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Contrails

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Outline

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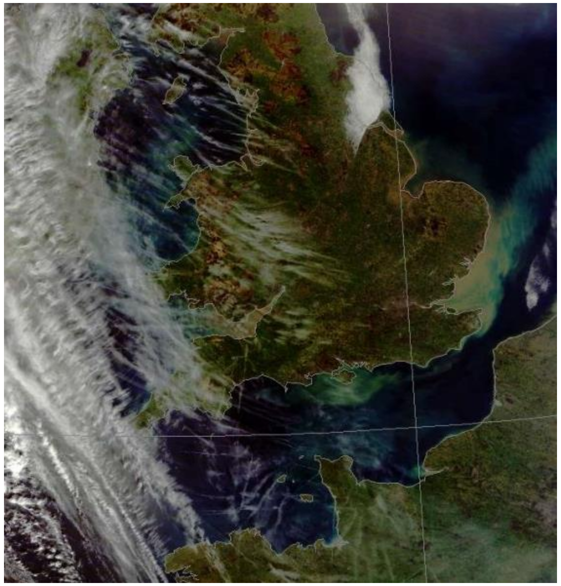
- Background
  - Contrail formation
  - Contrail climate impact
- Mitigation 1: simple framework
  - Single flight
  - Contrails vs CO_2
- Mitigation 2: more realistic framework
  - Trans-Atlantic flights
  - All climate impacts
- Challenges

Contrails and contrail cirrus

- Contrails form behind cruising aircraft under certain conditions
- Can last for a few minutes or hours (persistent contrails)
- Subtle changes in aircraft altitude or location greatly influence contrail formation and duration
- Contrails reflect sunlight (cooling) and trap infrared energy (warming) – makes calculating the net effect more difficult
- Expanding database of measurements of contrail properties and occurrence



Aviation Climate Impact

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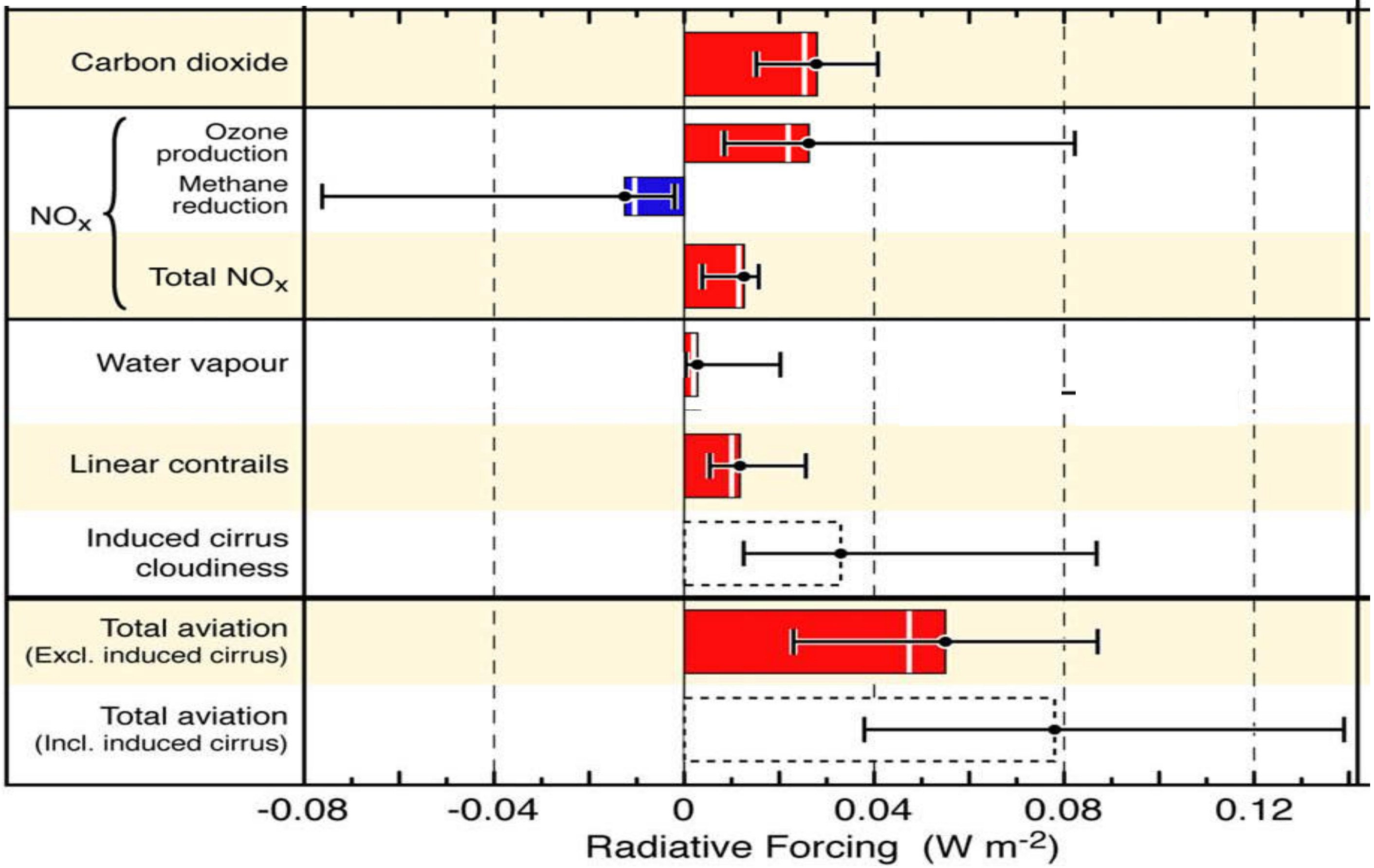
Aviation radiative forcing components (Lee et al., 2009)



- When non-CO_2 emissions are included, aviation emissions responsible for 3.5% (range 2-14%) of total RF (Lee, 2009)

Contrail climate impact: IPCC update

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- There has been a significant convergence in estimates (both modelled and empirical) of both “linear” contrails and the total contrail plus contrail cirrus forcing

- IPCC 5th Assessment Report (2013) findings:
  - Linear contrail radiative forcing of 10 (5 to 30) mW m^{-2}
  - Total (linear contrail plus contrail cirrus) of 50 (10 to 120) mW m^{-2}
  - Improved *confidence* that the actual value lies within stated ranges

Contrail Formation

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- Contrails form if ambient air temperature below value specified by Schmidt-Appleman criterion (roughly < 233 K)
- Contrails persist if humidity > 100% w.r.t ice (ice-supersaturated)

- Temperature threshold depends on: aircraft engine efficiency, fuel characteristics and so is impacted by technological changes

DLR Research flight chasing an A340 (left, with contrail) and B707 (right, without contrail)

Schumann et al., 2000

Potential mitigation measures

Technological

- Alternative fuels, if decrease water vapour emission index, or increase specific heat content of fuel (so not LH_2)
- Temporary reduction in propulsion efficiency, e.g. Haglind (2008). However it increases specific fuel consumption

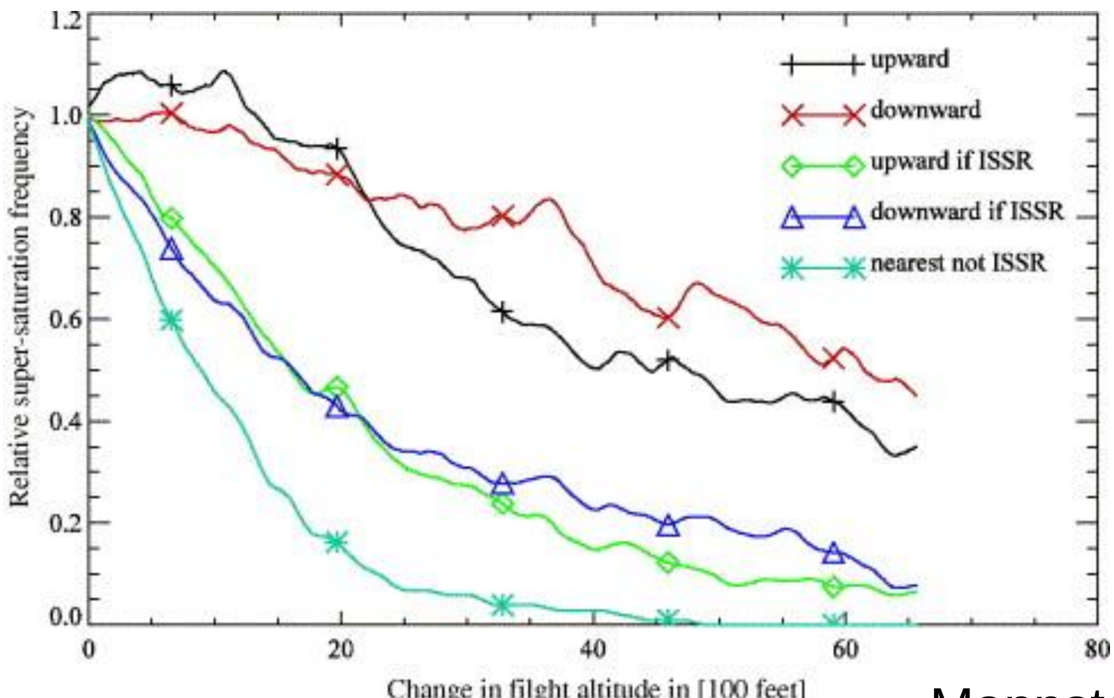
Operational

- Altitude changes or restrictions. Corresponding increase in CO_2 emissions, reduced airspace capacity.
- Avoiding contrail formation regions. Requires ability to accurately forecast contrail regions.

