Climate-optimised air traffic routing for trans-Atlantic flights

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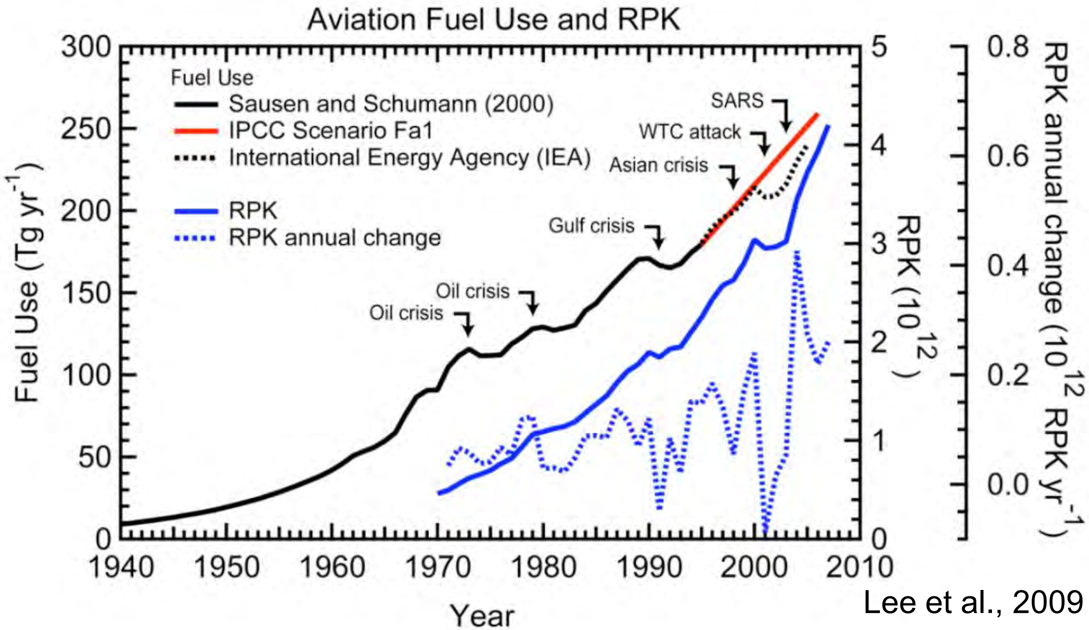
Air traffic and climate change

- High **air traffic growth rates** of 3 – 5 % per year.
- **Measures required** to reduce aviation climate impact to counteract this development
- **Possible reduction through**:
  - alternative fuels
  - novel engine concepts
  - modification of aircraft design
  - different routing
  - etc.
- **Optimization of routes (horizontally and vertically) wrt. the climate impact of CO_2, H_2O, and NO_x emissions and contrail-cirrus**



Lee et al., 2009

General routing changes:
e.g. “Flying lower for individual routes”
=CATS project

Adaptation of flight profile for every weather situation =REACT4C

Climate optimized routing by using climate cost functions

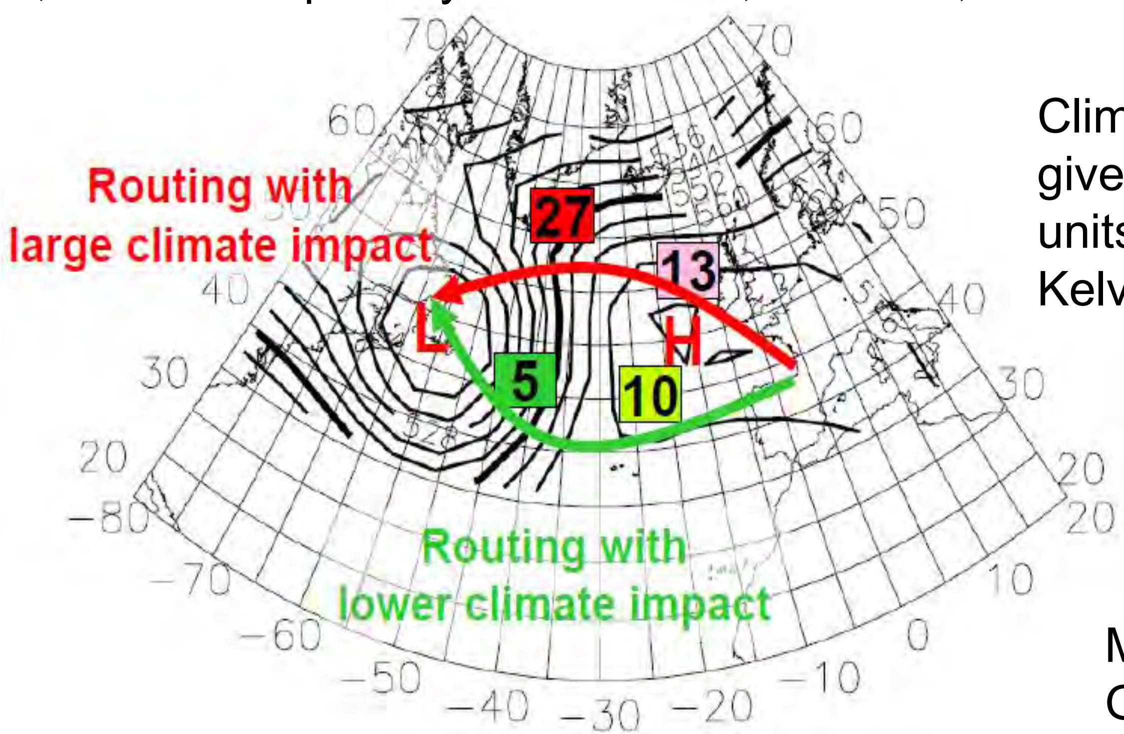
Climate cost functions:

= Measure for climate impact of individual aviation emissions depending on emission **location**, emission **altitude**, and local emission **time**

⇒ **Depending on weather situation**

⇨ Aviation impacts investigated:

- Ozone, Methane + primary mode ozone, Contrails, Water vapour, CO_2



Climate cost function is given as number with units
Kelvin per kg emission

Matthes et al., 2012
Grewe et al., 2014a,b

Climate optimized routing by using climate change functions

Climate change functions:

= Measure for climate impact of individual aviation emissions depending on emission **location**, emission **altitude**, and local emission **time**

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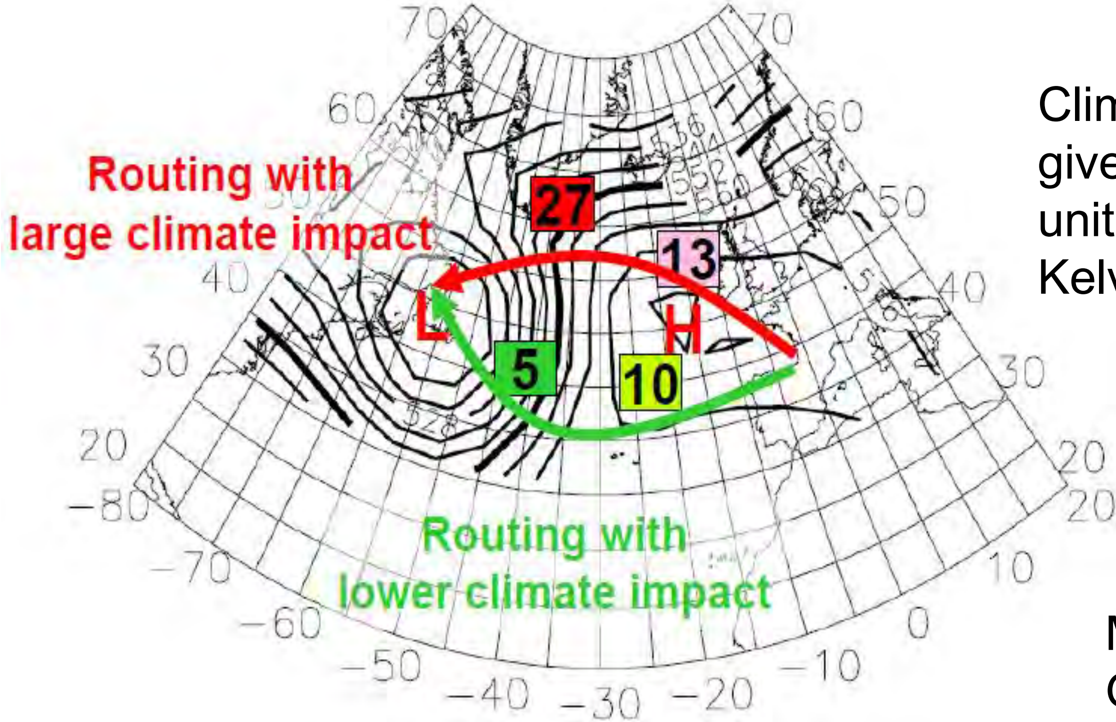
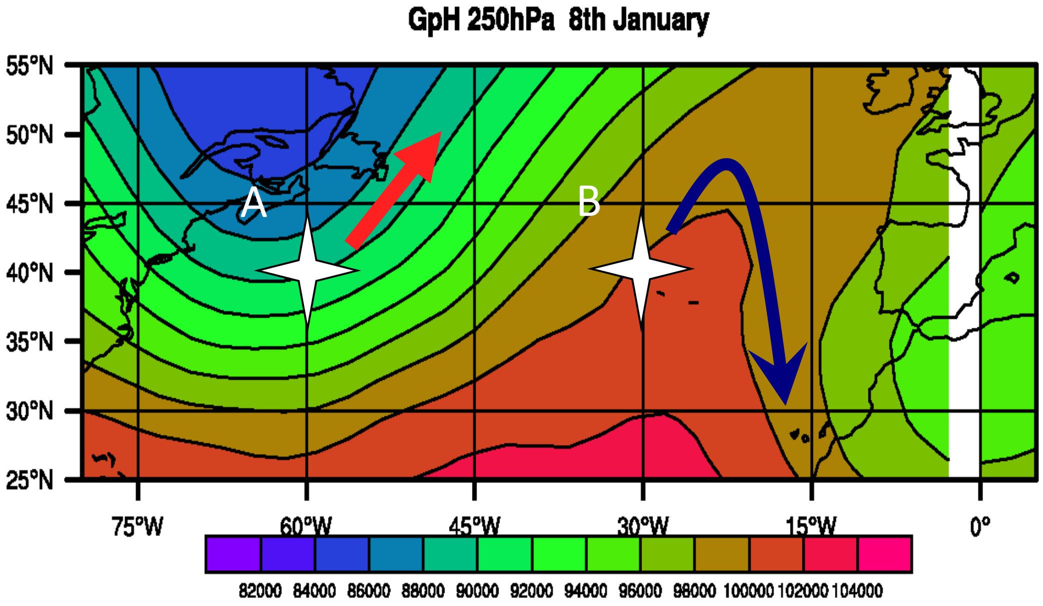


Climate cost function is given as number with units
Kelvin per kg emission

Matthes et al., 2012
Grewe et al., 2014a,b

Evolution of aircraft NO_x at two different locations

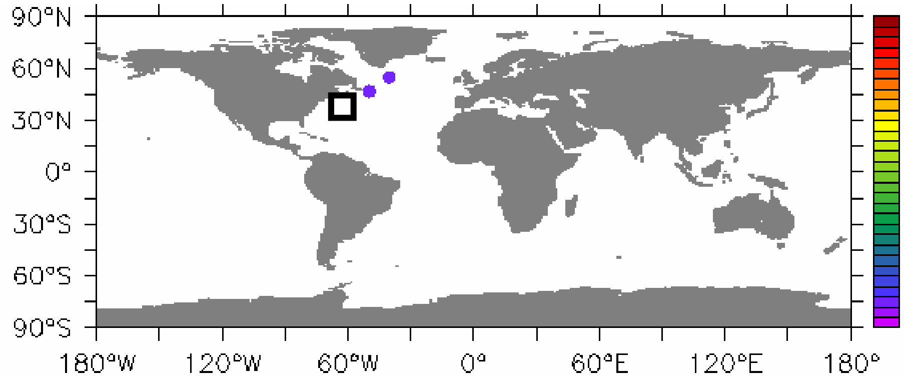


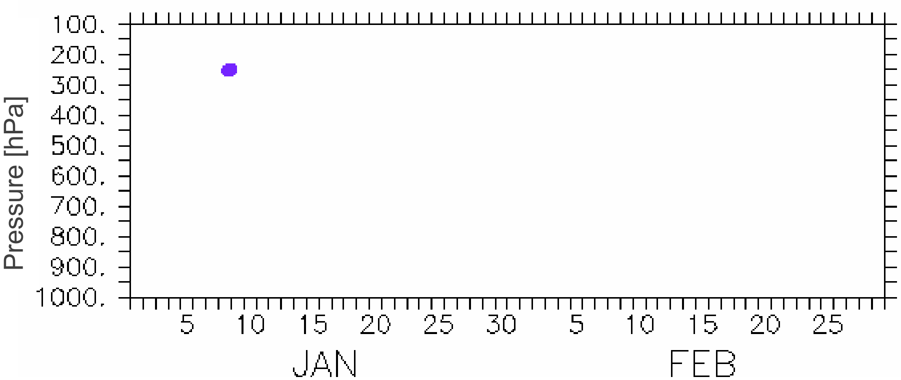
What happens if an aircraft emits NO_x at location A compared to location B?

