	October 10, 2018 Gatwick Airport	October 21-22, 2019 DLR Oberpfaffenhofen
DLR:	K Gierens, V Grewe, Schuman	K Gierens, U Schumann	K Gierens, V Grewe, R Sausen, U Schumann	A Bier, U Burkhardt, C Fremming, K Gierens, S Matthes, M Ponater, R Sausen, U Schumann, C Voigt
GBD:	J Green, I Poll, R Whitfield	J Counsell, J Green, I Poll, R Whitfield	J Green, I Poll, R Whitfield	J Green, I Poll, R Whitfield
NATS:	H Edwards, J Molloy	H Edwards, J Molloy	J Molloy	J Molloy
U of Reading:	E Irvine, K Shine	J Handsley, E Irvine, F Magnini, K Shine		
Imperial College:			M Stettler, R Teoh	M Stettler. R Teoh
IATA:				T Roetger

Some contributions since CAG formation

- **K Gierens, K Gröschl,** Characterisation of the Shanwick OACC in terms of contrail formation and ice supersaturation frequencies of occurrence, April 2017
- **J Handsley, E Irvine, K Shine,** Evaluating ECMWF forecast skill for predicting ice-supersaturation, April 2017
- **K Gierens,** Statistics of potential radiative forcing of persistent contrails, March 2018
- **K Gierens, M Vazquez-Navarro,** Statistical analysis of contrail lifetimes from a satellite perspective, March 2018
- **R Teoh, U Schumann, A Majumdar, M E J Stettler,** Mitigating the climate forcing of aircraft contrails by small-scale diversions and technology adaptation, February 2020
- **R Teoh, U Schumann, M E J Stettler,** Beyond contrail avoidance: efficacy of flight altitude changes to minimize contrail climate forcing, August 2020
- **K Gierens, S Matthes, S Rohs,** How well can persistent contrails be predicted? October 2020
- **D I A Poll, U Schumann,** An estimation method for the fuel burn and other performance characteristics of civil transport aircraft during cruise. Part 1, fundamental quantities and governing relations for a general atmosphere, July 2020, part 2, determining the aircraft's characteristic parameters, December 2020
- **NATS** has provided 10 years of air traffic data to the group to support research and analysis

EASA non-CO2 Report, September 2020

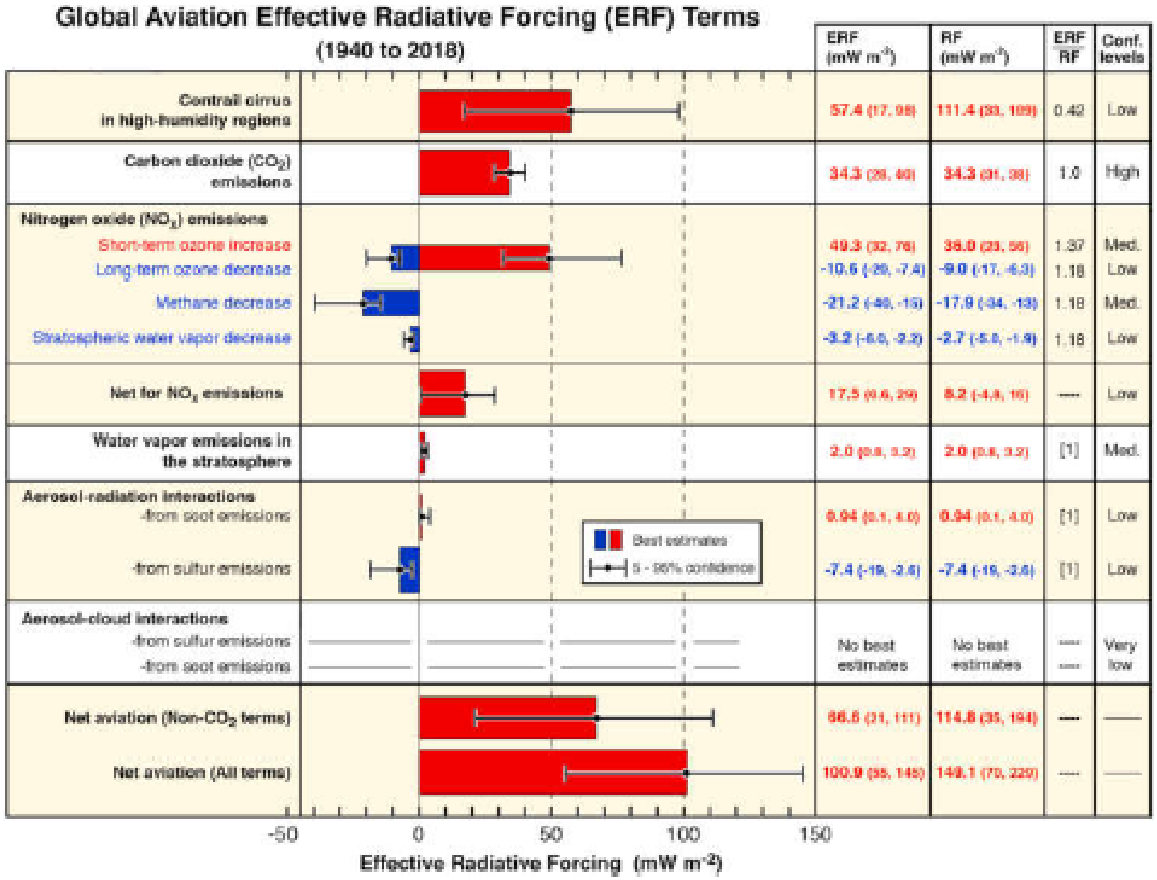
Greener by DESIGN

Report from the Commission

To the European Parliament and Council

Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4)