Review by Gierens et al., 2008

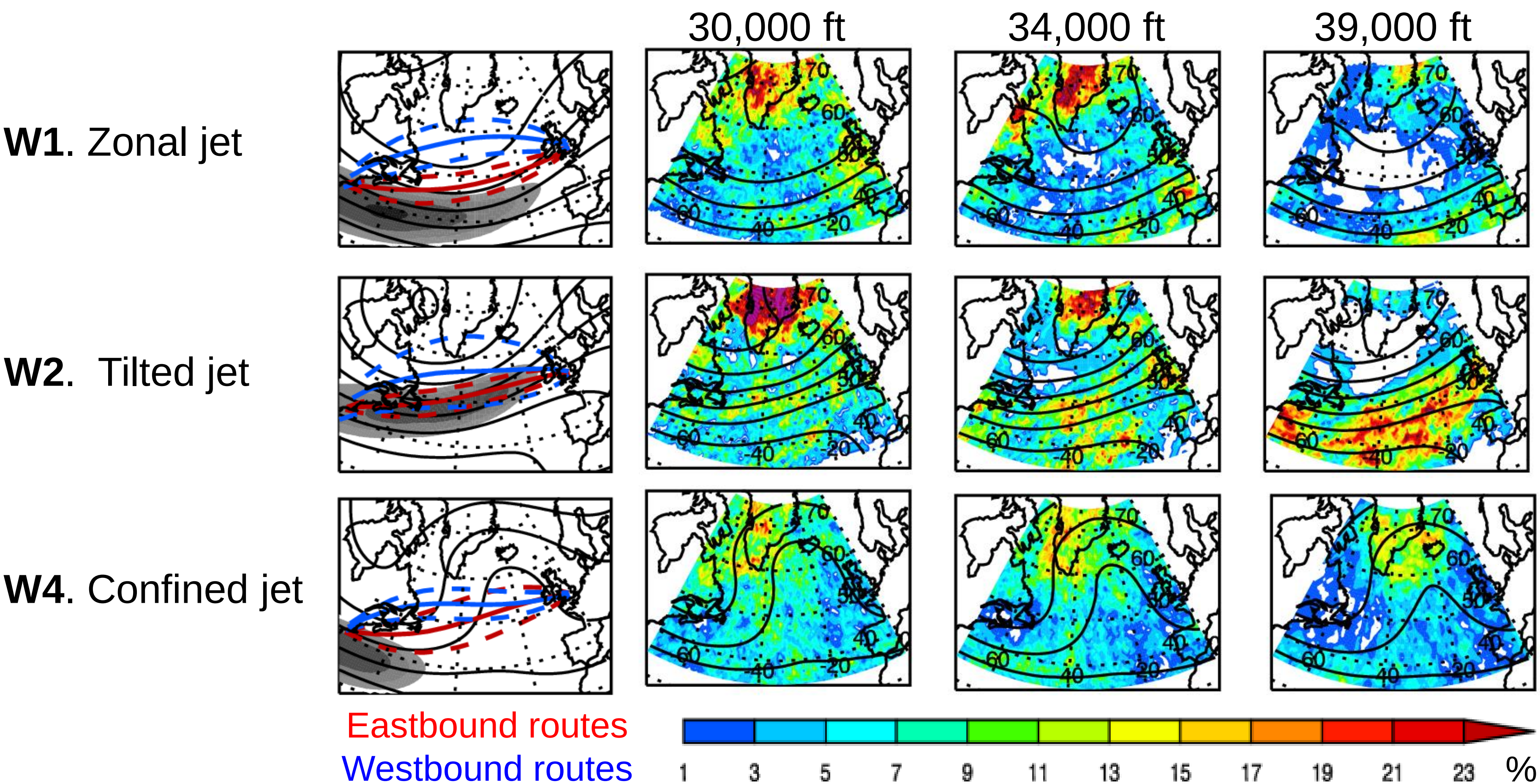
Avoiding contrails through altitude changes

- Ice-supersaturated layers occur most frequently around 10 km and are typically < 1 km deep (Rädel and Shine, 2007)
- Therefore require only small altitude changes to avoid



Mannstein et al., 2005

Potential contrail frequency by weather pattern and altitude



- Location linked to various features: jet stream, Greenland, ridges
- Altitude distribution depends on weather pattern

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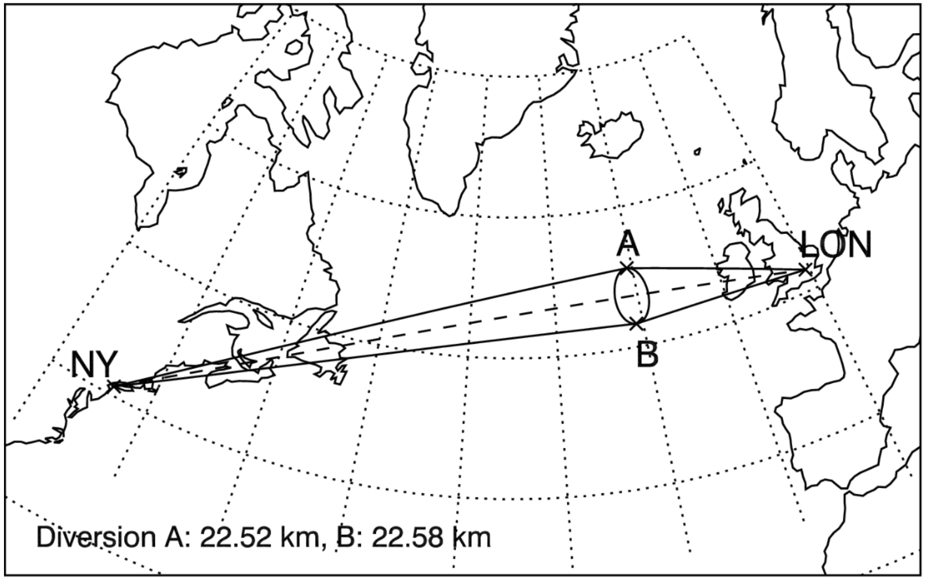
Re-routing to avoid contrails: trade-off CO_2 and contrail impacts



- How much extra distance can you add to a flight to avoid making a contrail and still reduce the overall climate impact of the flight?

Irvine et al., 2014, Environmental Research Letters

Climate optimal routes: should we avoid making a contrail?

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CLIMATE COST

CO_2 **VS**

Contrail

	CO_2	Contrail
Lifetime:	Decades	Hours
Scale:	Global effect	Local effect

Re-routing to avoid contrails: trade-off CO_2 and contrail impacts

CO_2 vs contrail

Rate of fuel consumption

Climate impact

Do larger aircraft produce thicker contrails? (Jeßberger et al., 2013)

Contrail area

Contrail lifetime

Climate impact

Efficacy

- We assess with typical parameters for a range of aircraft classes
- Metric needed to equate the CO_2 and contrail climate impacts: absolute global warming potential (AGWP) and absolute global temperature potential (AGTP)

Re-routing to avoid contrails: trade-off CO_2 and contrail impacts

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AGTP (top) and AGWP (bottom) metrics

	Time scale (years)	
Aircraft class	**20**	**100**
Small jet	1310	170
Medium jet	740	100
Large jet	510	70
Very large jet	350	50

Small jet	4530	1230
Medium jet	2550	690
Large jet	1780	480
Very large jet	1210	330

Alternative route to avoid 100km^2 contrail is preferable if extra distance less than this

Re-routing to avoid contrails: trade-off CO_2 and contrail impacts

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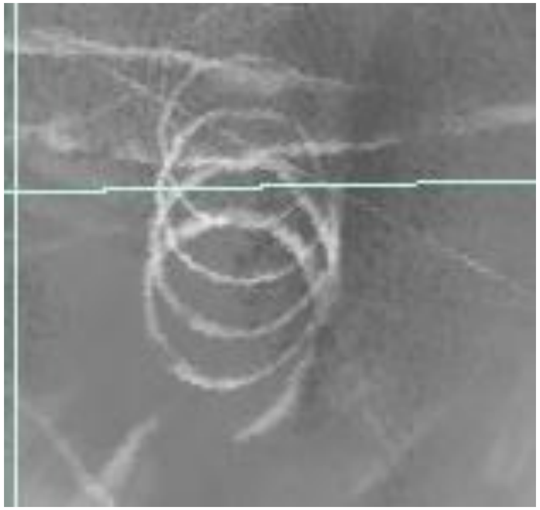
- Uncertainty estimate: factor of 20
- Major sources of uncertainty are efficacy of contrail climate impact, and calculation of contrail climate impact
- Possibility that some contrails have a RF much larger than most studies suggest,

  e.g. Haywood et al. (2008)

  single contrail RF > 1000x larger

  If contrail climate impact this large would always be beneficial to avoid!