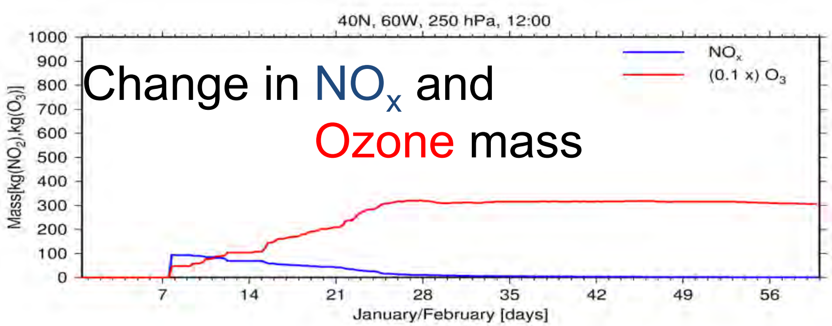
Frömming et al., 2011

Evolution of O_3 [ppt] following a NO_x pulse

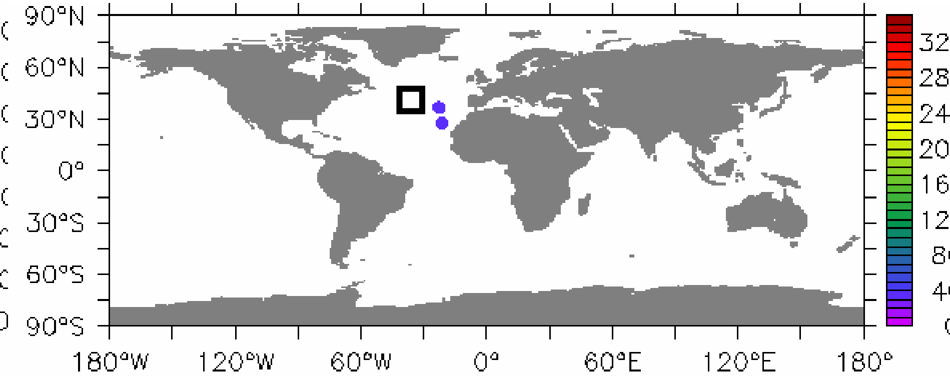
A: 250hPa, 40°N, 60°W, 12 UTC

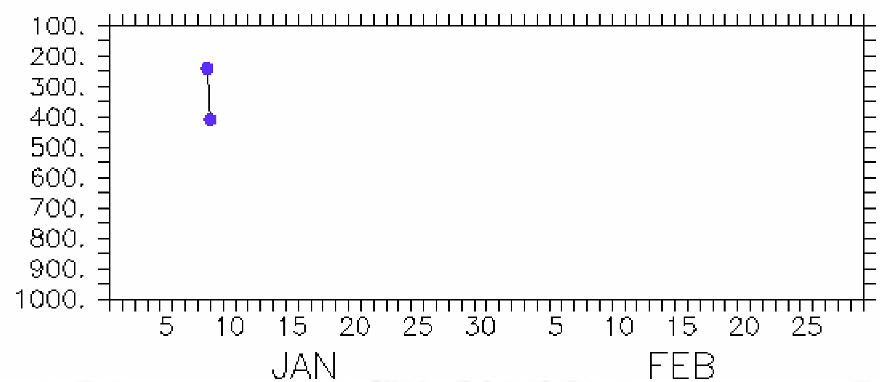


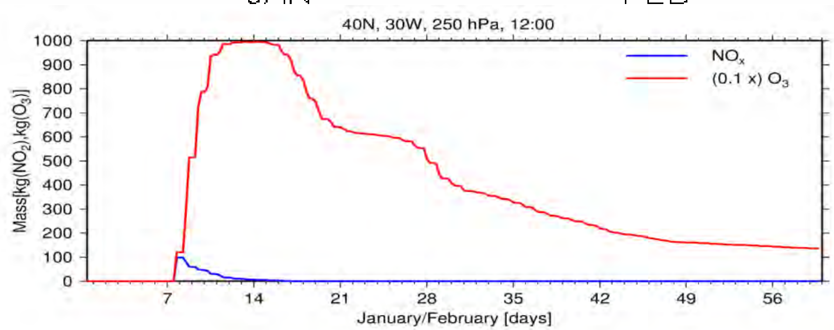




B: 250hPa, 40°N, 30°W, 12 UTC







Modelling of the climate cost functions include

Base model:

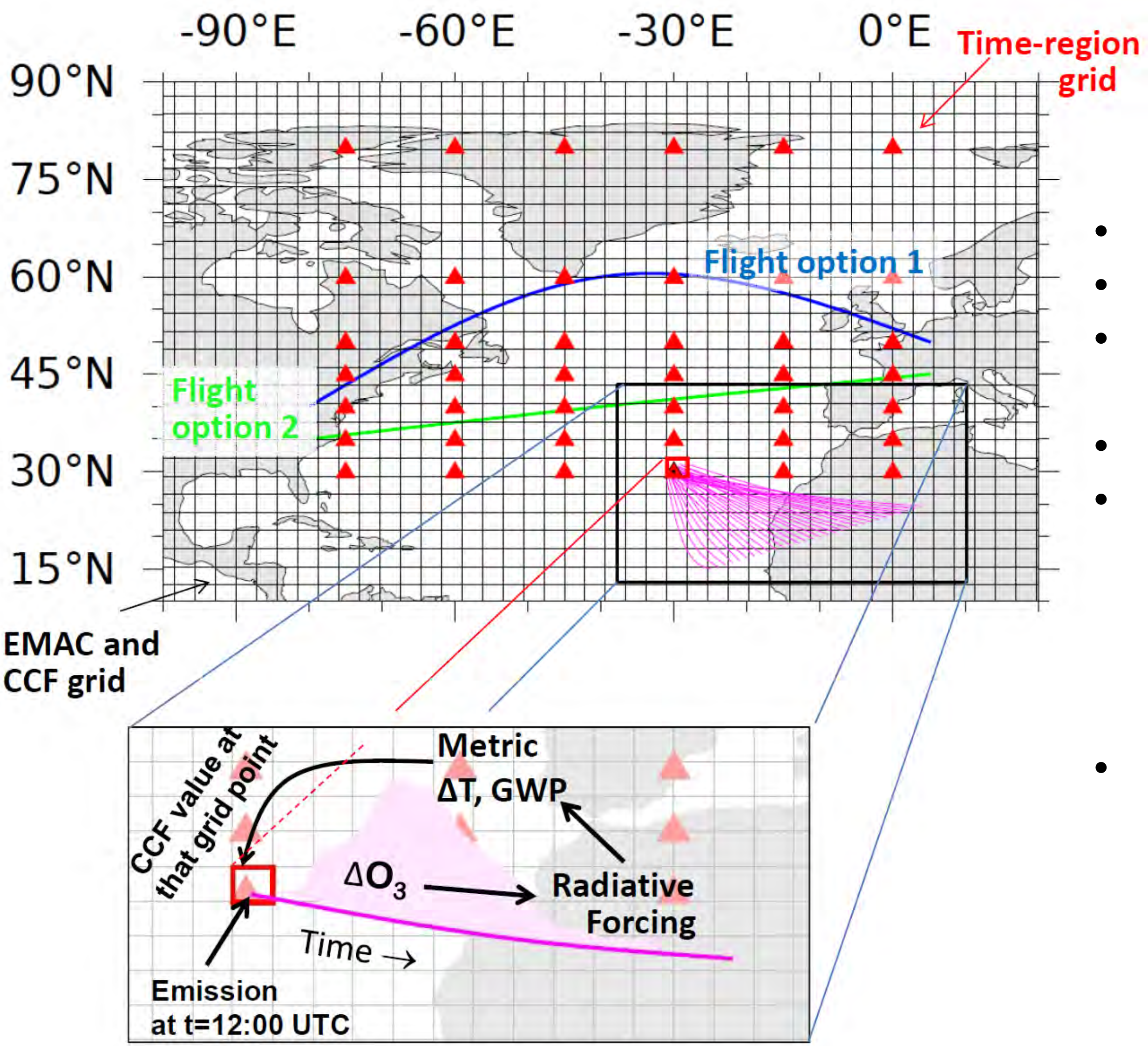
- ⇨ Community climate-chemistry model EMAC

AIRTRAC submodel for calculating CCFs:

- Chemistry:
  - ⇨ Nitrogen oxides, ozone, methane, ozone from methane changes, …
  - ⇨ Rain-out,
- Micro-Physics
  - ⇨ Formation and spreading of contrails
  - ⇨ Sedimentation, growth and sublimation of ice particles
- Radiation:
  - ⇨ Change in radiation caused by ozone, methane, contrails, water vapour
  - ⇨ Radiative forcing
- Metrics:
  - ⇨ Focus on both long-term and short-term effects
  - ⇨ GWP, GTP, ATR

Grewe et al. (2014)

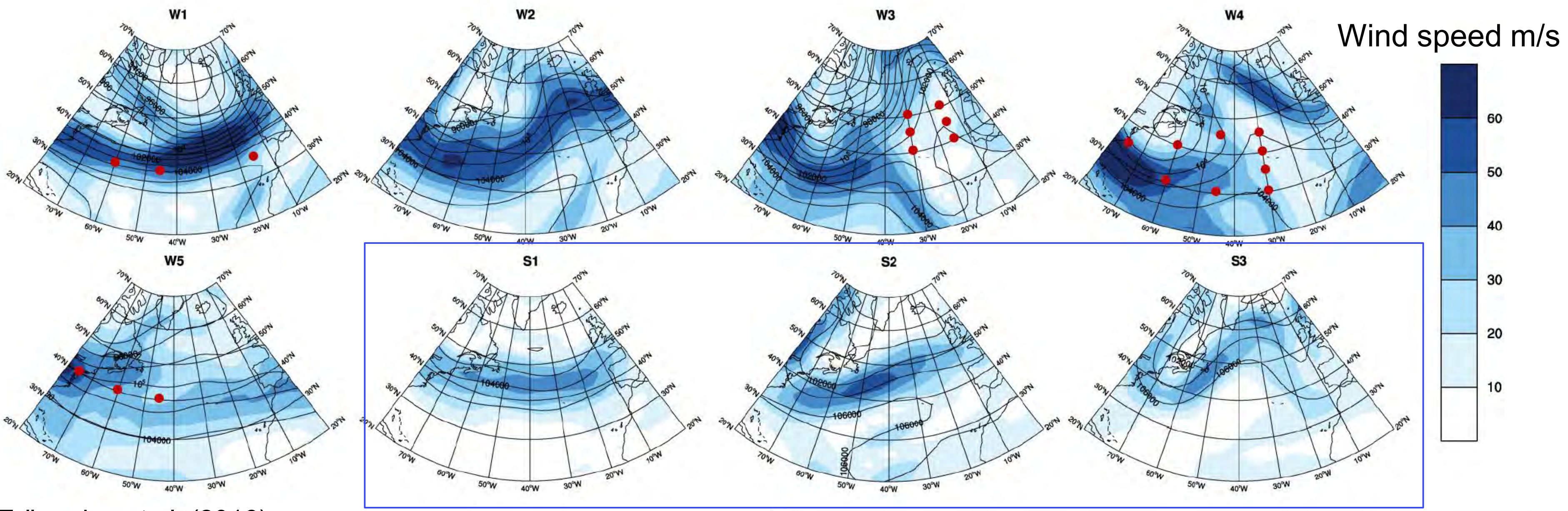
Modelling overview: Grids and processes



- Climate-Chemistry Model
- Locally confined emissions
- Transport calculation with trajectories
- NMHC chemistry
- Calculation of effects of NO_x emissions on
  - Ozone
  - Methane
  - Primary mode ozone
- Calculation of the change in climate metrics