Key conclusion: the non-CO2 effects contribute at least 2/3 of total aviation Effective Radiative Forcing (ERF)



Lee et al 2021

GBD CAG Conference, 23-24 March 2021

Conference Programme

The Science Base
- Overview
- NOx
- Contrail forecasting and observation

Mitigation possibilities
- Emissions reduction
- Novel fuels
- Contrail avoidance
- Impact on fuel burn
- Regulation and governance

Way forward

Full report on conference available on:
aerosociety.com/news/easy-does-it-for-greener-skies/

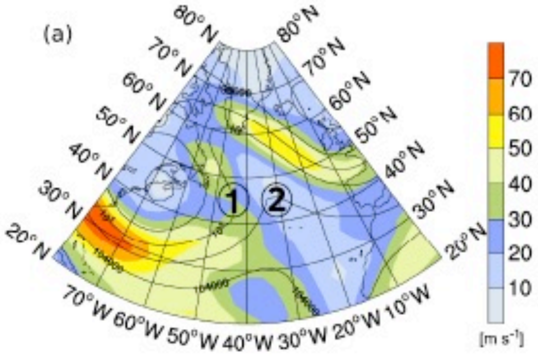
This presentation focusses on key issues relating to the "low-hanging fruit" – NOx and contrail-cirrus

NOx: Volker Grewe 1

What is this talk about?

Weather

1



Aviation NOx - RF

2

Revisiting diagnostics to calcualte NO_x RF

Temporal mismatch methane

Ozone contribution

NOx: Volker Grewe 2

Total Aviation NO_x Radiative Forcing

Radiative forcing of Aviation NO_x emission in 2005 in mW/m^2	Lee et al. 2009	Additional processes (PMO, SWV)	Revised methane RF formula	correction of flaws	
				#1 Methane lifetime	#2 Ozone contribution method
Ozone	26.3	26.3	26.3	26.3	41.2
Methane	-12.5	-12.5	-15.4	-10.0	-10.0
PMO		-5.0	-5.0	-3.3	-3.3
SWV		-1.9	-1.9	-1.2	-1.2
Total NO_x-RF	13.8	6.9	4.0	11.8	26.7

Grewe et al. 2019

Lee et al al 2021 **Factor 2 difference due to diagnostics**

Total NO_x-RF 2018	17.5	→	35.2

NOx: Agnieska Skowron

Effect of future atmospheric background composition on NOx climate impact in the longer term

Overall message

- The aviation net NOx forcing is sensitive to background emissions
- There is no such thing as a fixed net NOx response to emissions
- It could be that for the same aviation emissions, but different surface emissions of ozone precursors, the aviation net NOx forcing could be zero or even negative.

NOTES

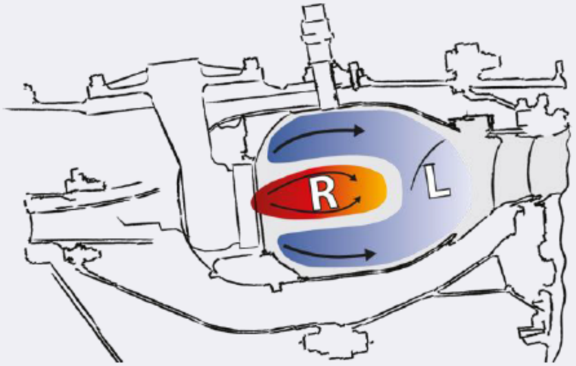
- Presentation draws on material from "Greater fuel efficiency is preferable to reducing NOx emissions for aviation's climate impacts, by Skowron, Lee, De Leon, Lim and Owen, *Nature Communications,* Jan 2021. The overall sense of this paper is that measures to reduce NOx that increase CO2 should be avoided
- Net NOx RF taken as 4 mW/m2 in 2005, which is substantially lower than value cited in the EASA report from Lee et al 2021 (of which Skowron is also cited as an author) and Grewe's evaluation of 27.7 mW/m2 for that year