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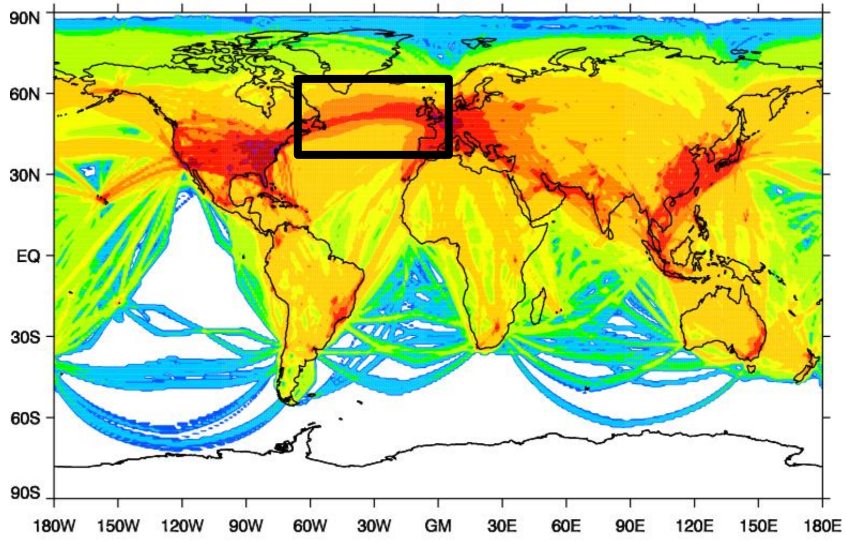
Reducing Emissions from Aviation by Changing Trajectories 4 the benefit of Climate

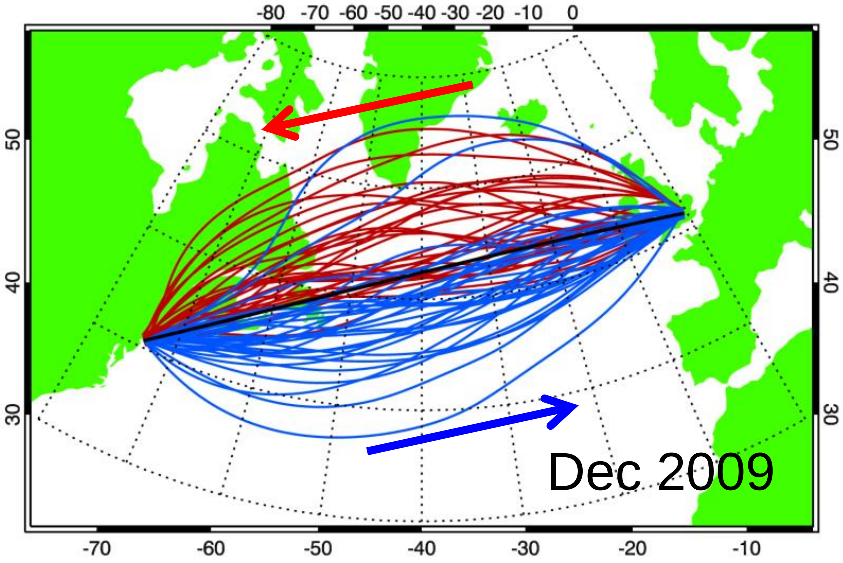
- Feasibility study of climate-optimal routes for trans-Atlantic flights
- For a given set of weather situations design “minimum climate impact” alternatives to the traditional quickest – least fuel – cheapest routes, subject to air traffic constraints
- Calculations for both current aircraft fleet and ‘greener’ aircraft (Airbus) optimised for climate-optimal routing

- EU FP7 project, 2010 – 2014 (completed)
- Project partners: DLR, MMU, Reading, Aquila, CICERO, EUROCONTROL, Met Office, Airbus

North Atlantic flight corridor

From Laura Wilcox





- > 300 flights per day in each direction
- 6.5% total aviation CO_2 emissions (Wilkerson, 2010)
- Strong dependence of route location and time on the jet stream. Leads to a large daily variation in optimal route location (quickest route at 250hPa)

Climate-optimal routing

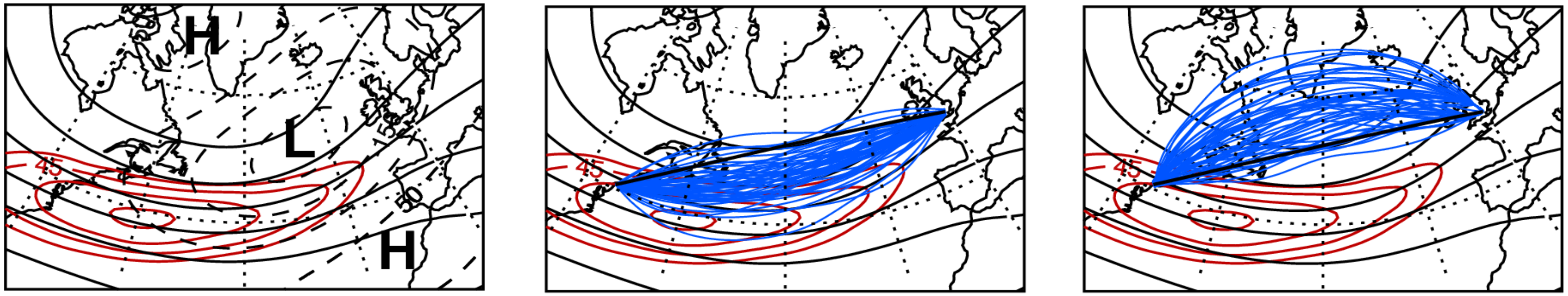
- For one day of trans-Atlantic air traffic, calculate and compare:
  - Climate-optimal routes
  - Economic-optimal routes
  - Real planned-routes

- Climate cost is the sum of: CO_2, NO_x (O_3, CH_4), H_20, contrails
- Economic cost is 25€/minute of flight + 0.75€ /kg of fuel

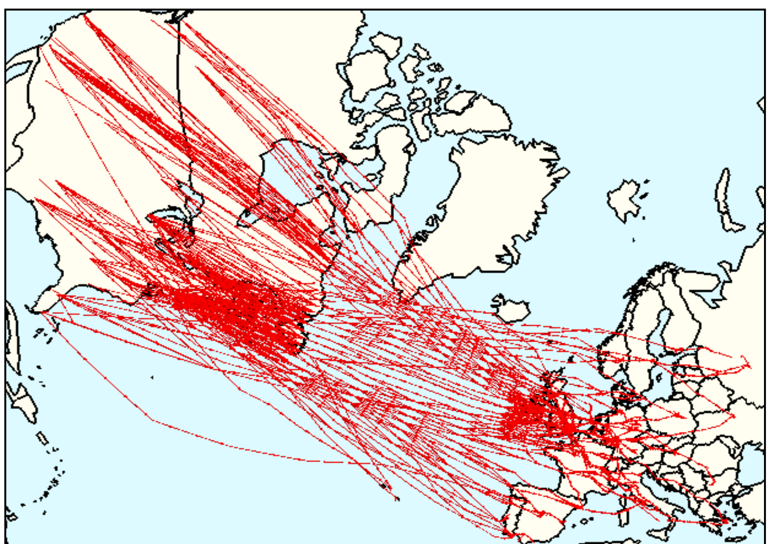
- Qu: What reduction in climate impact can be achieved and at what (economic) cost?