Grewe et al.,GMD (2014)

Representative weather patterns



Frömming et al. (2016)

Classification of weather pattern according to Irvine et al. (2013)

- 5 winter pattern
- 3 summer pattern
- Jet location and strength largely differs

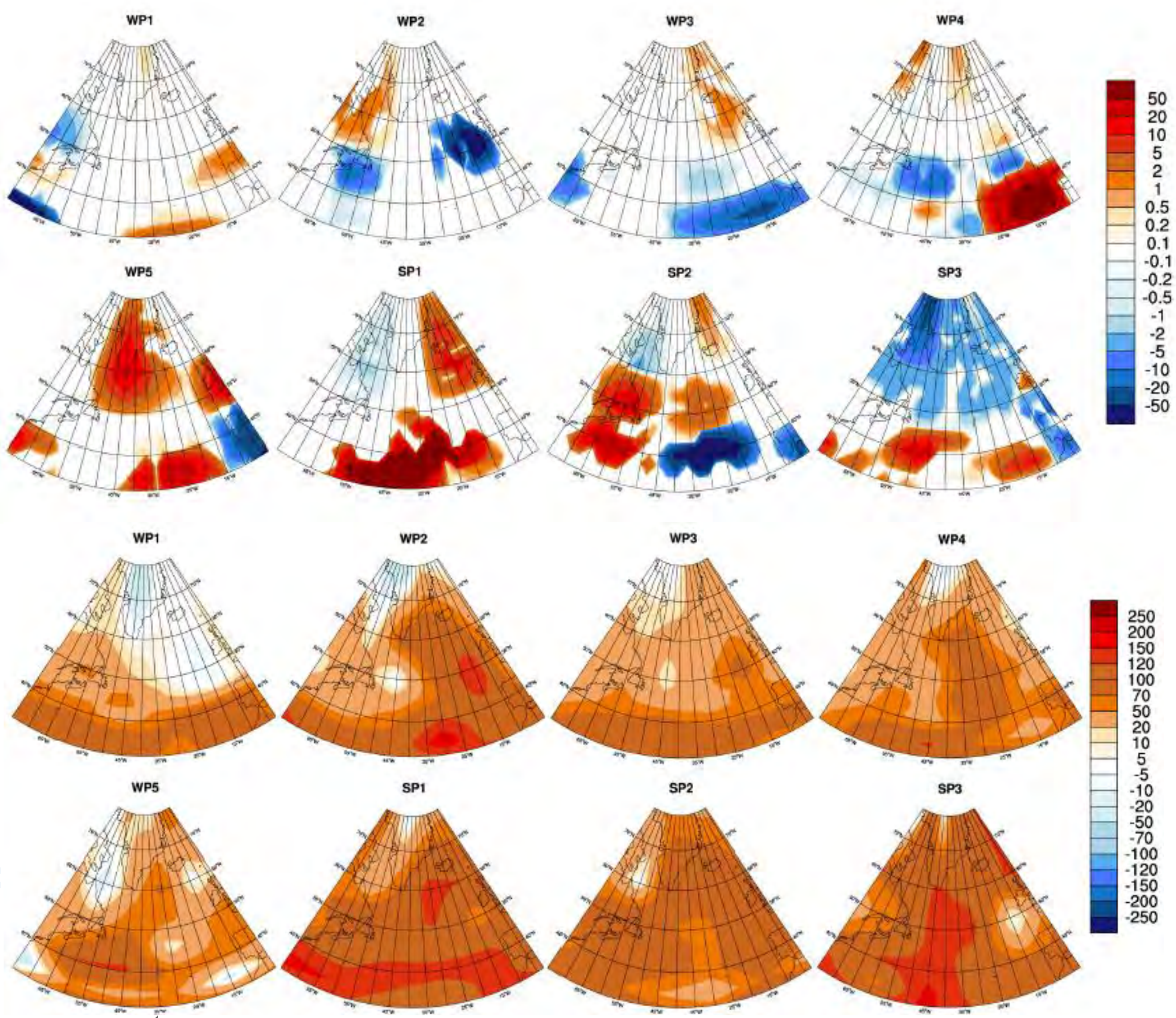
Type	Jet stream		Frequency (days/season)
	Position	Strength	
W1	Zonal	Strong	17
W2	Tilted	Strong	17
W3	Tilted	Weak	15
W4	Confined	Strong	15
W5	Confined	Weak	26
S1	Zonal	Strong	19
S2	Weakly tilted	Weak	55
S3	Strongly tilted	Weak	18

Irvine et al. (2013)

Climate Change Functions 250 hPa

Contrails

NO_x emissons

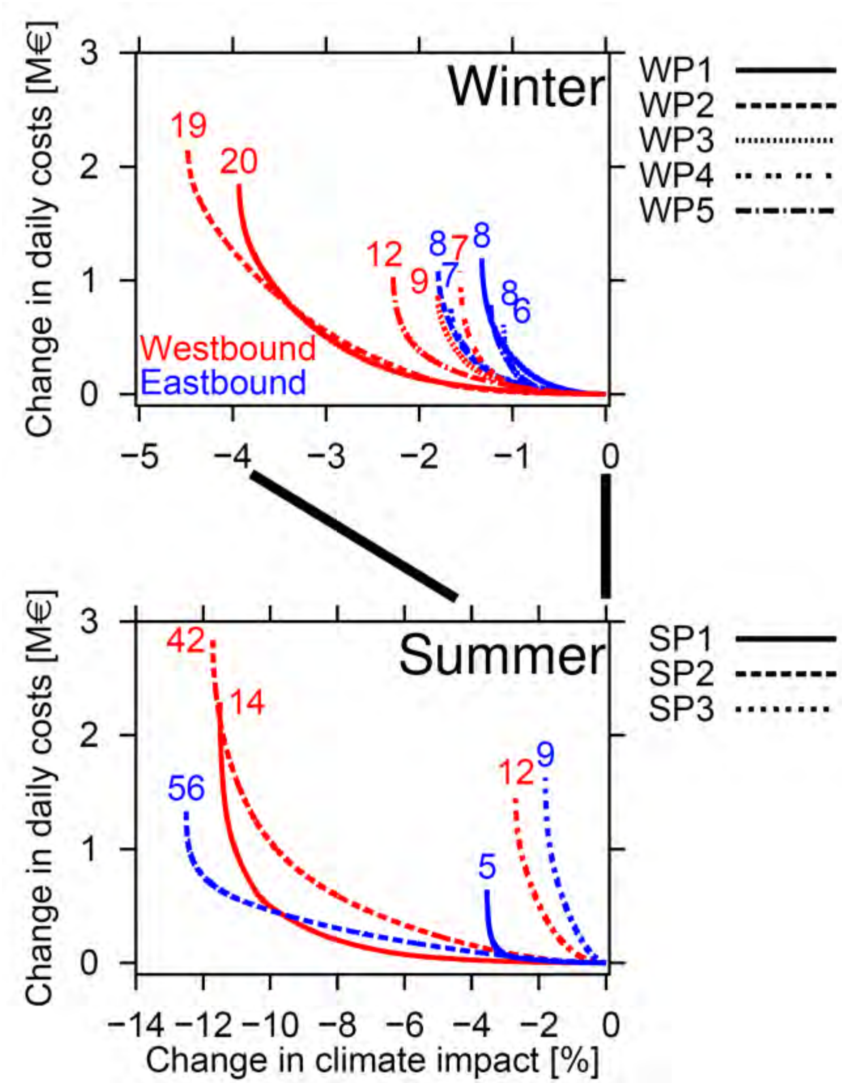


- ATR20 per flight-km
- 10^{-14}K/km
- Very patchy

- ATR20 per Emission
- 10^{-14}K/kg(N)
- related to weather pattern

Frömming et al. (2016)

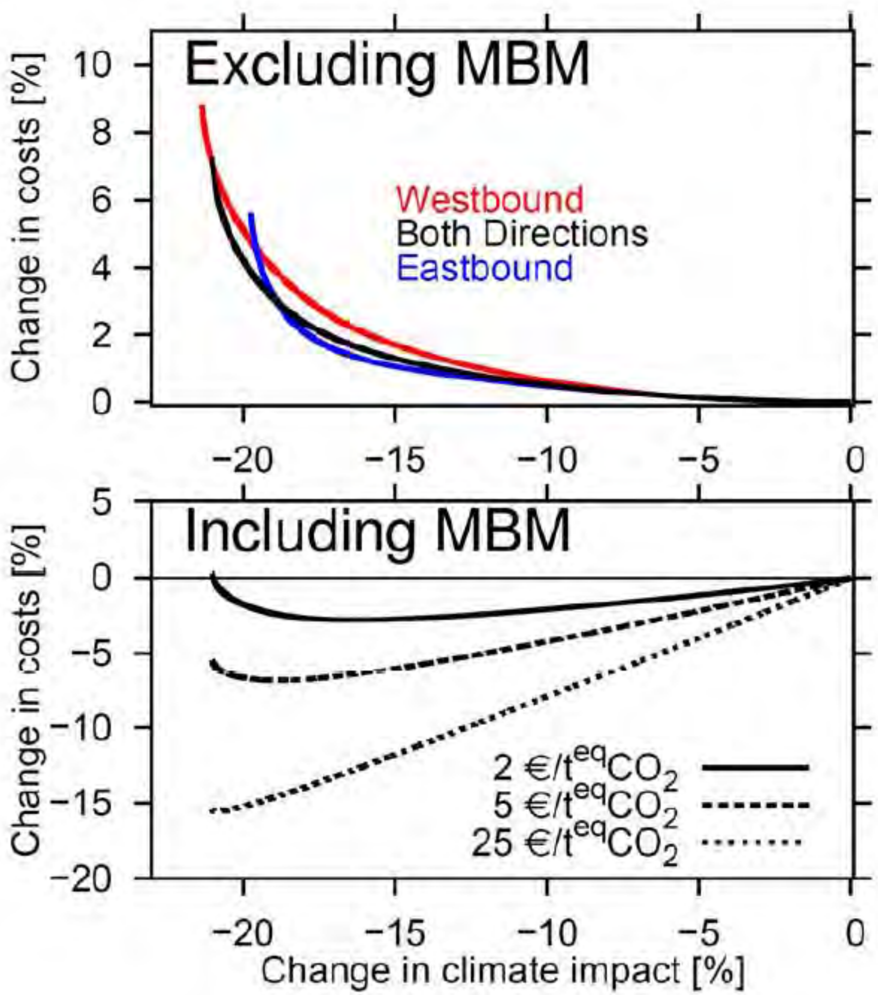
Cost-Benefit Relations for the 8 weather situations



- Large variety of climate impact reduction potentials
- WP1 (zonal) large difference between West and East-bound
- WP3 (Omega): No difference between West and East-bound
- Larger potentials in summer.