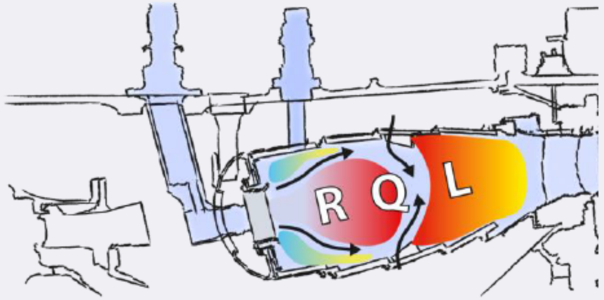
NOx: Paul Madden 1

Rolls Royce Lean Burn Technology

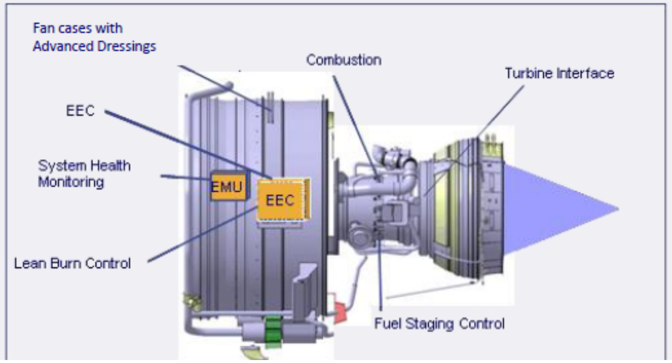
ALECSys
Advanced
Low
Emissions
Combustion
System

- Rich Burn (phase 5 technology) is a robust, proven technology but is fundamentally limited in the level of NOx and smoke achievable.





- Lean premixing of fuel and air is needed for a step change in high power NOx and smoke performance.
- Fuel staging is used for operability:
  - Rich pilot for low power stability
  - Lean main zone for minimised NOx and smoke



For an optimised solution, lean-burn is developed as a system within other engine systems (ALECSys):

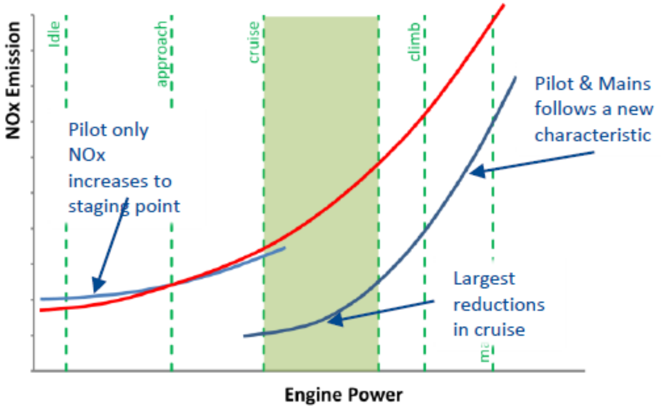
- Control system
- Control laws
- Turbines
- Heat management system
- Installation

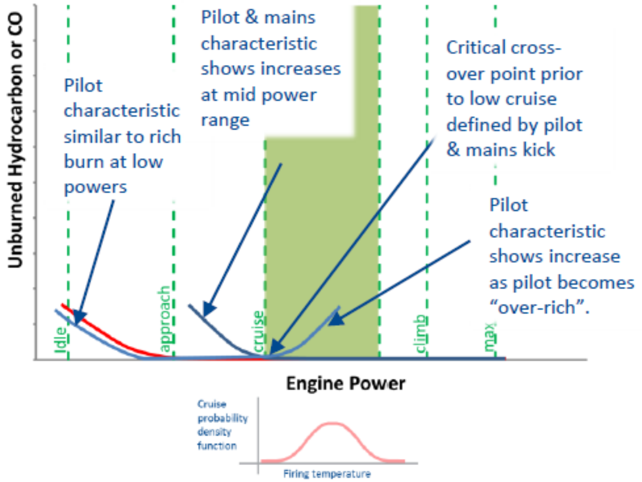
NOx: Paul Madden 2

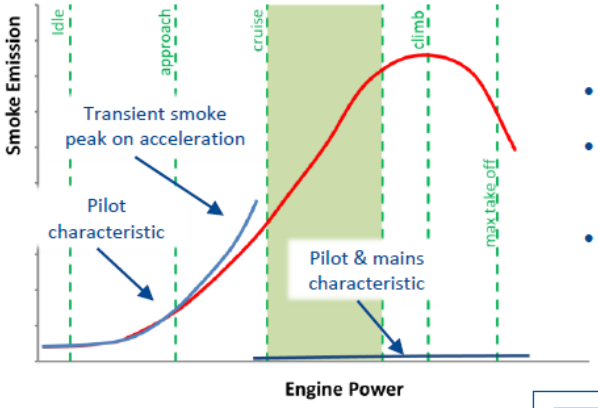
Greener by DESIGN

Illustrative Chart Showing Emissions Evolution of the RR Lean Burn System

ALECSys Demonstrator Engine
“Advanced Low Emissions Combustion System







- Two fuel stages – pilot, pilot & main
- Key design criteria for lean burn is cross-over from pilot to main.
- Staging point from pilot to pilot & main dictated by Efficiency, operability and pilot smoke

Lean burn
Rich Burn

Rolls-Royce

NOx: Paul Madden 3

Commissioning

Ice shedding

Water ingestion

ALECSys (Advanced Low Emissions Combustion System) Technology Demonstrator Programme

- Two ex flight test Trent 1000 engines for ground and flight testing of our lean-burn system
- Phase 1 ground testing completed in 2018
  - Commissioning, Icing testing and Core Water Ingestion
- Phase 2 ground testing Aug-Nov 2020
  - Starting Optimisation, Operability and Stability, Handling Optimisation, Quick relights, Emissions and thermo-acoustics.
- Flight testing planned on our 747 FTB
- 100% SAF ground test took place on the ALECSys demo engine in Nov 2020
  - To demonstrate Rolls-Royce engines can unlock SAF's potential to reduce emissions and move towards a more sustainable future for aviation.
  - Combining 100% SAF with our latest Combustion Technology and covering operability and emissions

Ground Operability and Emissions

100% SAF

Flight test

NOx: Low-hanging fruit?