Case study day: 30 Dec 2006

Weather pattern : strong zonal jet stream



Air traffic sample



Total ~ 600 flights

For each flight:
17 2D route options at 5 flight levels
= 84 possible routes

Case study day: 30 Dec 2006
Climate cost functions

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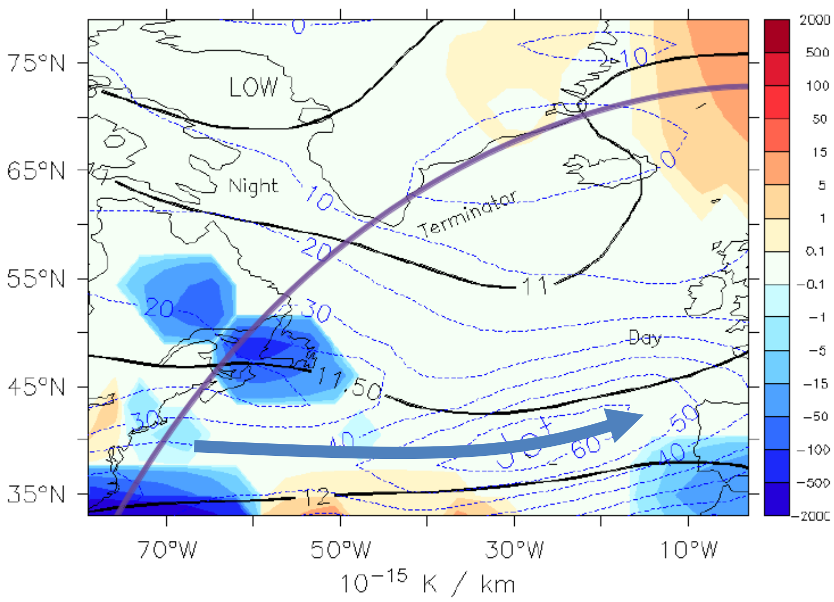
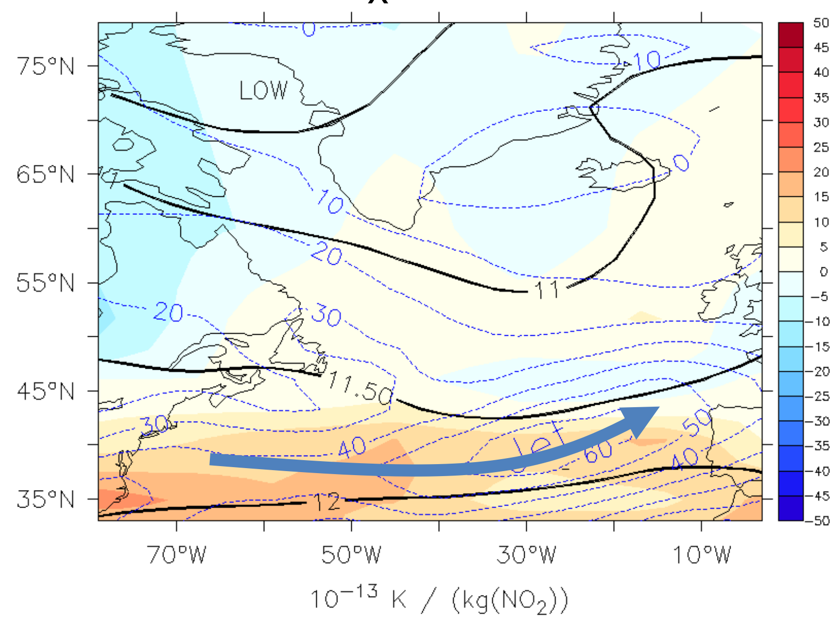
Contrail-Cirrus



Total NO_x



For one weather pattern at 39,000 ft for emissions at 1200 UTC

Example flight: Washington to Vienna

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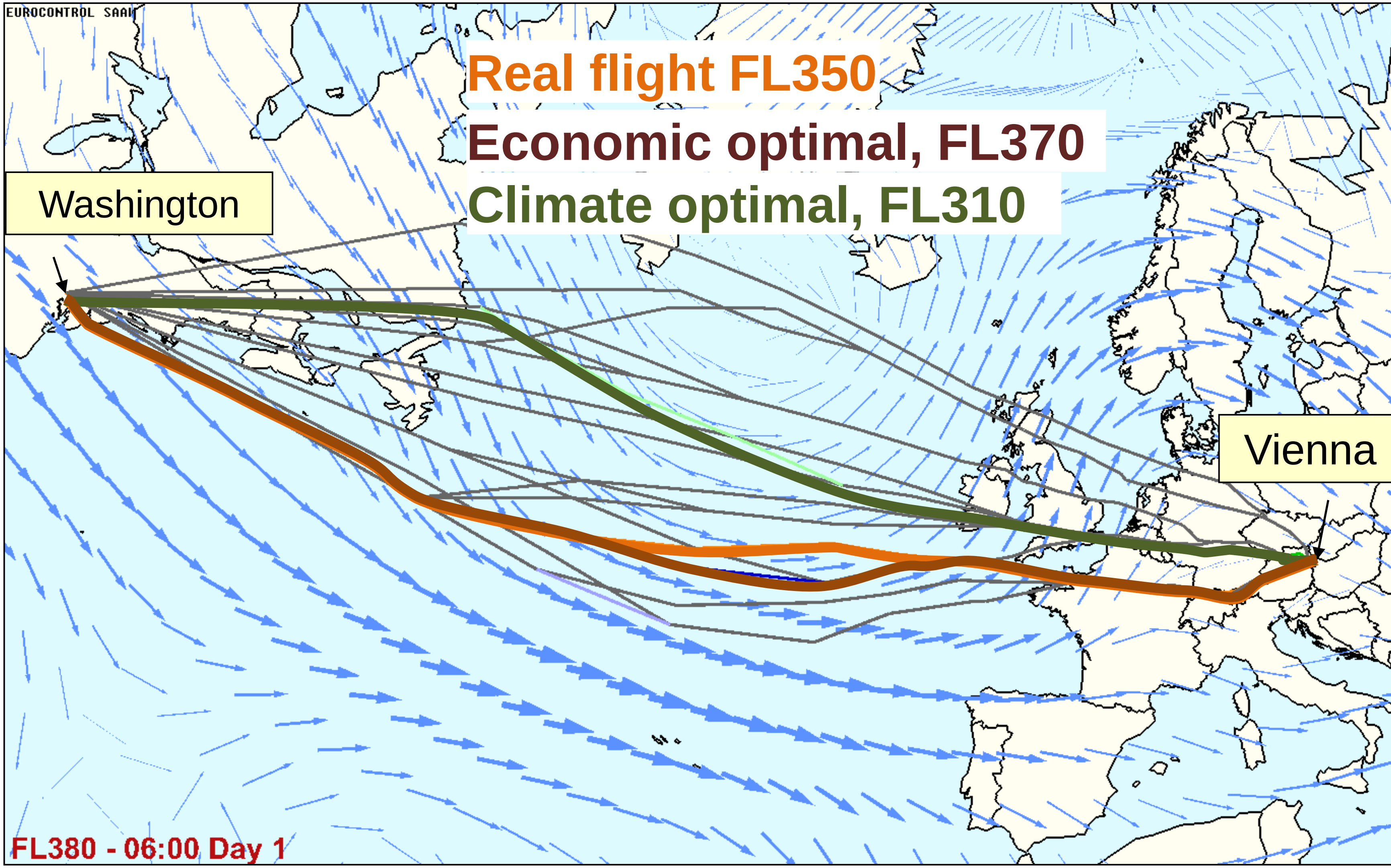
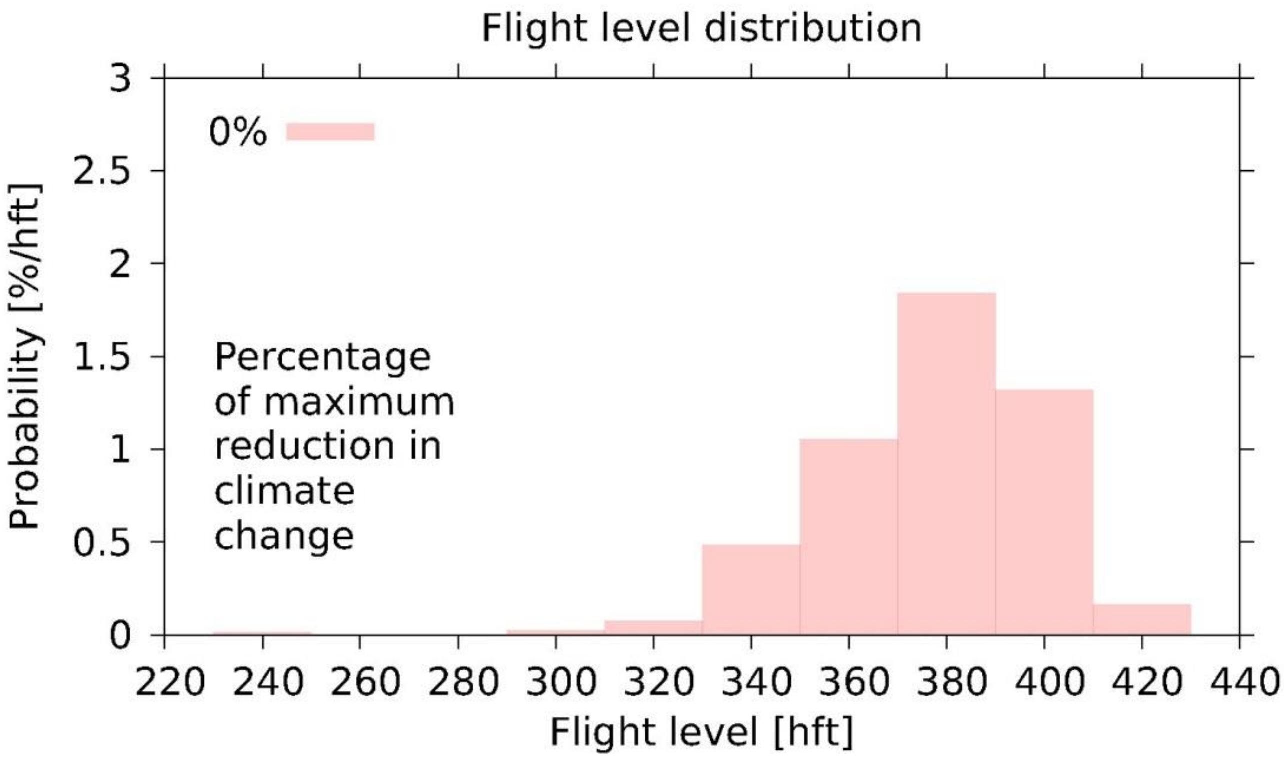
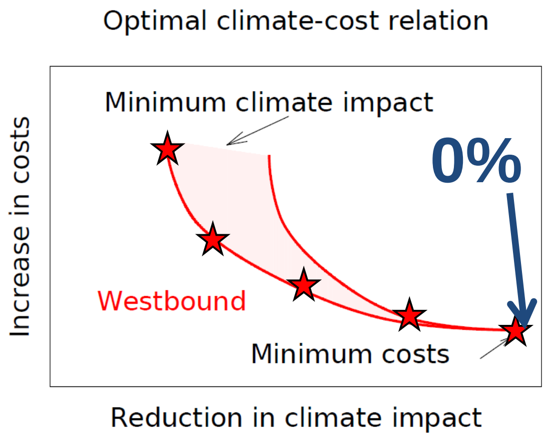