Grewe et al. (2016)

Climatology based on 8 representative weather pattern

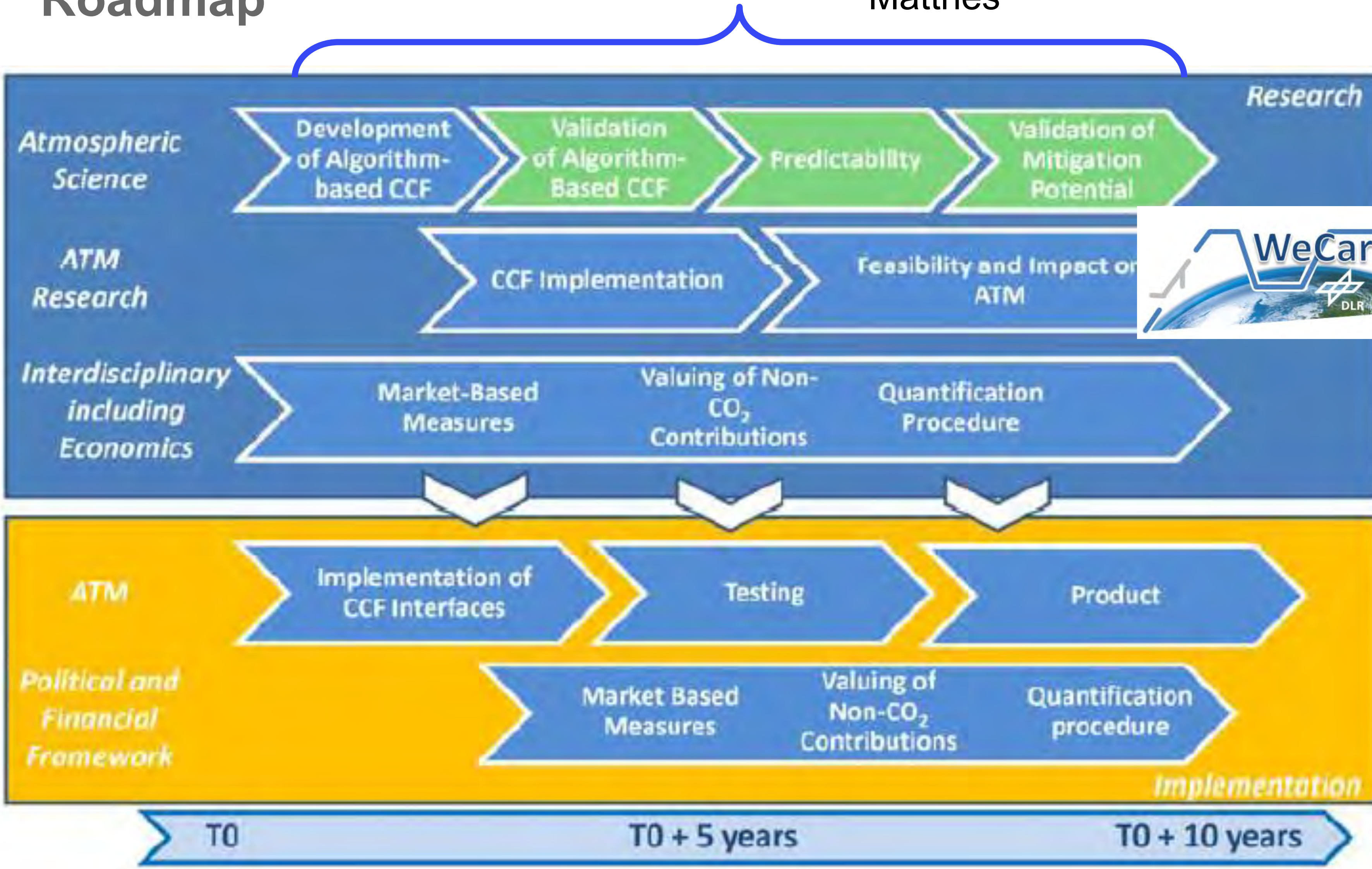


- Large difference between west- and eastbound vanishes in the climatological view
- But "very flat" Pareto-Front ⇒ Large Benefits at low costs
- Market based measures would enable climate optimised routing, if non-CO_2 effects were taken into account

Grewe et al. (2016)

Roadmap

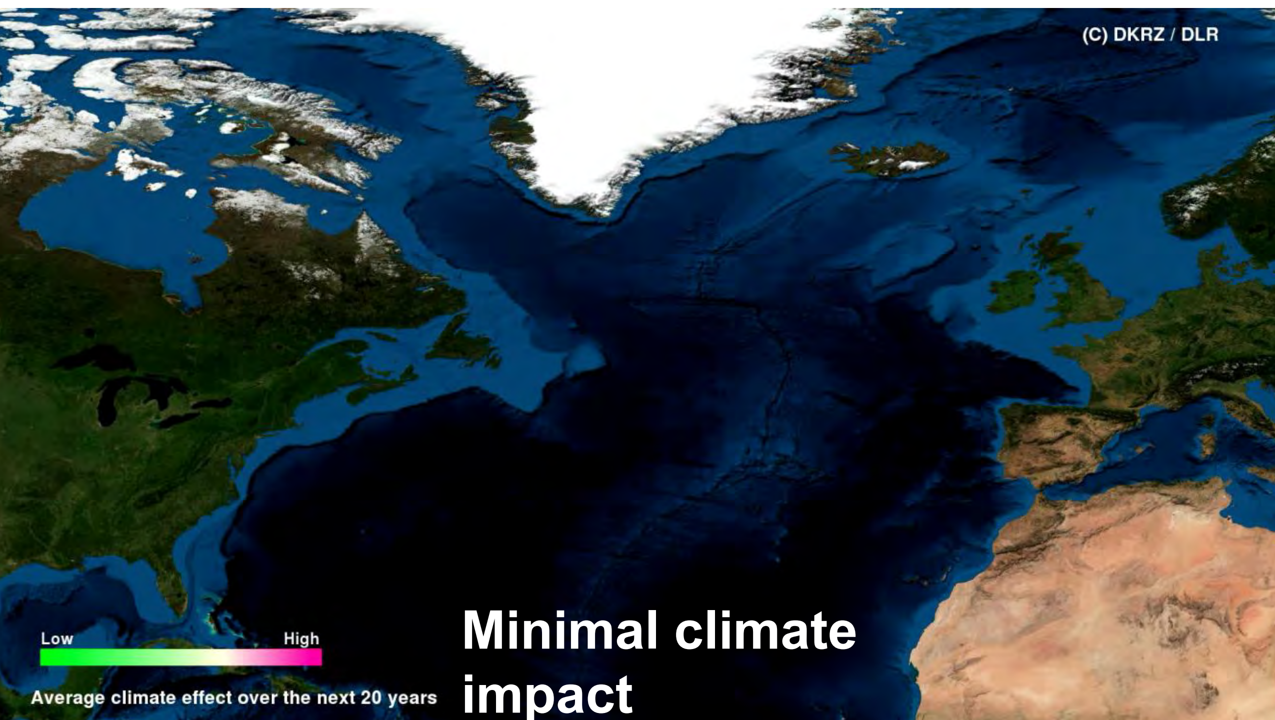
ATM4E Lead by S. Matthes



Grewe et al. (2016)

Example: New York - London

Clear difference between West- and eastbound traffic



Larger overlap of routes

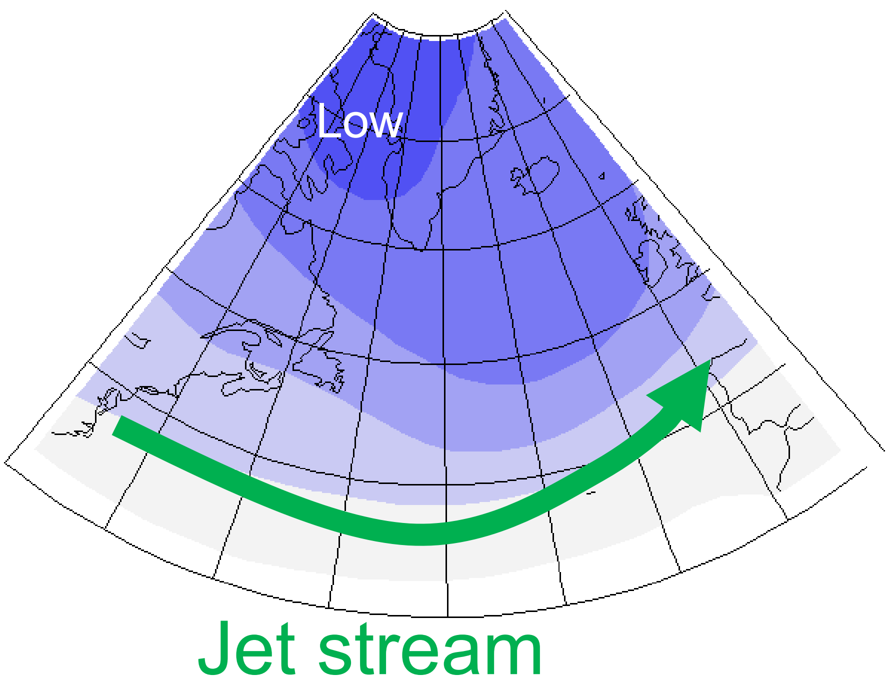
Fleet basis

- Only small differences visible
- Smaller flight corridor
- Difference between flights from and to Europe

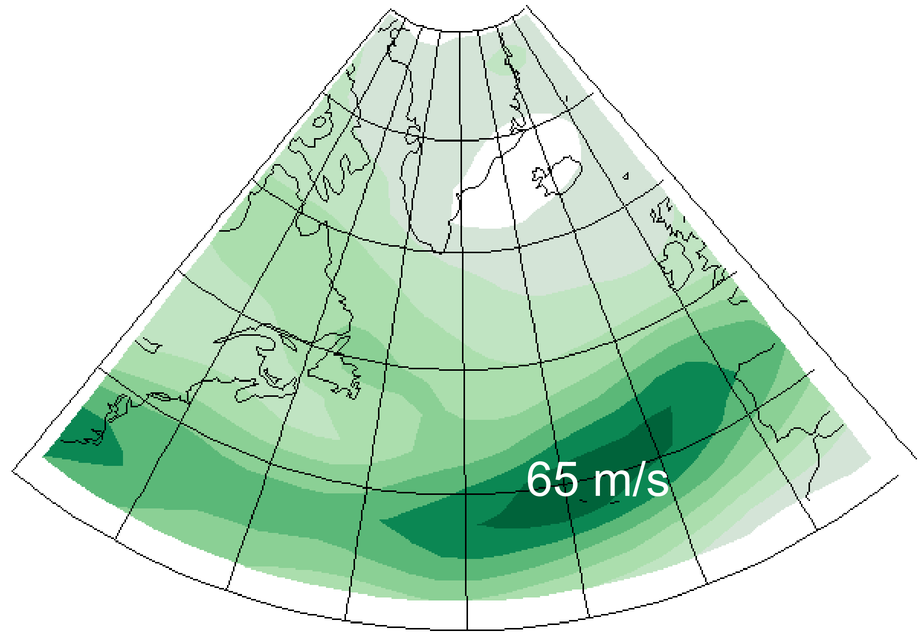

Thank you for your attention

Weather situation at cruise levels
Strong jet stream, basically in West-East direction