Low hanging only if you bring a step ladder

- Engine companies have low NOx technology available but there is no incentive to introduce it sooner than dictated by commercial reasons
- The magnitude of the climate impact of NOx needs to be resolved; the diagnostic questions raised by Grewe et al need to be settled
- There needs to be agreement on a metric to enable the climate impact trade-off between NOx reduction and CO_2 increase to be evaluated.
- The concept of trajectory optimization using Climate Change Functions, discussed elsewhere, should be pursued to its logical conclusion.
- It will take many years to collect all the fruit

NOx: EASA potential policy action

EASA environmental certification standards are based on ICAO SARPS

Aircraft engine emissions standards for NOx emissions are defined for the LTO cycle. There is no standard for NOx emissions at cruise

Potential financial related measures (NOx emissions charge/inclusion of NOx in EU ETS): key issues are

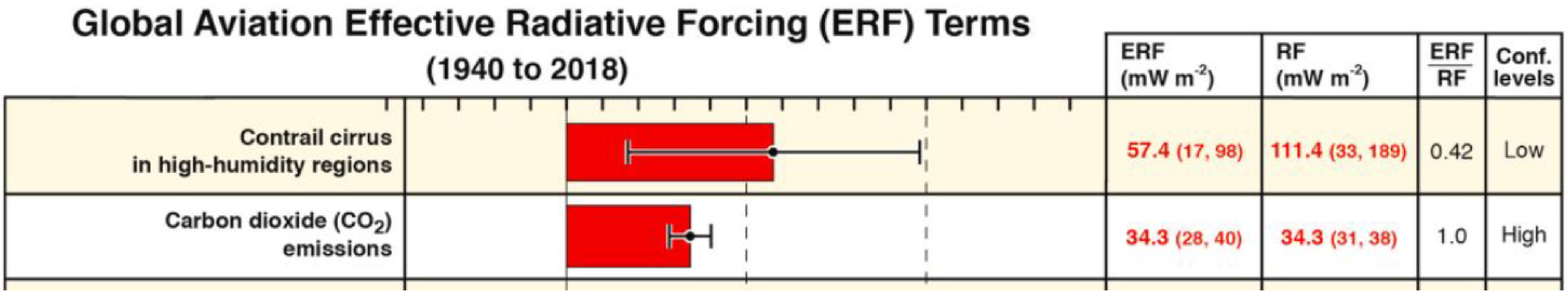
- Reducing scientific uncertainty on climate impact from aircraft NOx emissions
- Selecting appropriate CO2 equivalent emissions metric and time horizon
- Agreeing on climate damage costs to determine level of charge

Uncertainty on climate impact, and potential unintended consequences, introduces a potential risk for the integrity of the EU ETS

Implementation would be through the SES Performance and Charging Scheme

Envisaged timescale: Mid term (5-8 years)/Long term (8+ years)

Reducing contrail-cirrus



Note: the order of magnitude of **annual and global mean** forcing is + 50-100 mW m^{-2}