How is the air traffic modified? Changes along the Pareto-Front





CAUTION: results are for one case study day only!
Grewe et al., 2014, Atmospheric Environment

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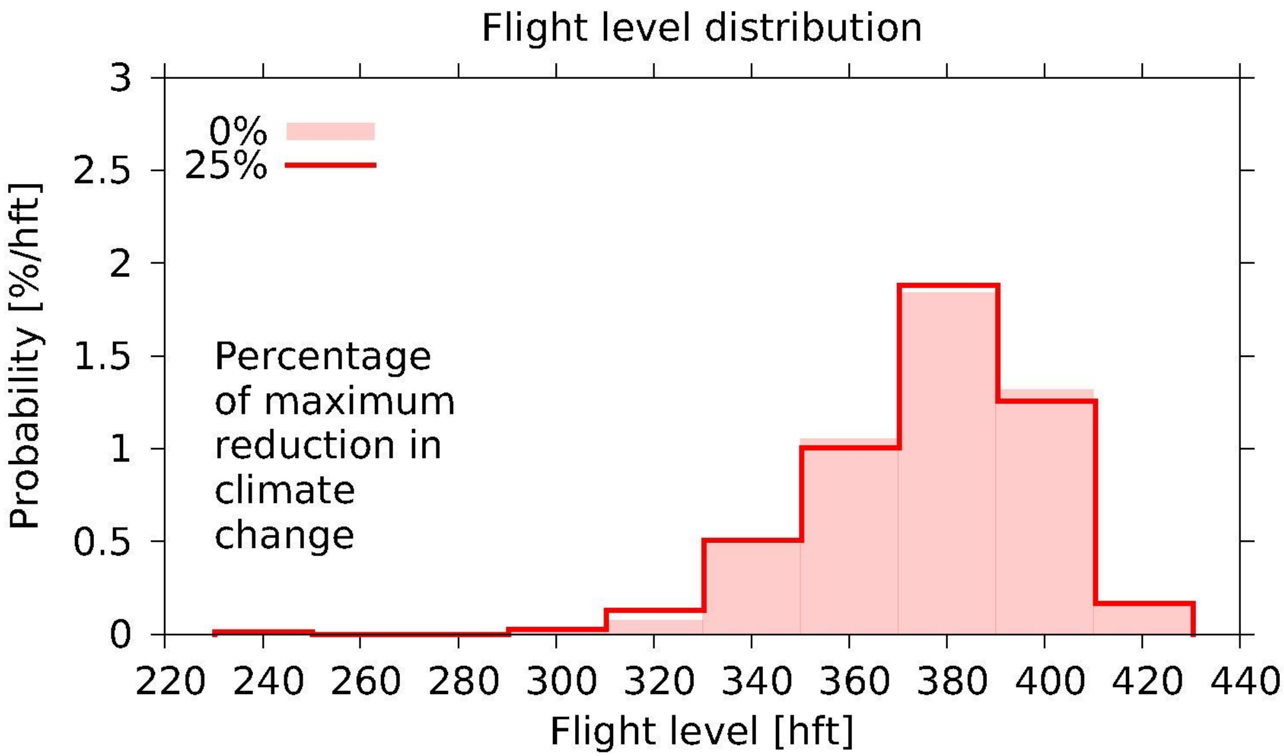

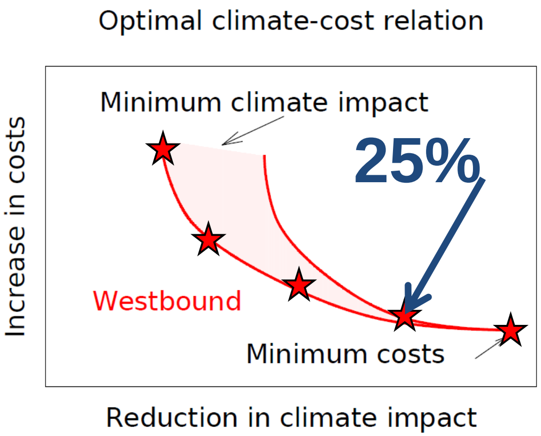

Only small changes in flight altitude

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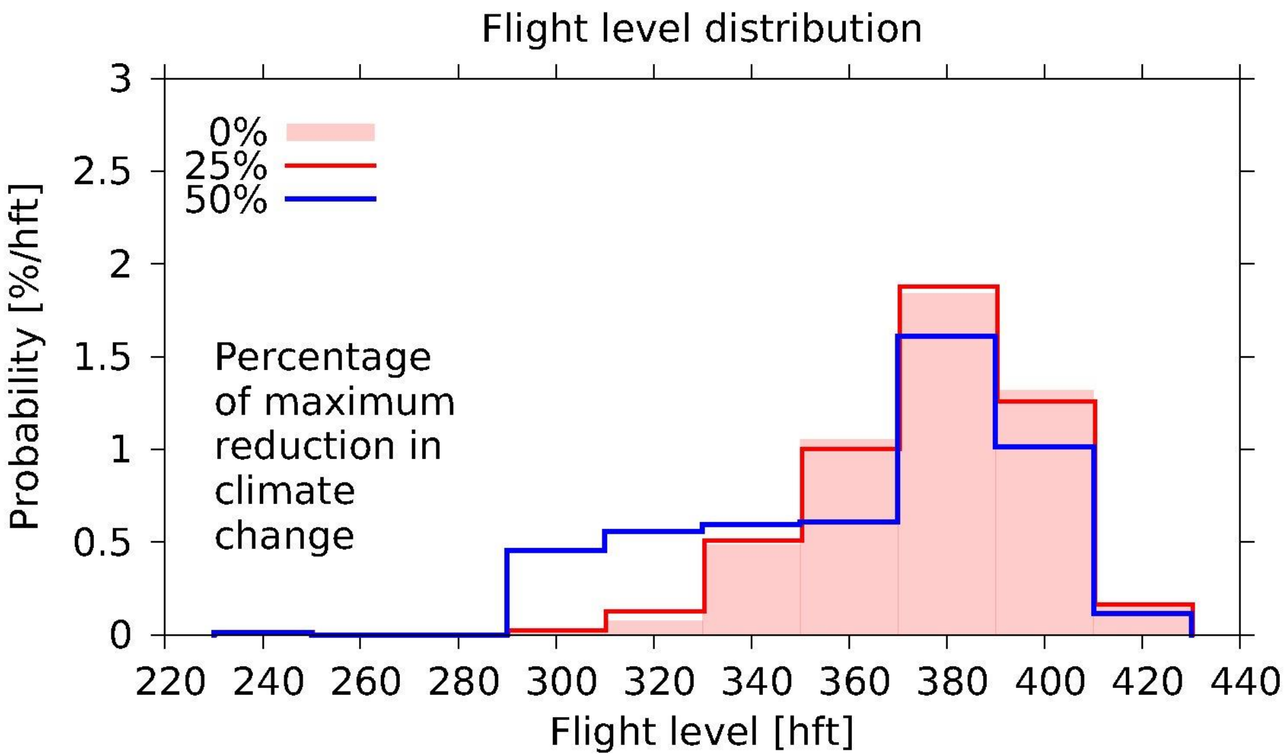
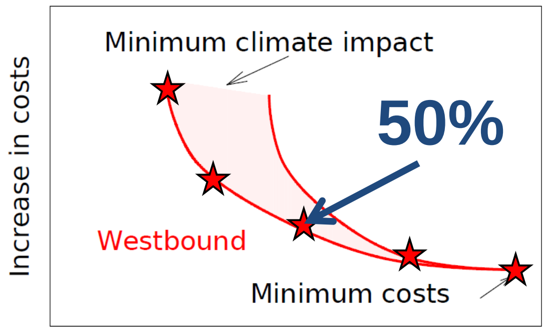


Optimal climate-cost relation



Reduction in climate impact

Some flights are shifted to lower flight altitudes

CAUTION: results are for one case study day only!