Geopotential heights



Wind velocity

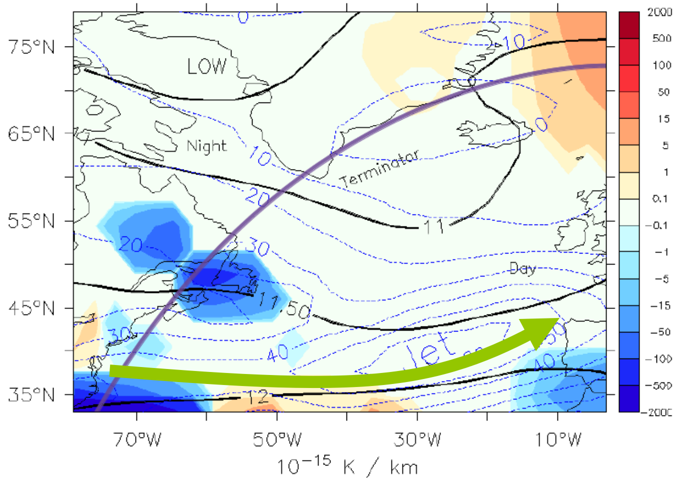


65 m/s = 230 km/h = 120 kn

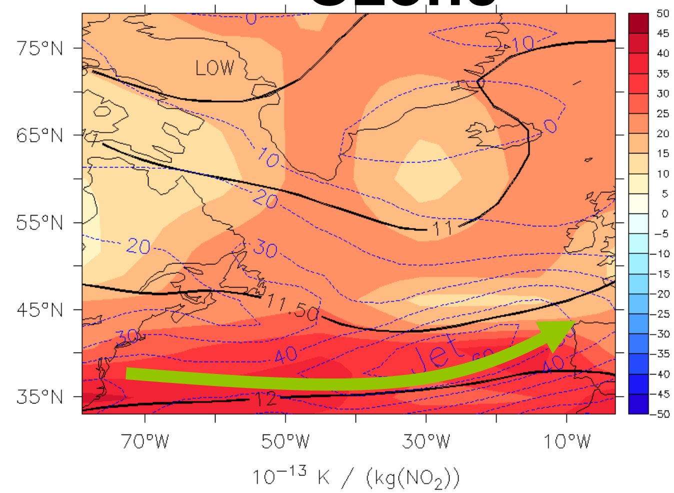
Grewe et al., 2014b

Climate cost functions at 200 hPa for 12:00 UTC

Contrail-Cirrus

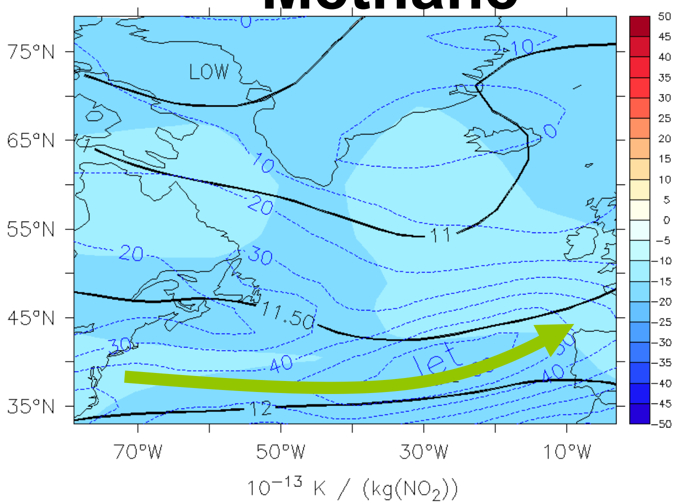


Ozone

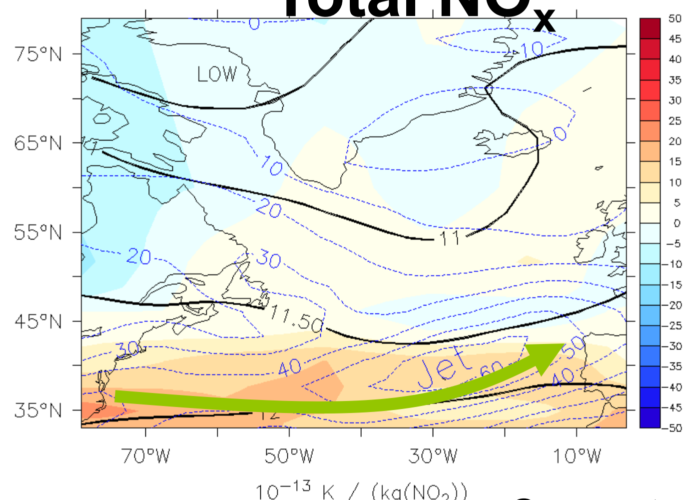


Contrails complex:
Depending on
- Lifetime
- Solar angle day/night
- Transport
- Loss processes

Methane



Total NO_x



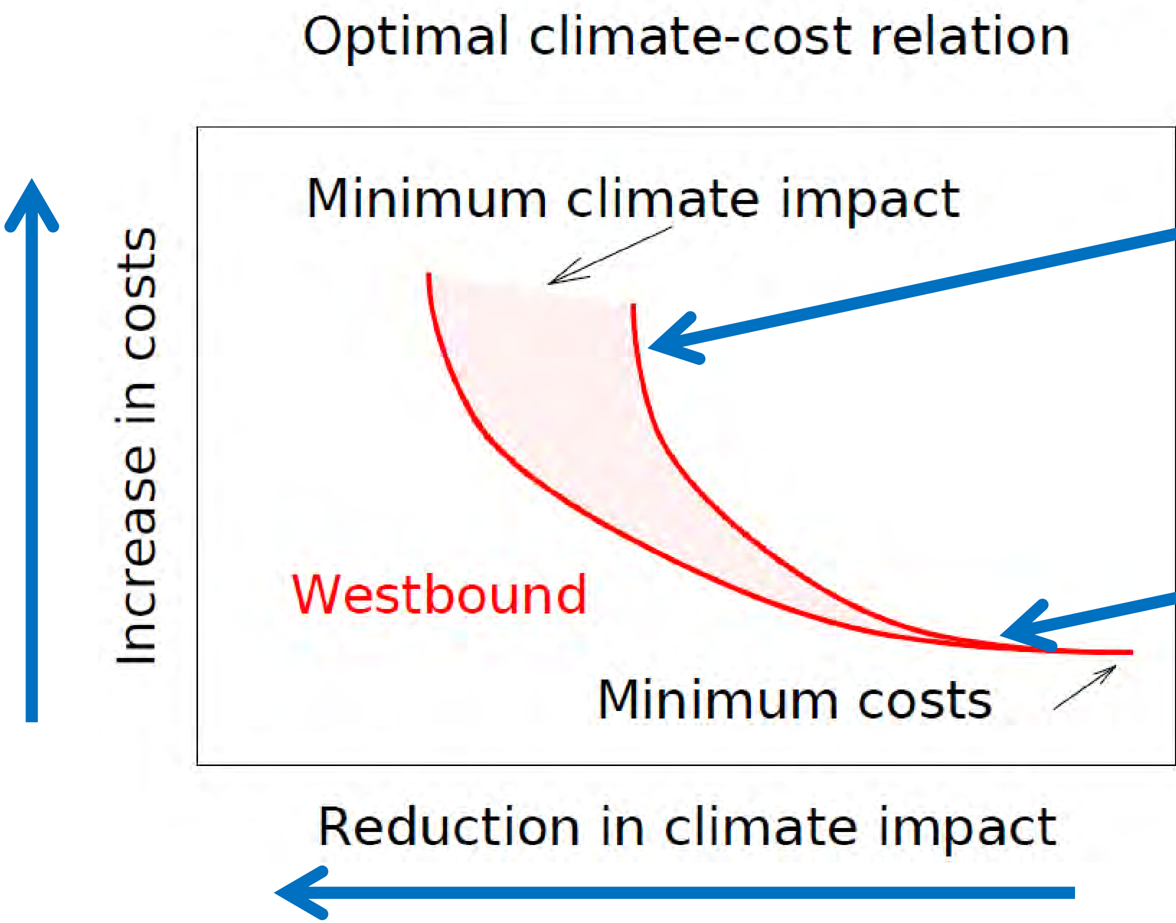
Chemistry:
Ozone / NOx pattern
- Follows meteorology
- Jet: Large values
- Low pressure: Smaller values

Grewe et al., Atmos. Environm., 2014b

Air Traffic

- One day
- ~800 flights between USA and
- Real air traffic taken into account
- Flight simulations performed by Eurocontrol
- Optimisation:
  - Costs: Fuel and Crew
  - Climate with different metrics

Relation between costs and climate: Pareto front

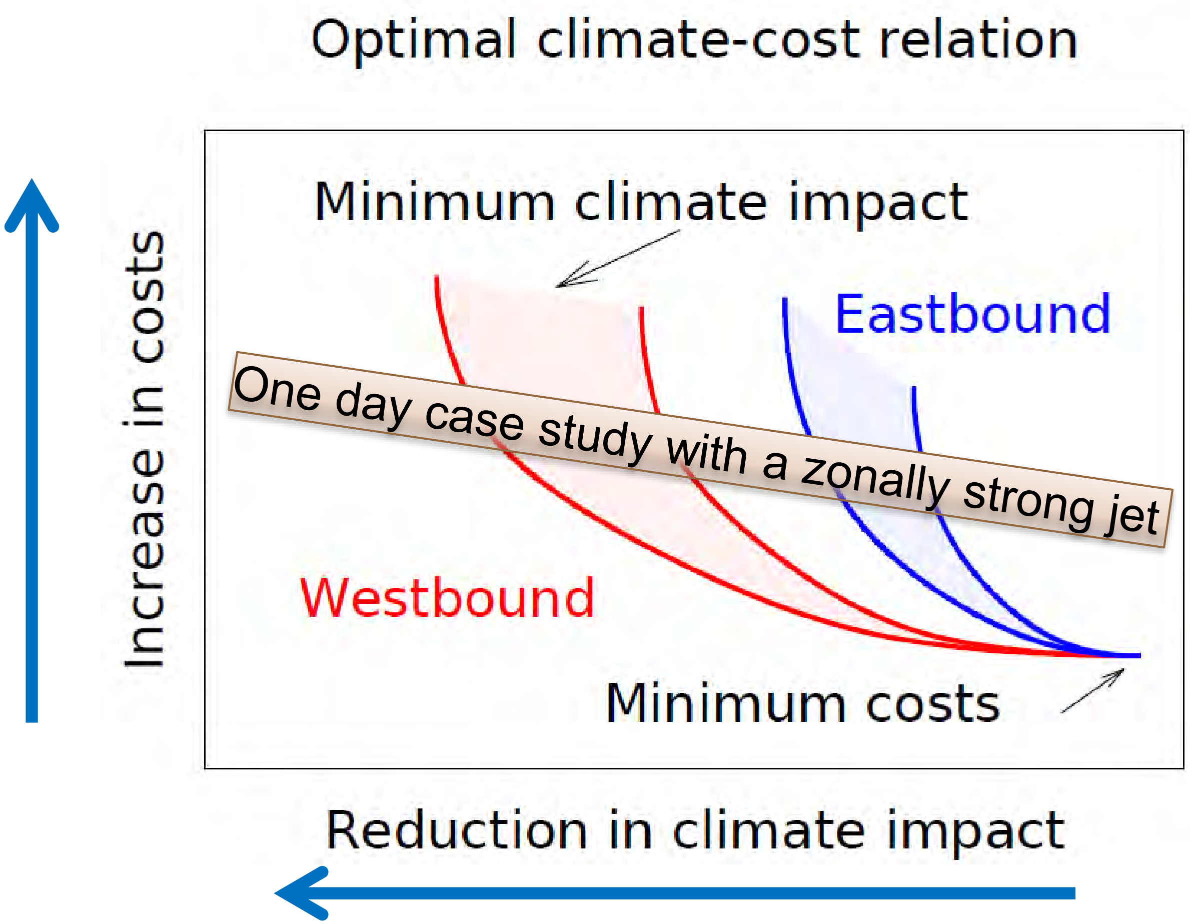


Climate optimal solution at higher costs

Large potential for climate impact reduction (25%) at low costs (0.5%)

Grewe et al., 2014b

Relation between costs and climate: Pareto front

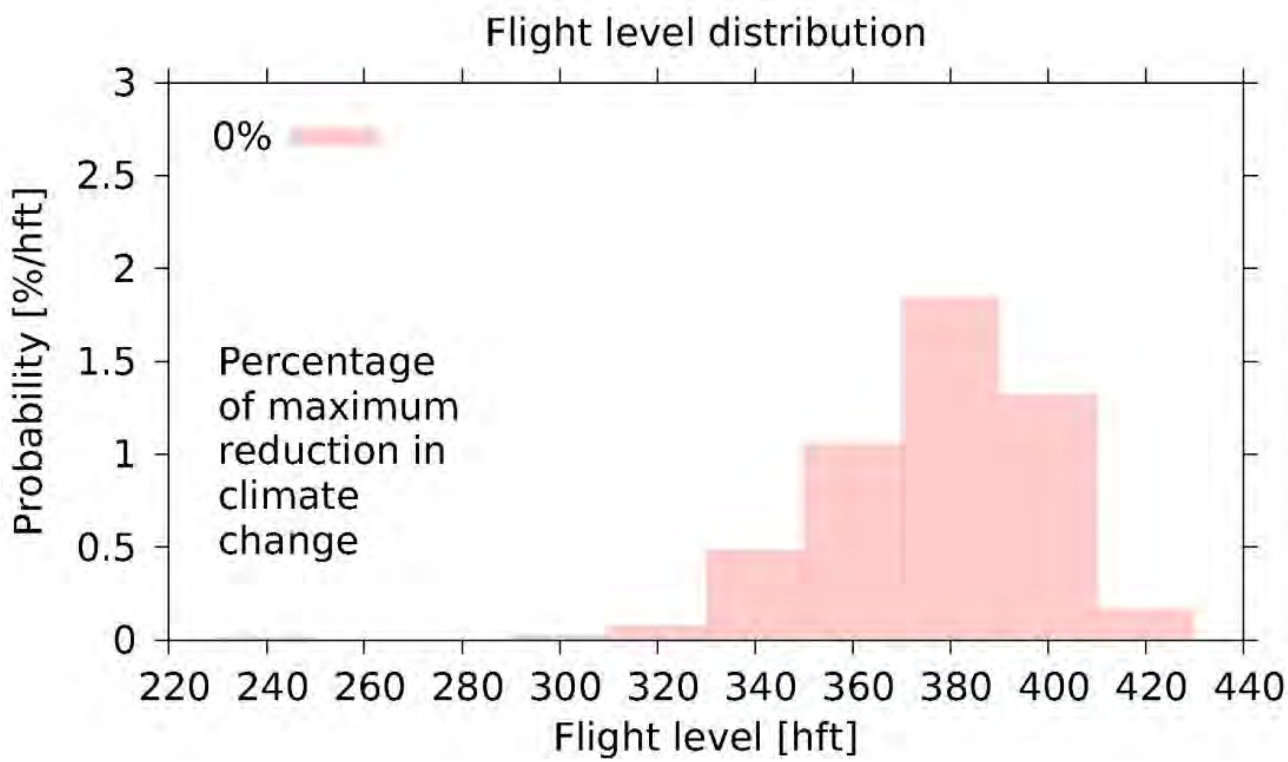


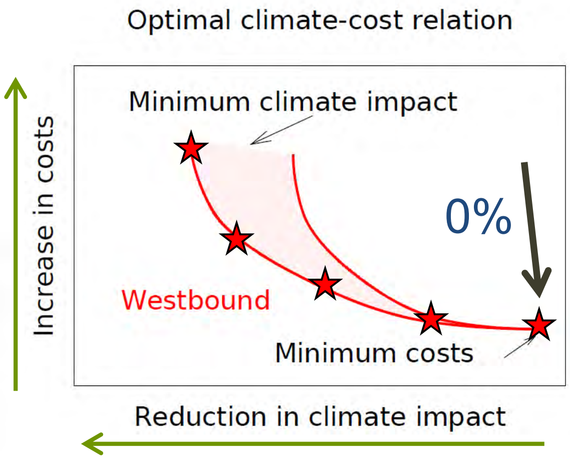
Eastbound traffic has less climate reduction potential, because it is more bound to the jet stream:

Leaving the jet stream leads to fuel and NO_x penalties

Grewe et al., 2014b

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





Grewe et al., 2014b

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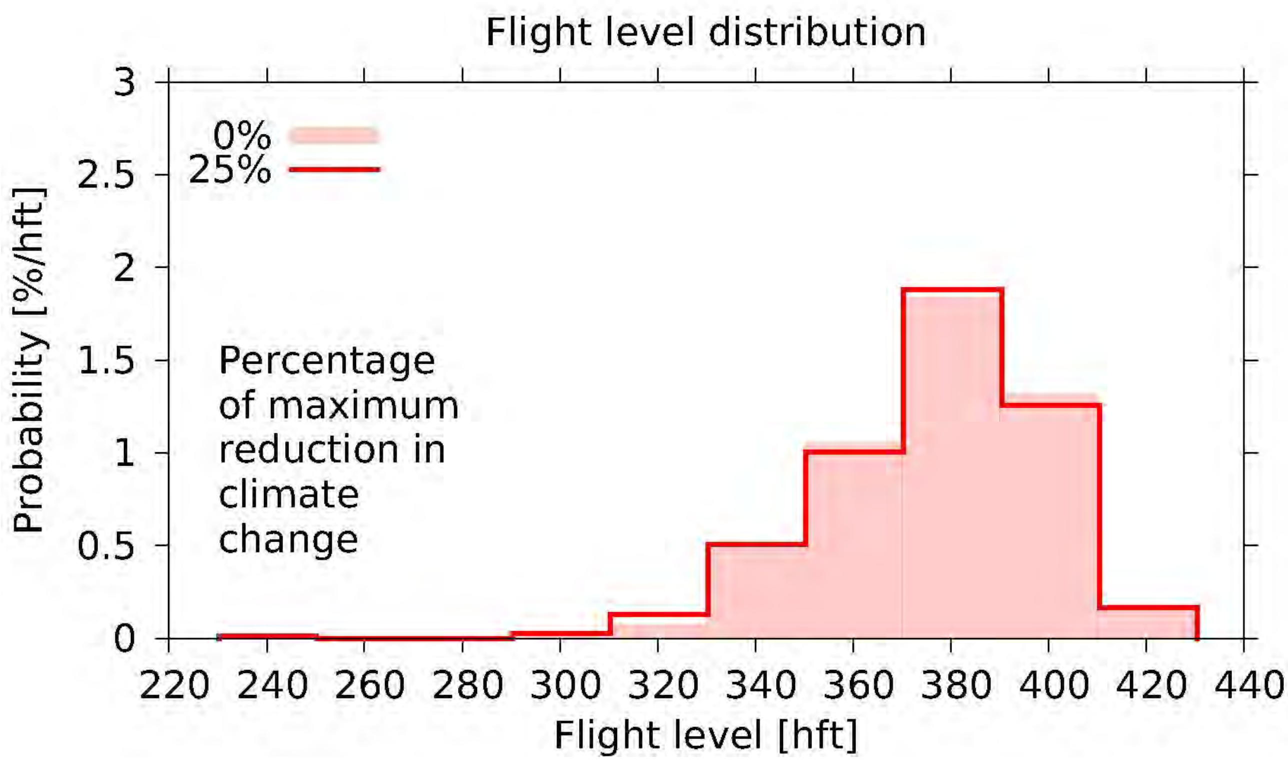

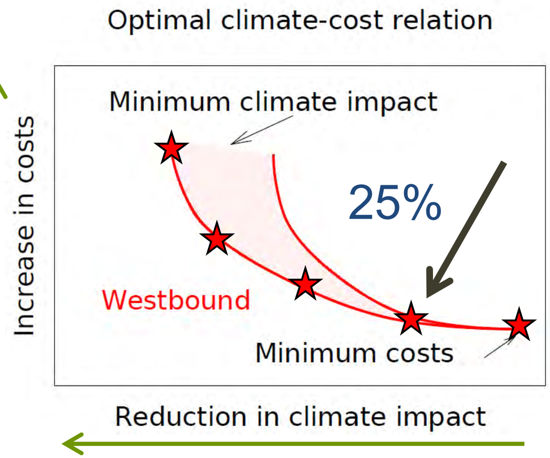

Only small changes in flight altitude

Grewe et al., 2014b

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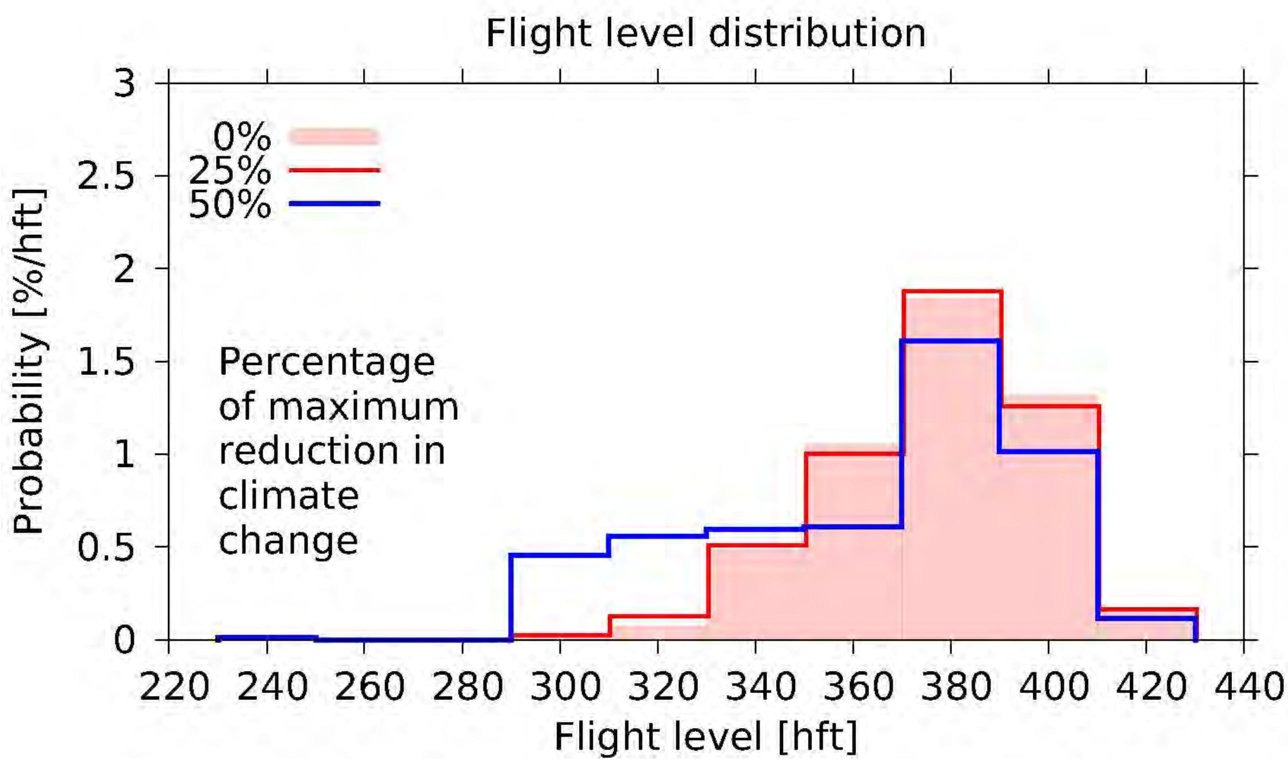

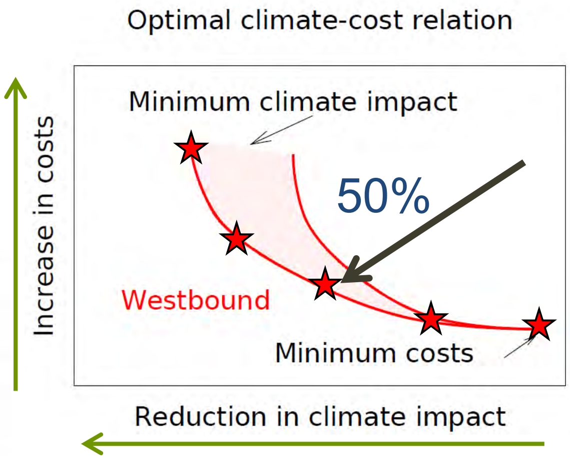

Some flights are shifted to lower flight altitudes

Grewe et al., 2014b

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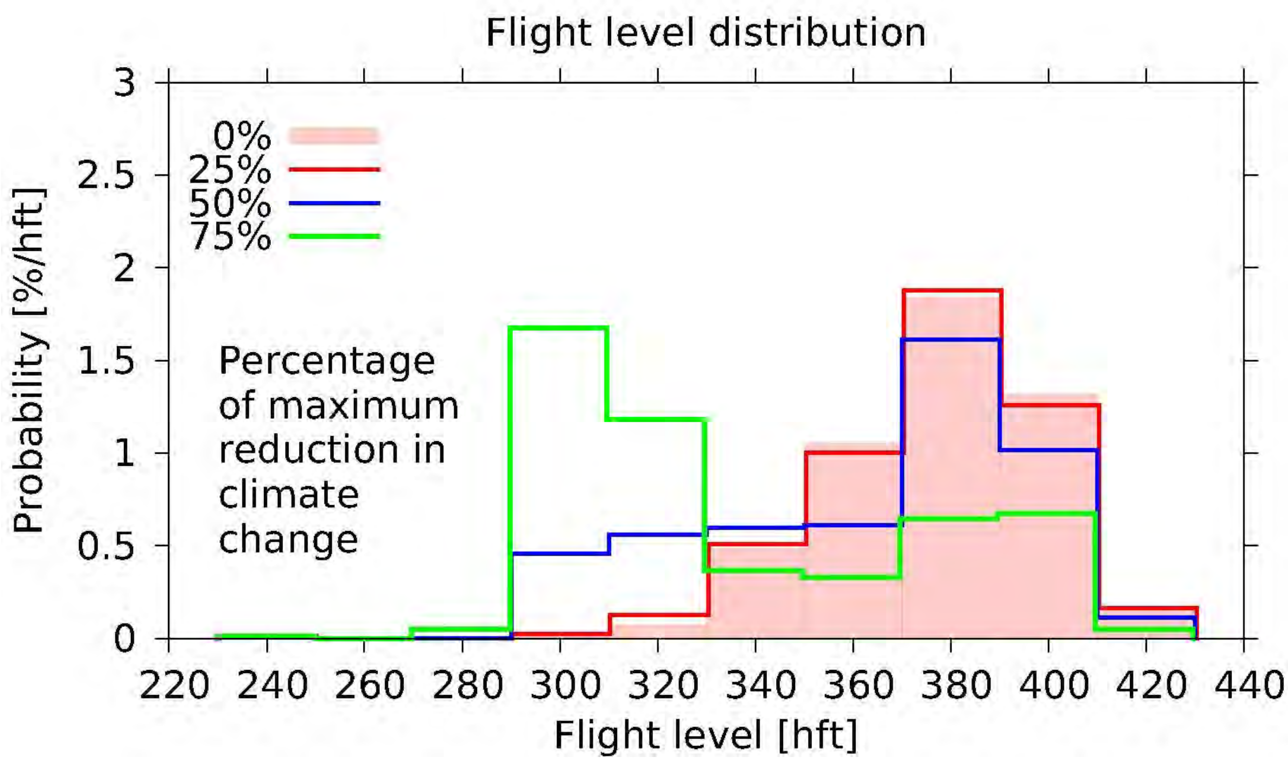