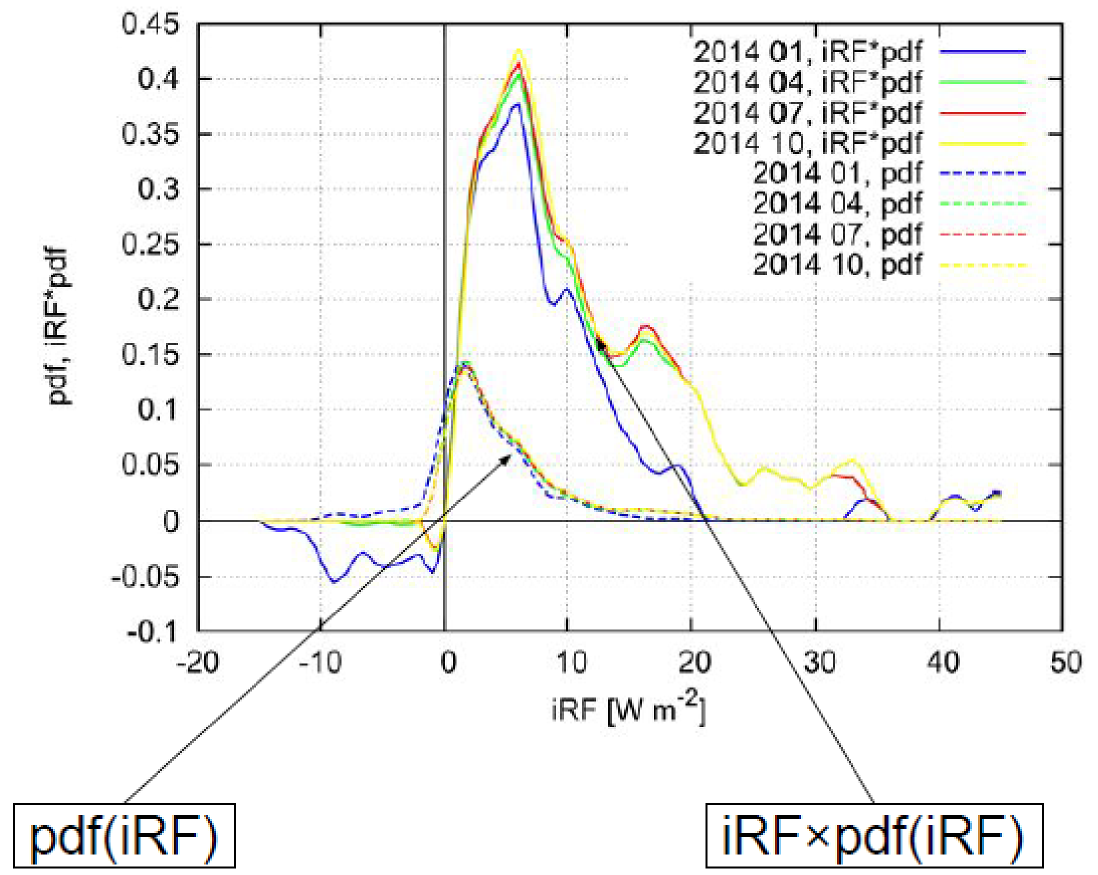
- Fuel: reduce soot emissions by increased use of low aromatic blend and SAF
- Combustor design to reduce soot emissions
- Avoid Ice Supersaturated Regions (ISSRs) , by ATM working with met forecasters

Gierens: contrail statistics and big hits

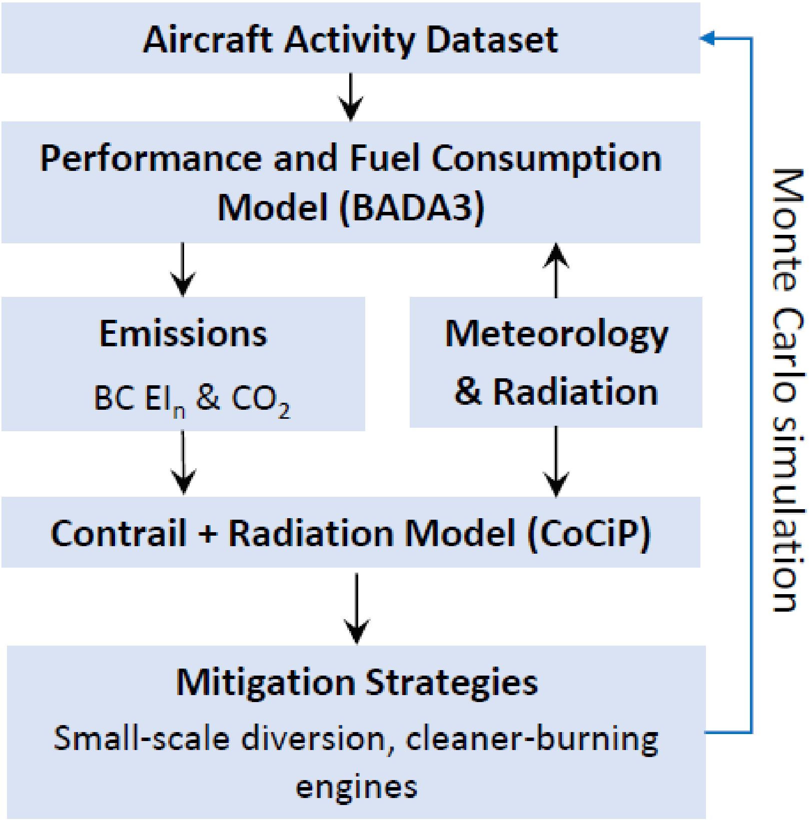
- About 15% of all flight distances occur in ISSRs
- Only contrails formed in ISSRs have a non-negligible effect on climate forcing