Grewe et al., 2014, Atmospheric Environment

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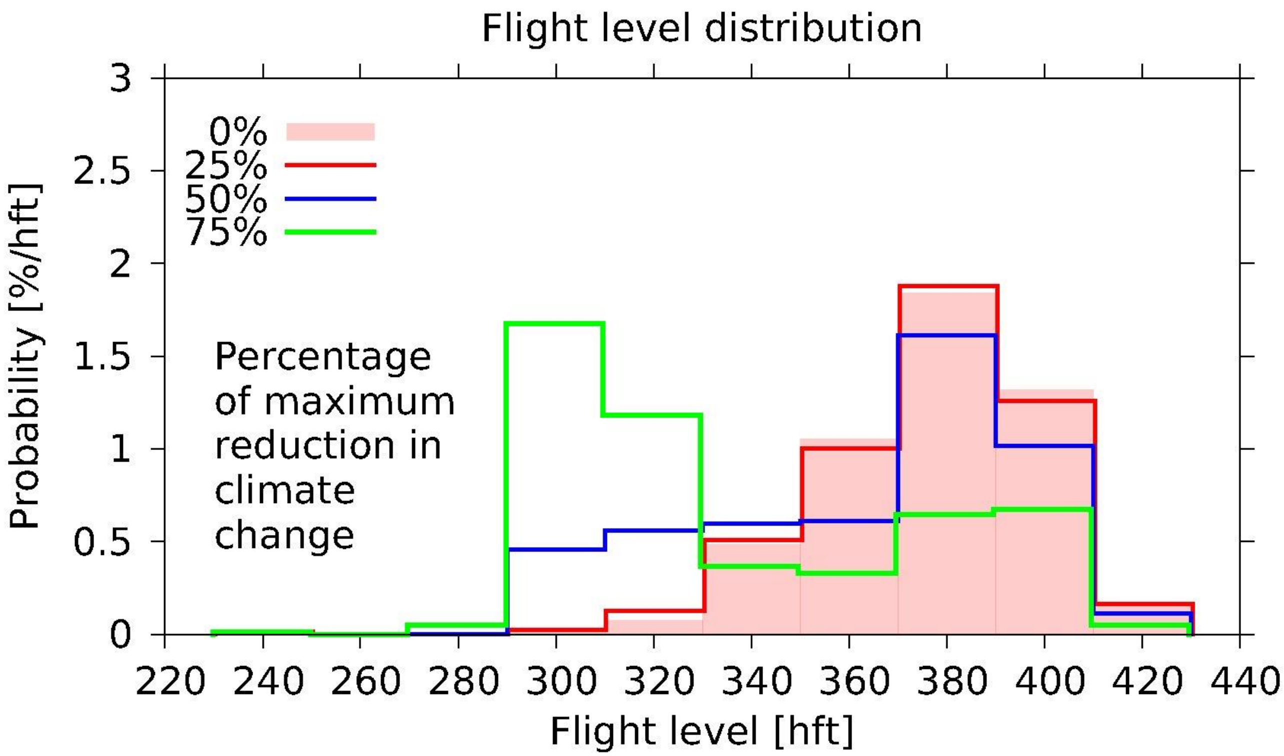

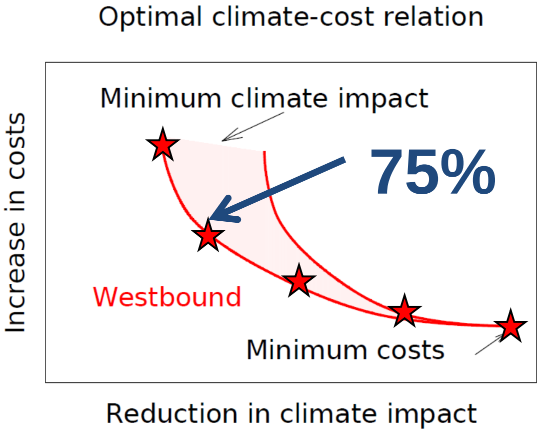

Many flights shifted from FL380 to FL300

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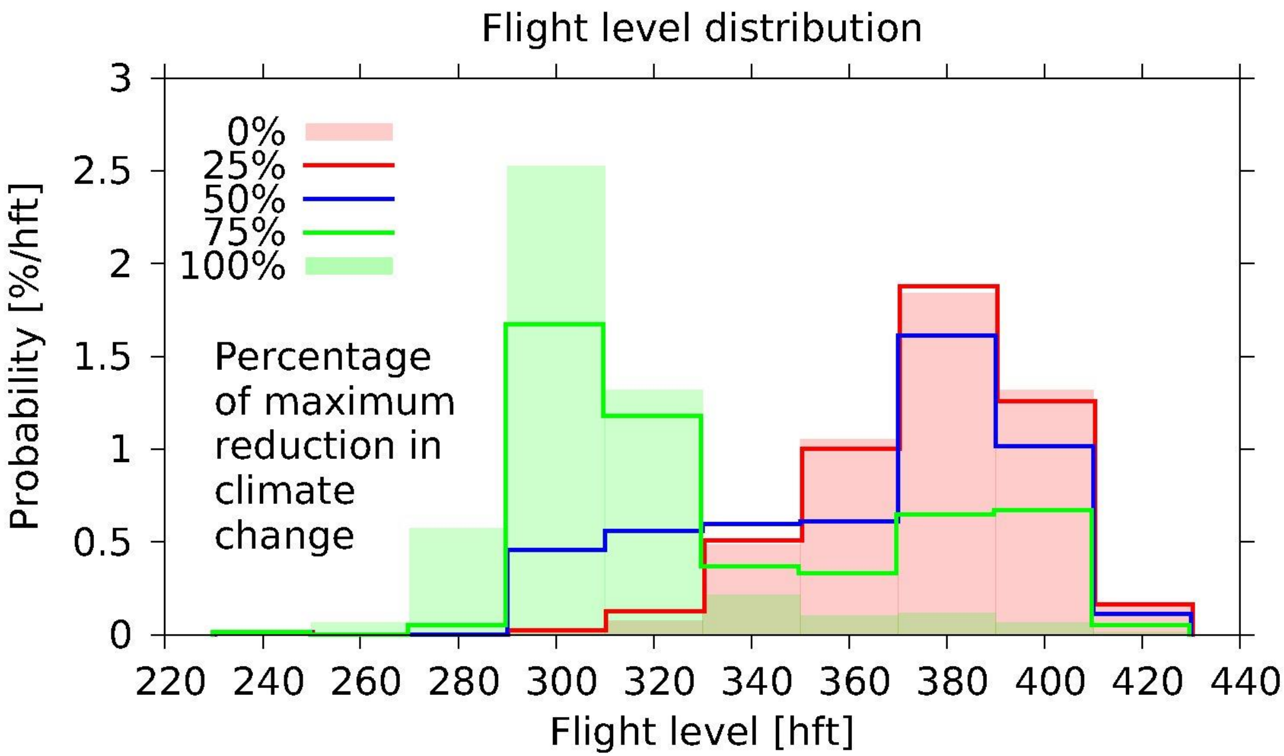

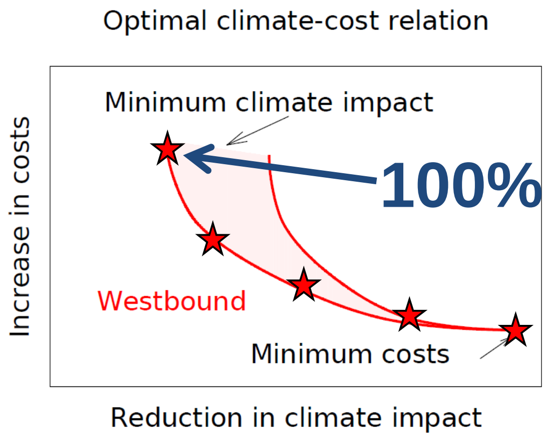

Main flight altitude: FL 300

CAUTION: results are for one case study day only!