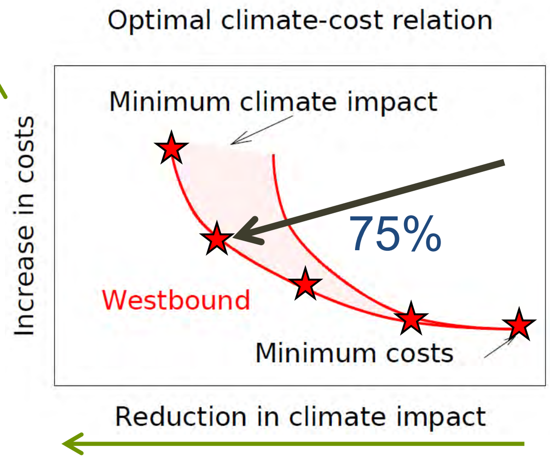

Many flights shifted from FL380 to FL300

Grewe et al., 2014b

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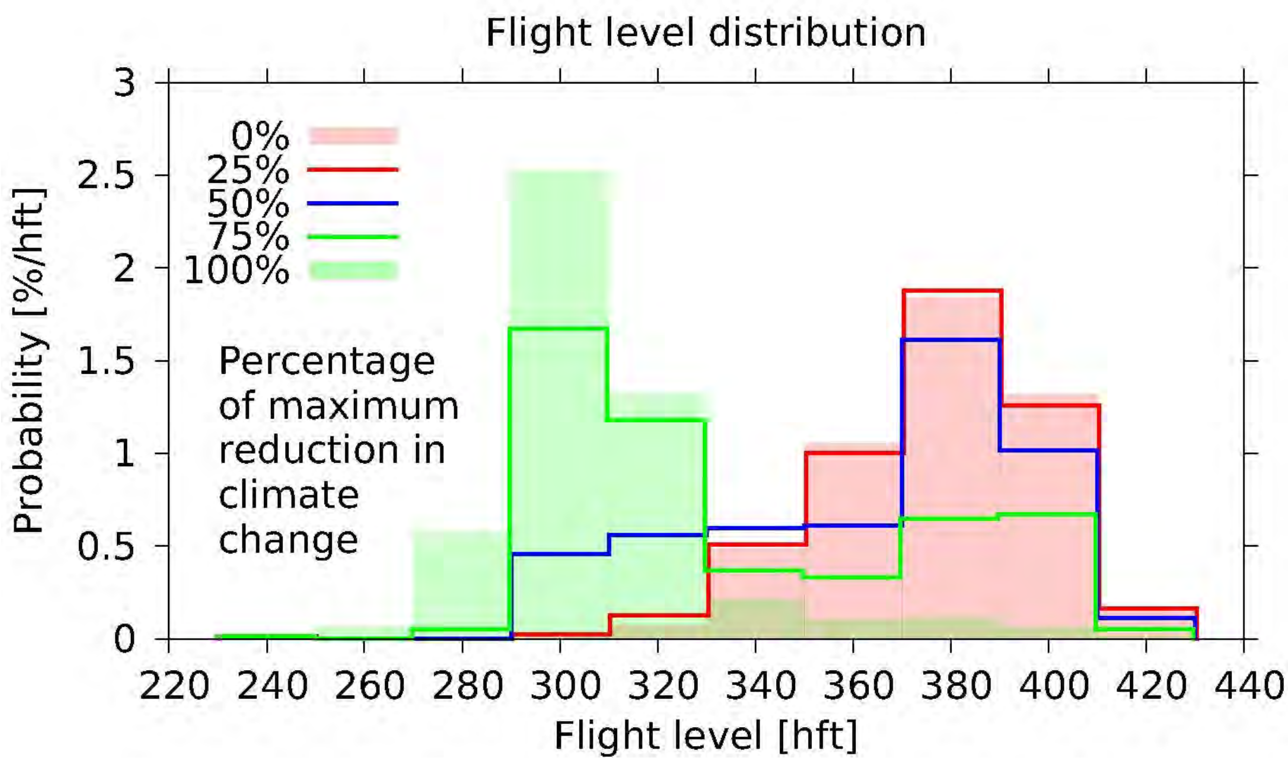
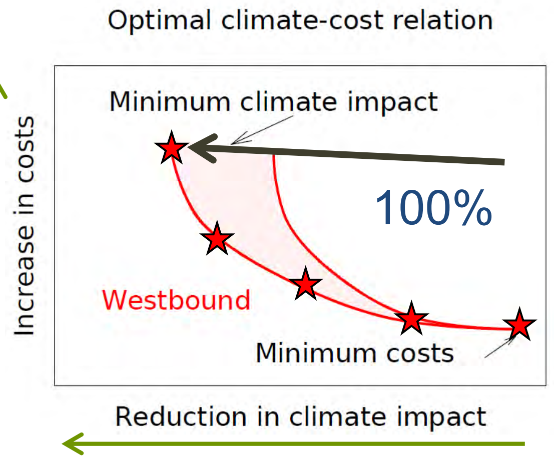
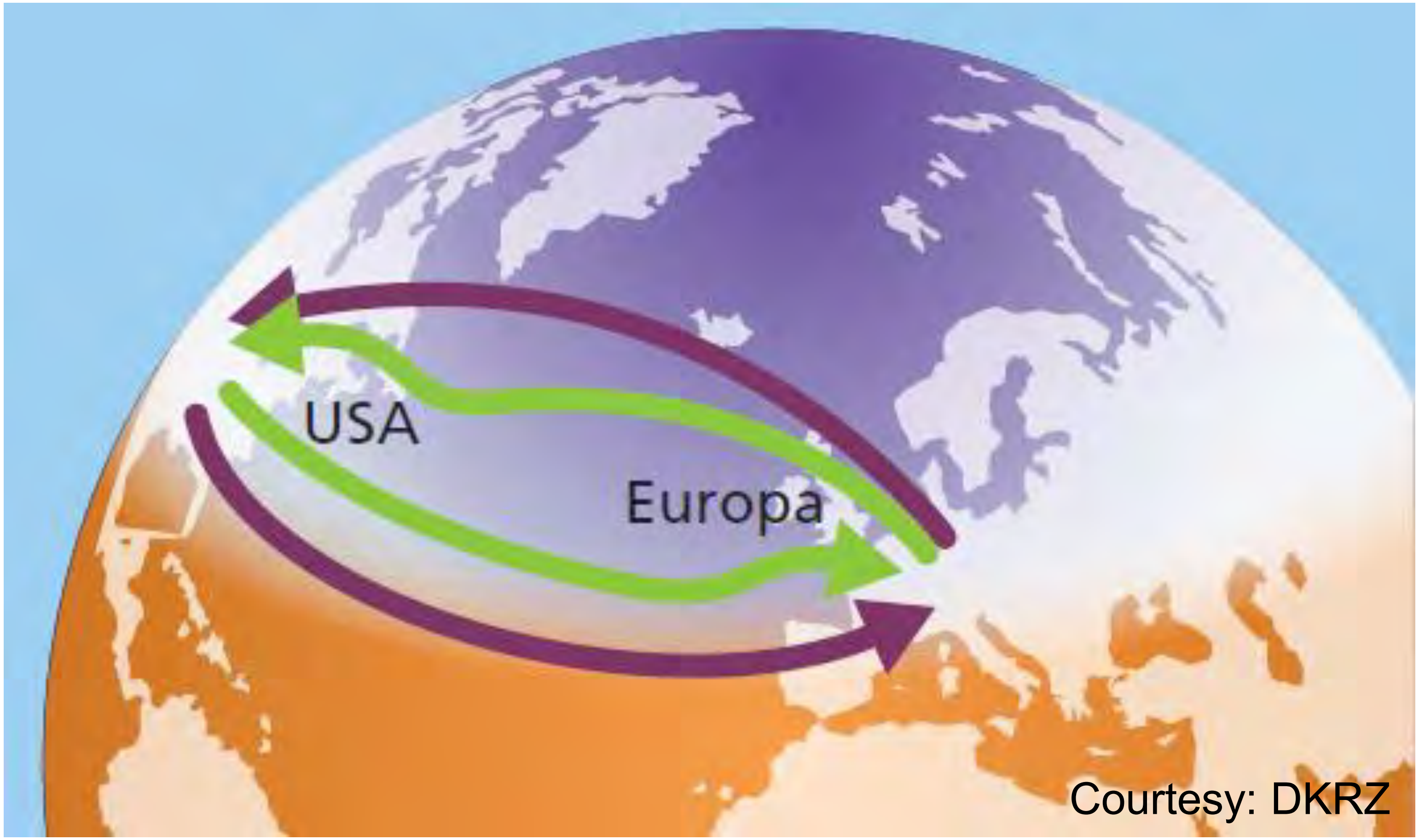




Main flight altitude: FL 300

Grewe et al., 2014b

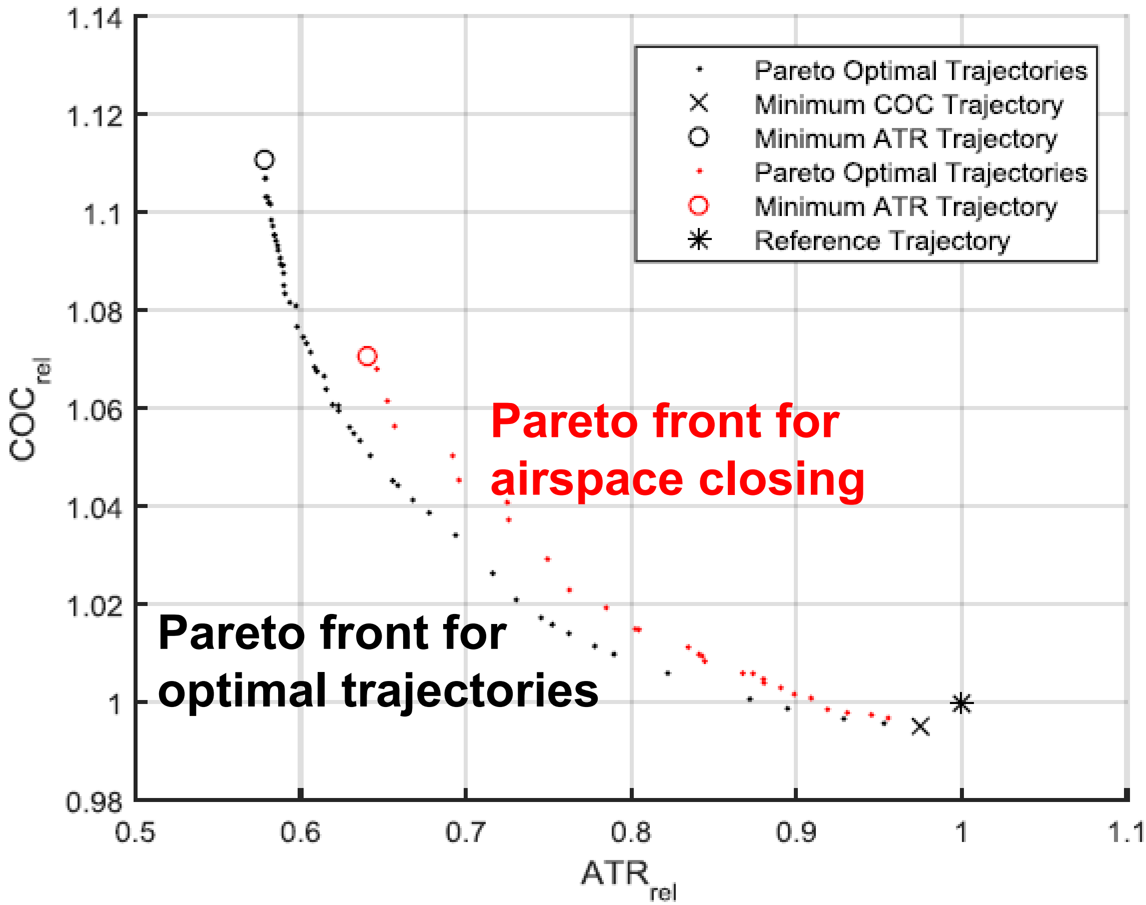
Horizontal re-routing is effective



Is closing of airspace an option to achieve routings with a reduction in the impact on climate?