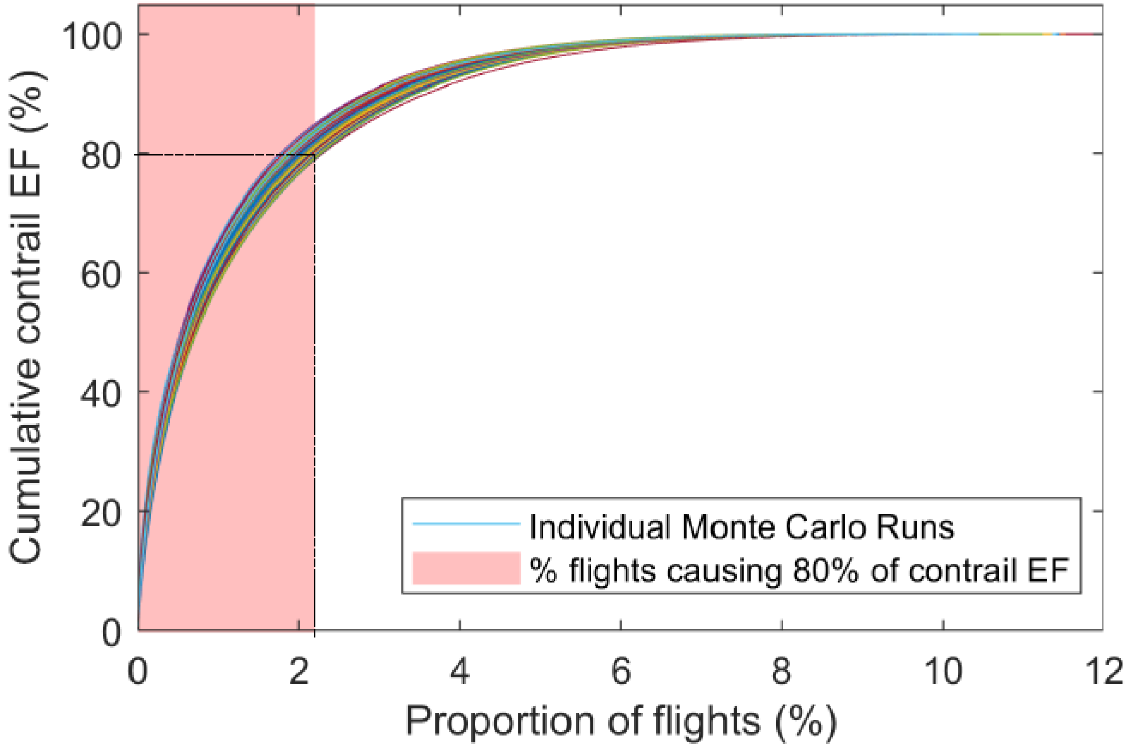
<u>Minimally invasive contrail avoidance strategy: Avoid Big Hits</u>

- Big Hits: those contrails with the strongest warming effect
- Big Hits comprise only about 1-2%of all flown flight distances
- Three steps needed for minimally invasive avoidance
  - Predict contrail formation (Schmidt-Appleman)
  - Predict contrail persistence (ISSR)
  - Predict individual radiative forcing (CoCiP)



Stettler worked example in Japanese airspace





Further details:

Teoh, R., Schumann, U., Majumdar, A. and Stettler, M.E., 2020. Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption. *Environmental Science & Technology*, *54*(5), pp.2941-2950.

- 2.2% [2.0%, 2.5%] of flights account for 80% of the total $EF_{contrail}$.
- Fleetwide diversion strategy is neither practical nor necessary.

Small-scale diversion of Japanese air traffic

For any flight in the group that contributes to 80% of the total contrail energy forcing, generate alternate trajectories ± 2000ft and pick contrail with lowest Energy Forcing (ie ERF integrated over length, width and lifetime of contrail)

	Approach	% flights diverted	% change in contrail EF	% change in fuel burn	% change in total EF (CO_2, 100-yr TH)
1	Small-scale diversion	1.7%	-59% [-66, -52%]	+ 0.014% [0.010, 0.017%]	**-36% [-44, -28%]**
2	Cleaner DAC engines	0	-69% [-82, -45%]	0*	**-42% [-53, -33%]**
1+2	Diversion + cleaner engines	~2%	-92% [-96, -87%]	+ 0.027% [0.021, 0.033%]	**-57% [-70, -44%]**

*Assuming no change to fuel efficiency for DAC engines

Poll on impact of avoidance on fuel burn

- Motivation: to provide a simple accurate, analytic, open source, peer reviewed and independently verifiable method for predicting fuel burn for specific aircraft, for use in studies of contrail avoidance
- *Nullius in Verba* - motto of the Royal Society (1660) – take nobody's word for it and avoid "black box" methods
- Based on four papers, three with Ulrich Schumann, published in *The Aeronautical Journal,* two key ones in February 2021.

- General observation that increasing cruise altitude by 2000ft from optimum increases fuel burn by 1.5%, reducing by 2000ft increase it by 1.4% and these results are approximately the same for all turbofan aircraft. The increased fuel burn applies only for that part of the flight at changed altitude.
- Method enables comparison between effects of flying under, over or around ISSRs. The differences in trip fuel usage are small, typically < 1%, with diversions adding less than 5 minutes to a trans-Atlantic flight

MUAC live contrail avoidance trials

- Within Eurocontrol, Maastricht Upper Area Control (MUAC) provides air traffic control for all traffic above 42,500ft over Belgium, Luxembourg, the Netherlands and north west Germany