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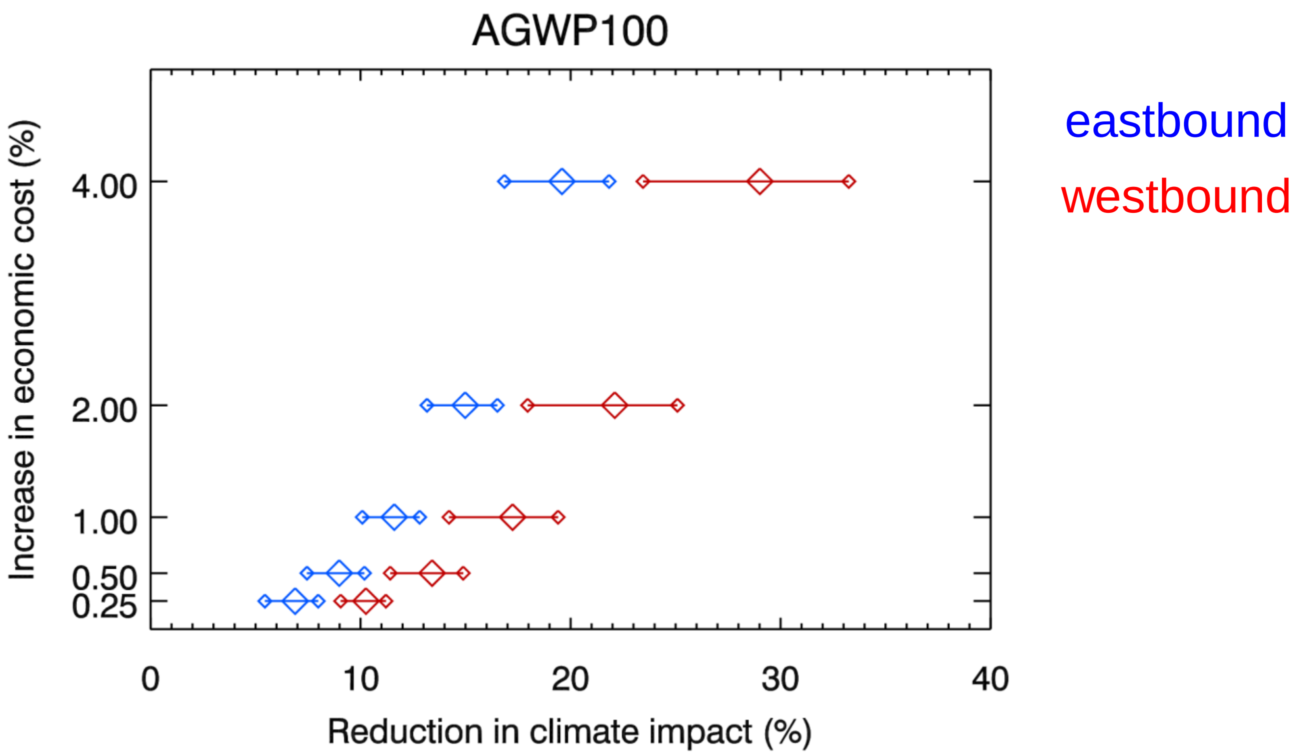
Potential mitigation gain: winter



- Larger reduction in climate impact for a given increase in operating cost for westbound flights than eastbound flights
- Size of potential gain is dependent on metric and time horizon

Summary

- Improved confidence in estimates of contrail and contrail cirrus climate impact, but still large uncertainty compared to CO_2
- From a theoretical standpoint, flying extra distance to reduce contrail formation may reduce the overall climate impact of a flight
- How much extra distance can be flown depends on aircraft type, contrail size, metric used (political decision)
- Considering CO_2 and non-CO_2 climate impacts, climate-optimal routes are found which reduce the overall climate impact of trans-Atlantic air traffic for small increases in operating cost
- Less potential to reduce the climate impact of eastbound flights, particularly for weather situations with strong jet streams

Challenges

- Can we forecast contrail regions with sufficient accuracy, and can we verify these forecasts?
- Accuracy and delivery method of required weather information – flight planning, provision to ATC, cockpit?
- How will future technology developments (e.g. engine efficiency, fuel type) impact contrail formation or contrail properties?
- Can contrail formation by reduced by technological means?
- How will climate change impact contrail formation? Changes to flight-level humidity and temperature are expected.
- Issues around contrail avoidance will be different for highly congested airspace and different climatic regions (i.e. tropics)

Thank you!

Information from:

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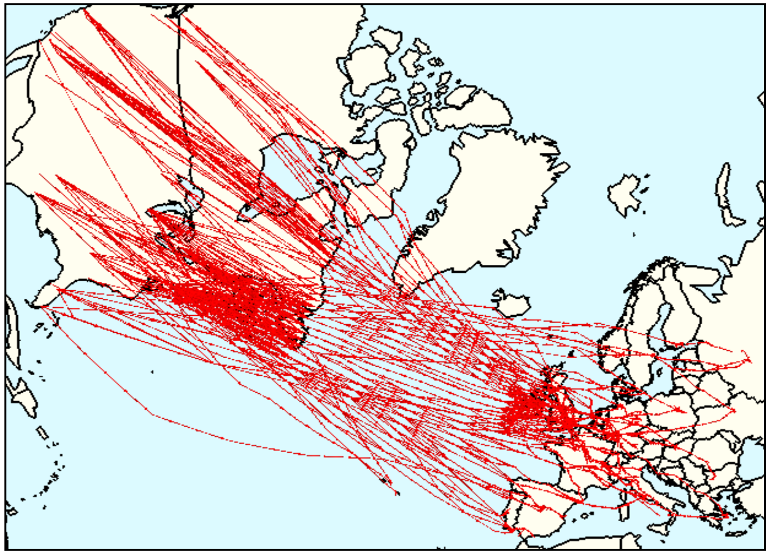
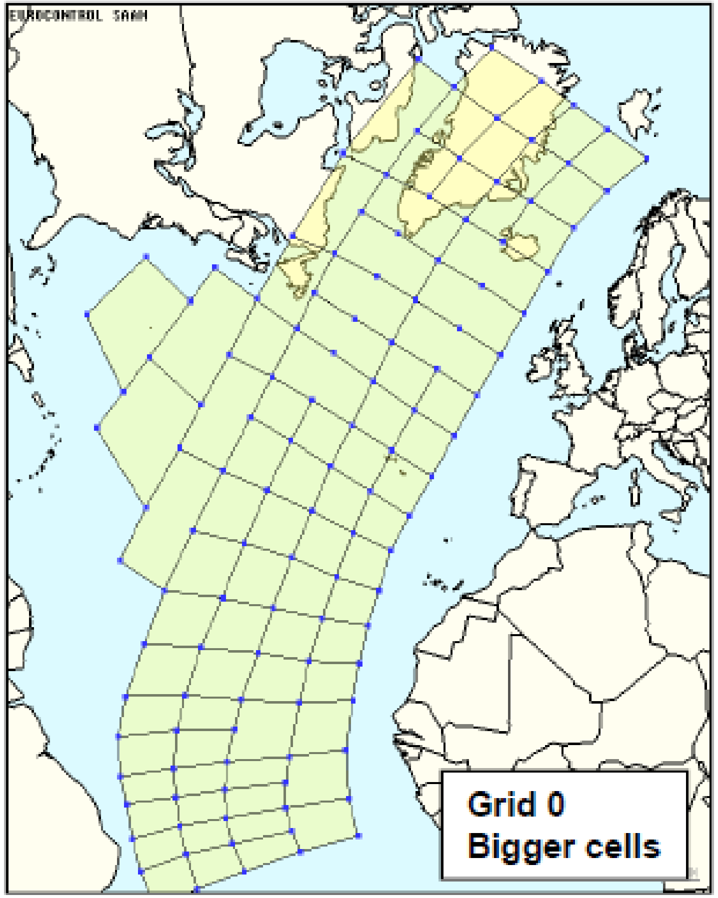
www.react4c.eu

Generate route options for air traffic sample

Air traffic sample





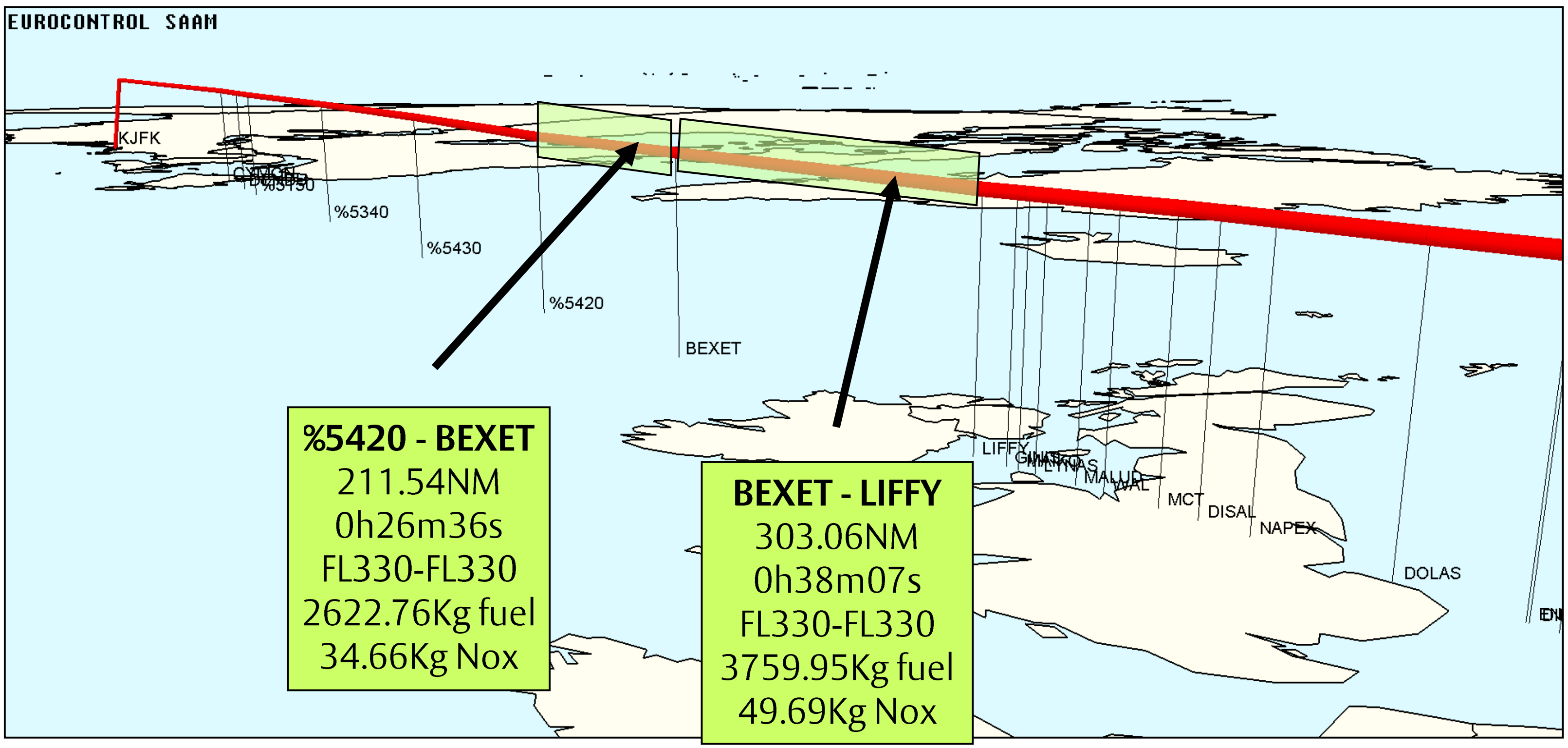
For each city pair:
17 2D route options at 5 flight levels:
= 84 possible routes

Calculate emissions along each route

- For each flight segment, the AEM model (Advanced Emission Model) calculates the length, time, FL, azimuth, fuel consumption, CO2 and Nox emission.

  ➔ We assumed the last to be No2 value.

Example for flight from New York to Dusseldorf



Calculate cost

Two costs are calculated per flight:

- Climate cost is the sum of: AIC, O_3, TMO_3, CH_4, H_2O, CO_2.
- Economic cost is 25€/minute of flight + 0.75€ /kg of fuel

e.g. Typical flight London – New York

FUEL: 10 kg fuel /km x 5500 km x 0.75 € /kg = €41 250

TIME: 360 min x 25 € /min = € 9 000

→ 82% of operating costs is fuel

Calculate cost for each of the 84 route options for each city pair. Now we can find which route has (a) minimum climate cost, and (b) minimum economic cost

Calculate safe route combinations

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- Minimum allowable separation between two aircraft is:
  - 60 NM in horizontal
  - 1000 ft (FL10) in vertical
- Conflict calculation every 5 s over N Atlantic

Example flight: Washington to Vienna
Comparison to real flight

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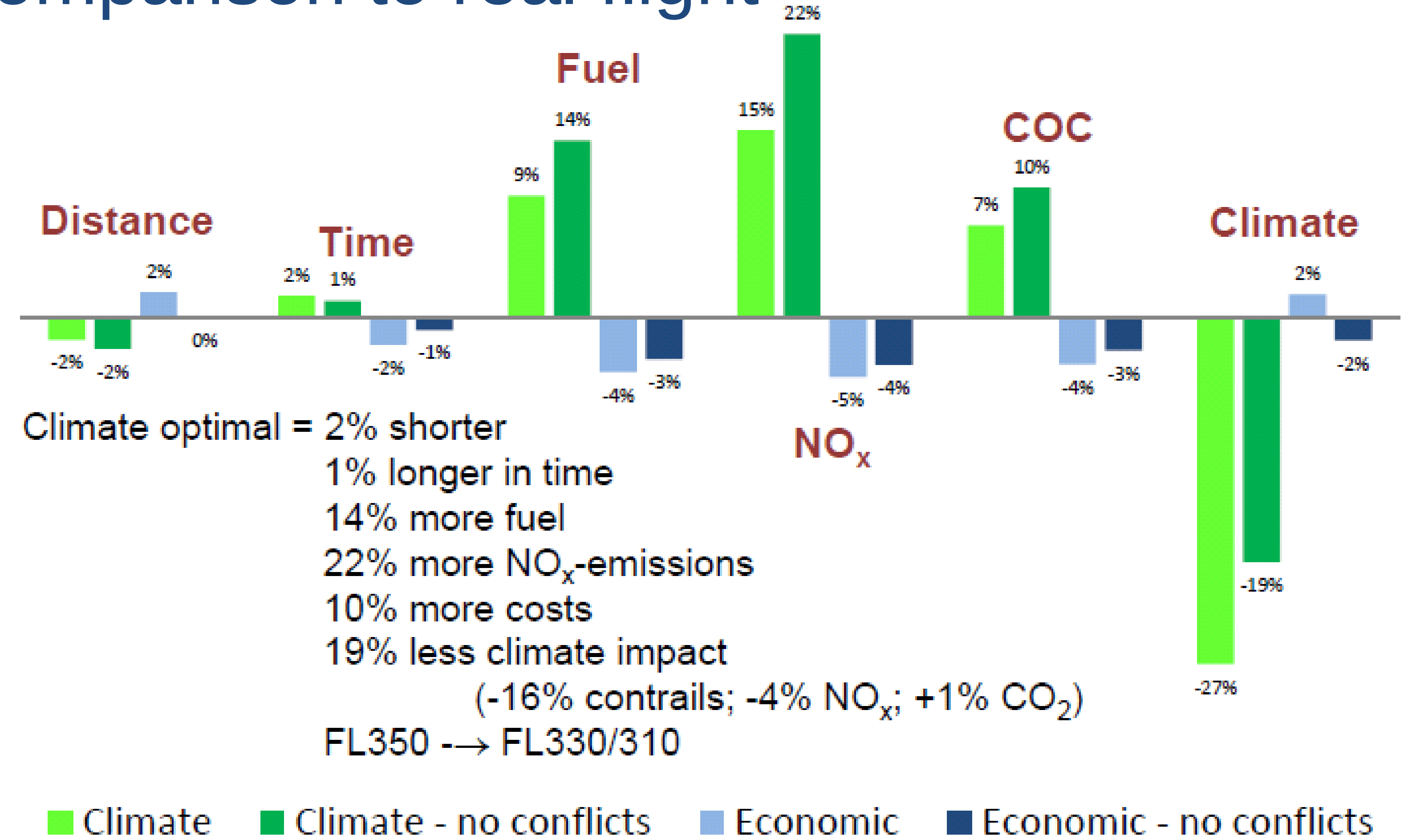

Climate optimal = 2% shorter
1% longer in time
14% more fuel
22% more NO_x-emissions
10% more costs
19% less climate impact
(-16% contrails; -4% NO_x; +1% CO_2)
FL350 -→ FL330/310

DLR

Radiative forcing

- Used to measure the climate impact of emissions, e.g. CO_2
- Quantifies the change in net energy of the climate system at the top of the atmosphere
  - POSITIVE forcing = surface warming
  - NEGATIVE forcing = surface cooling

"Total radiative forcing is positive, and has led to an uptake of energy by the climate system. The largest contribution to total radiative forcing is caused by the increase in the atmospheric concentration of CO_2 since 1750"

IPCC 2013