- Working with DLR and Deutscher Wetterdienst, contrail prevention trial launched to run from 18 January 2021 to 31 December 2021. Dependent on weather, any flight flying in MUAC sectors in this period may be selected for diversion
- Early days in trial, but some early conclusions:
  - Need to improve operational decision met/ATM decision making process
  - ISSR prediction a key challenge

- Outlook
  - Continue validation with DLR
  - Curious to see operations when traffic comes back
  - Tune and validate the ISSR prediction
  - Work on alternative validations for ISSR predictions
  - Work towards real-time online ISSR detection

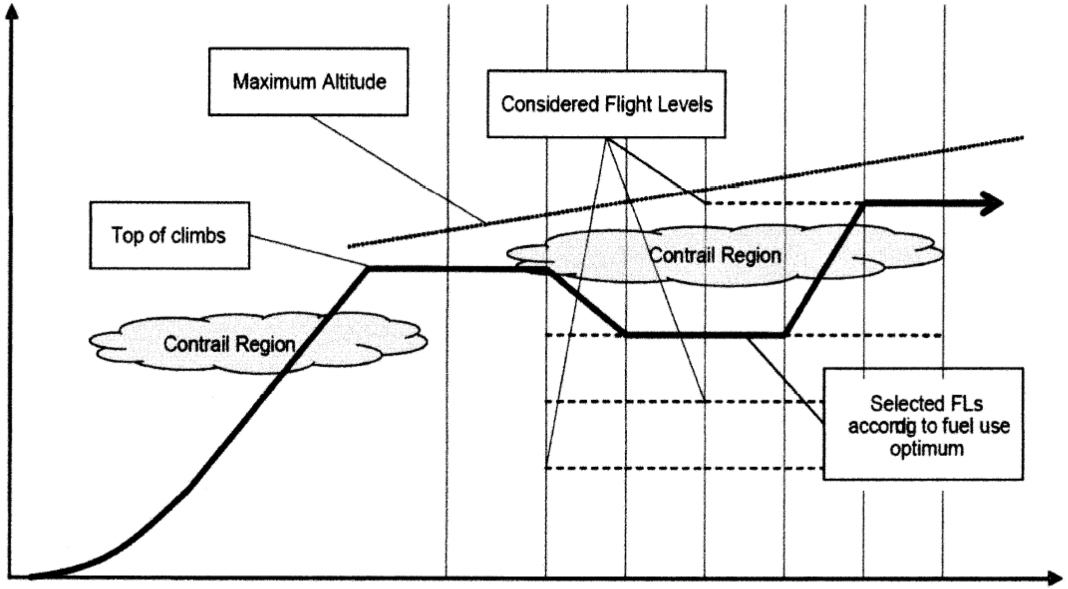
UK ATI interest in a trial in Shanwick OACC

- A practical demonstration of contrail avoidance by ATM under the control of NATS was the agreed aim of the CAG at its first meeting in 2016
- The Aerospace Technology Institute (ATI), which is funded by Government to promote innovation nationally, is now in discussion with a range of UK stakeholders with a view to forming a consortium, or consortia, to undertake one or more projects centred around contrail avoidance in the Shanwick OACC
- Although the ATI can fund only UK organisations, overseas organisations are also invited to join (eg DLR)

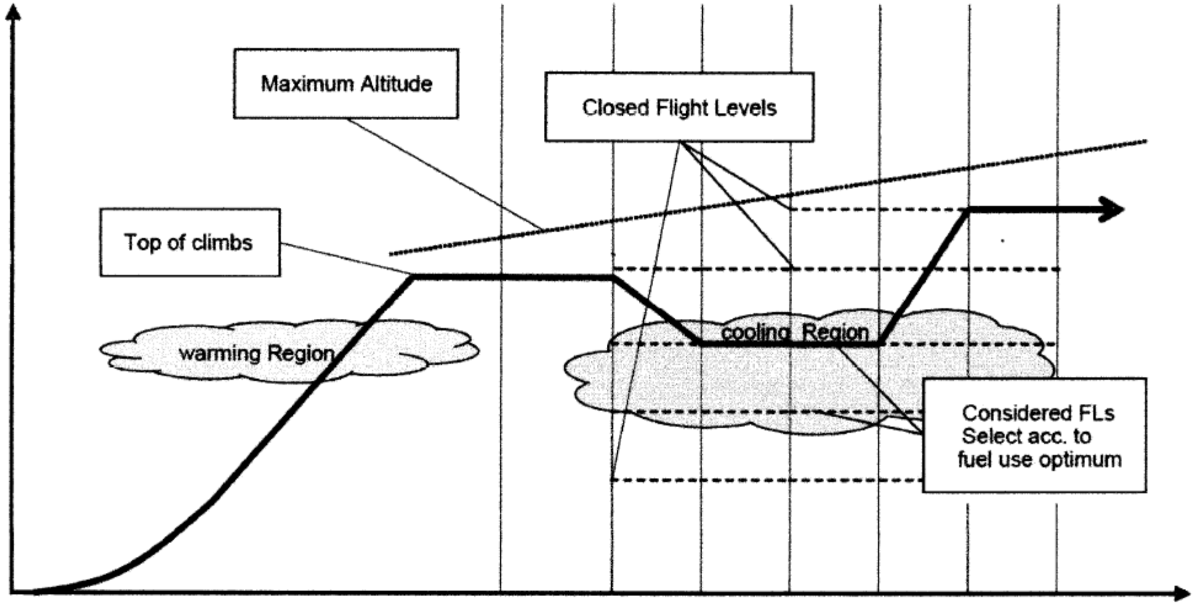
Oceanic Area Control Centre

- Manages airspace over eastern North Atlantic;
- Handles up to 80% of oceanic traffic (1,500 flights per day).

Cooling contrails controversy



Avoiding warming contrails

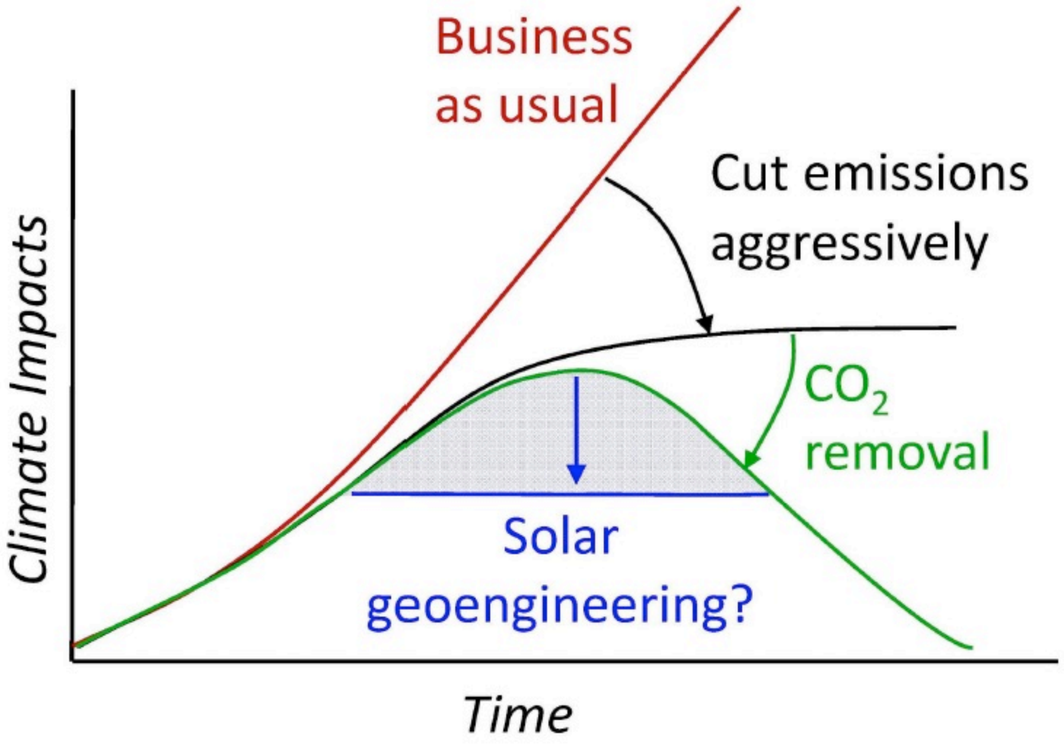


Creating cooling contrails

- CAG at first meeting split over forming cooling contrails –is this geoengineering?
- Decide to sidestep the issue and form a Governance Sub-Group
- Recent Work in the margins suggest cooling contrails are worth investigating

Solar geoengineering on the horizon

- Large scale removal of CO2 from the atmosphere ('carbon dioxide removal' – CDR)
- Reflection of more sunlight back into space to cool the planet ('solar radiation modification' –SRM)
- All scenarios that meet the 1.5 degree target without overshoot rely on CDR
- There seems every chance that STM will also be needed
- Harvard Stratospheric Controlled Perturbation Experiment (SCoPEx)



Low hanging fruit – final remarks

- The joint GBD/DLR conference in March 2021 was, we believe, a successful event. It covered some important issues not discussed today but reported in the conference report on the RAeS blog
- From my standpoint, the key take home messages are:
  - The non-CO2 climate impact of aviation is about twice as important as that of CO2 alone and the greater part of it is from contrails and contrail cirrus
  - The impact of contrails can be substantially reduced by a small alteration in cruise altitude or route with minimal effect on CO2 emissions and airline costs
  - This change in operational procedure can be adopted by the world fleet in much less time and at a fraction of the cost needed for equivalent improvements by new technology
  - The development of safe, worldwide procedures for contrail avoidance will require enlightened leadership. A high profile demonstration in the Shanwick OACC, managed by NATS, would be an excellent starting point
  - Contrail avoidance is the really low-hanging fruit of aviation. The bogeyman is that people still talk about it involving problems and costs for the airlines. People need to understand that recent work shows that you can achieve a substantial reduction in climate impact from air travel at very little cost to the airlines. The downside for the airlines is very small. Given the positive impact of this change on the perception of aviation's contribution to the world's climate problems, the airlines should be getting behind this.
  - We need our Shanwick demonstration