- Sensitivity study
- One route

⇒ Potentially yes!

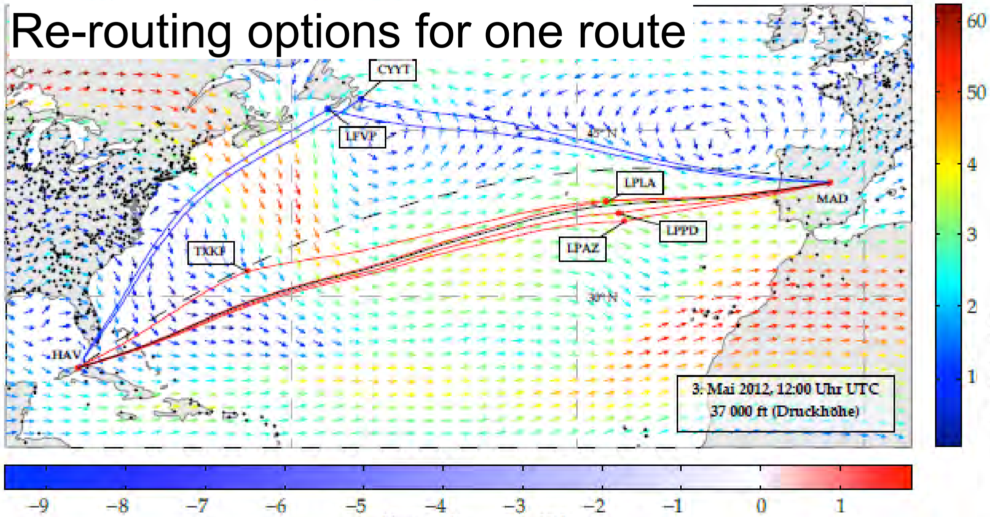


Niklaß et al., 2015

Intermediate Stop Operations (ISO)

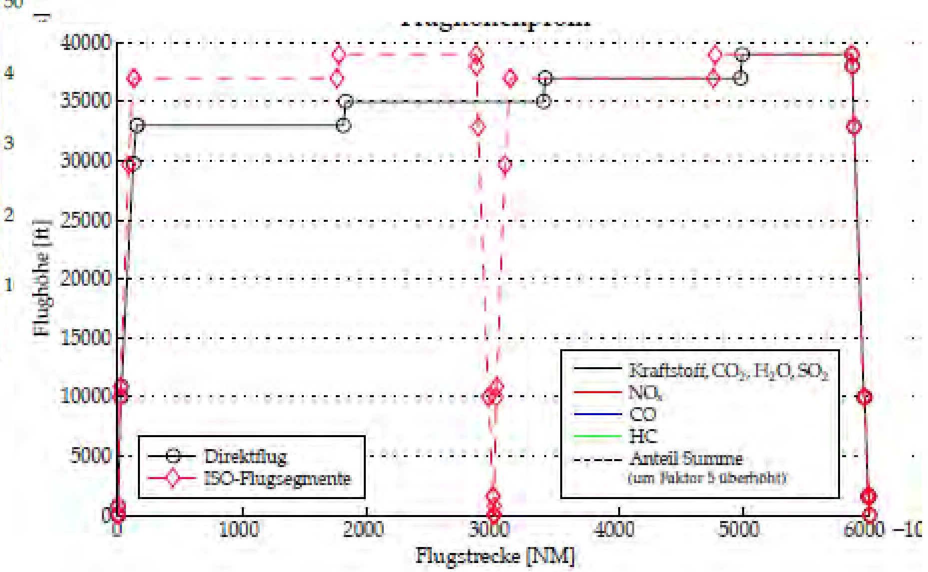
Refuelling implies: Lower weight / Re-routing / different altitude

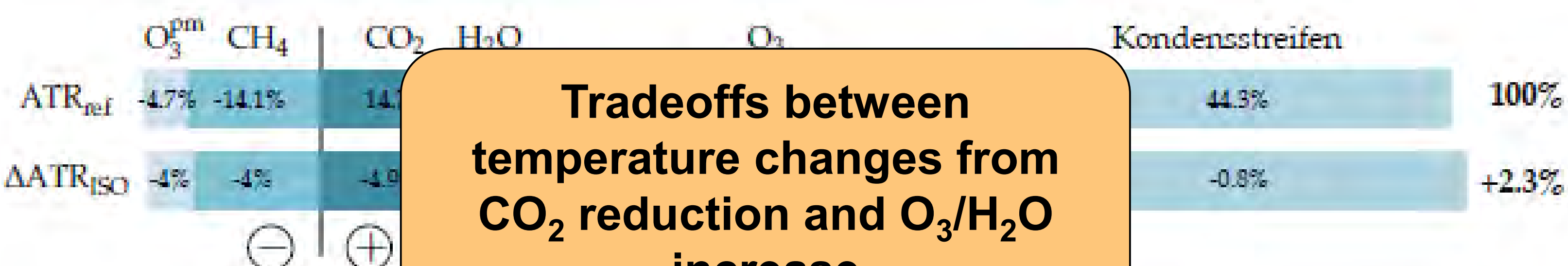
Re-routing options for one route



Fuel reduction [%]

Flight profiles





Tradeoffs between temperature changes from CO_2 reduction and O_3/H_2O increase

Linke, 2016; Linke et al., 2016

Outlook / Open Questions addressed in WeCare and ATM4E

What is the

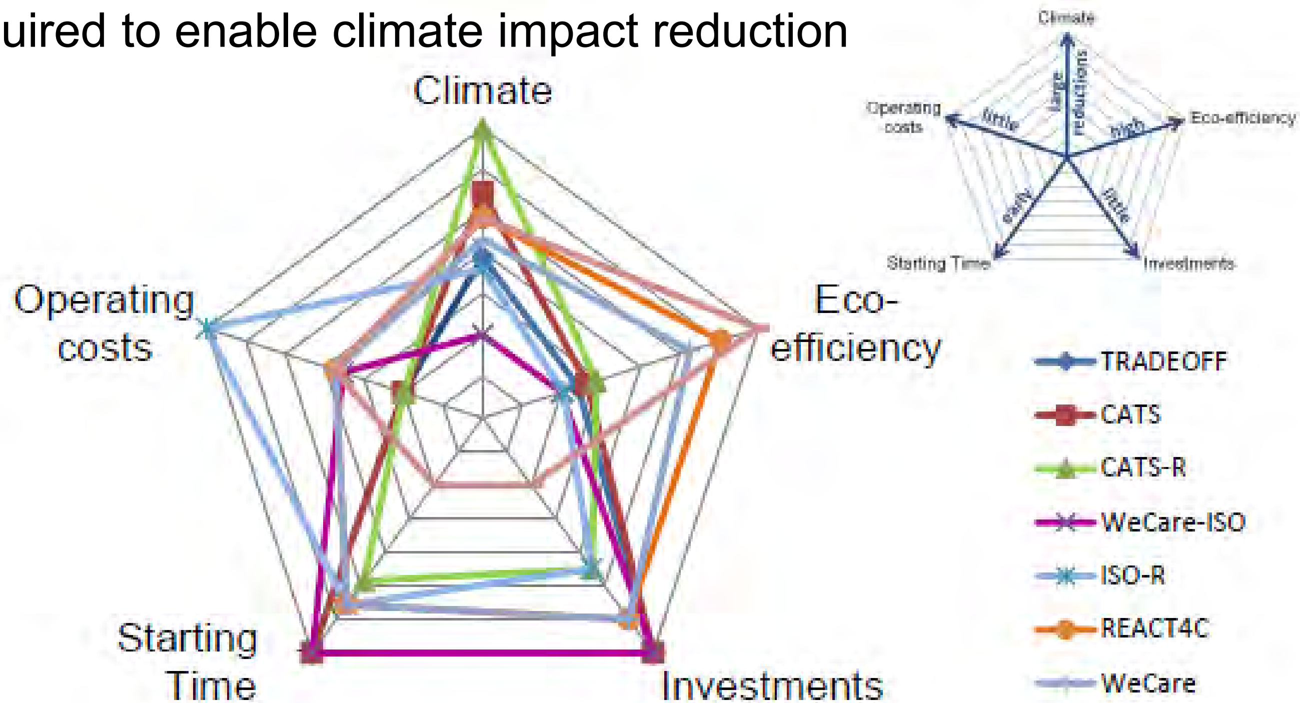
- cost-effects realtion for full 3D trajectory optimisations
- impact on ATC work load?
- impact on ATM, especially in Europe (higher air traffic density)?
- impact of uncertainties from atmospheric science on the results?
- impact of weather forecast on optimal routing?

Can we verify the results of climate optimal routing?

- Air traffic simulator within a Earth-System Model (Yamashita et al. 2016)

Summary

- Aviation has an impact on climate and routing is an important factor.
- Atmospheric uncertainties has to be key part of climate impact assessment
- We are moving from suggesting options to quantifying options
- Different options have different requirements, different type of costs, different time scales and effectiveness ⇒ Difficult to compare
- Political framework required to enable climate impact reduction



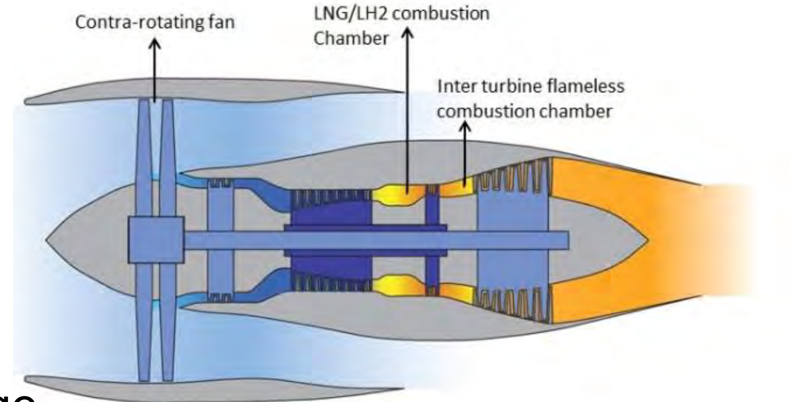
Grewe&Linke, submitted, 2016

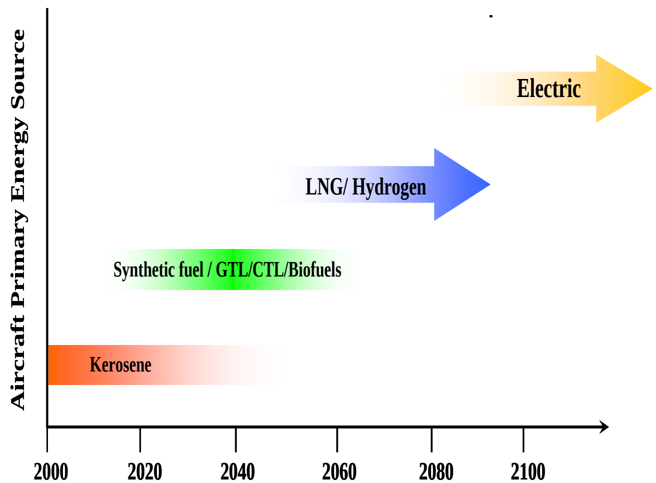
Thank you for your attention

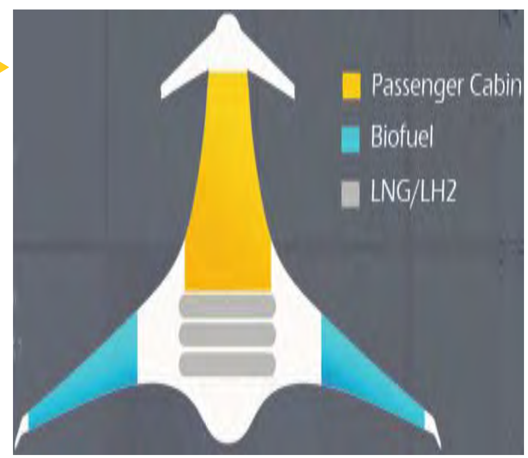
New Designs: AHEAD-Multi-fuel blended wing body

- Looking for alternatives to kerosene
  - LH2 and LNG
  - Bio fuels
- New combustion techniques
  - LH2/LNG combustor
  - Flameless kerosene combustion

    ⇒ Low CO_2 and NO_x emissions
- Blended wing body for better L/D and fuel storage







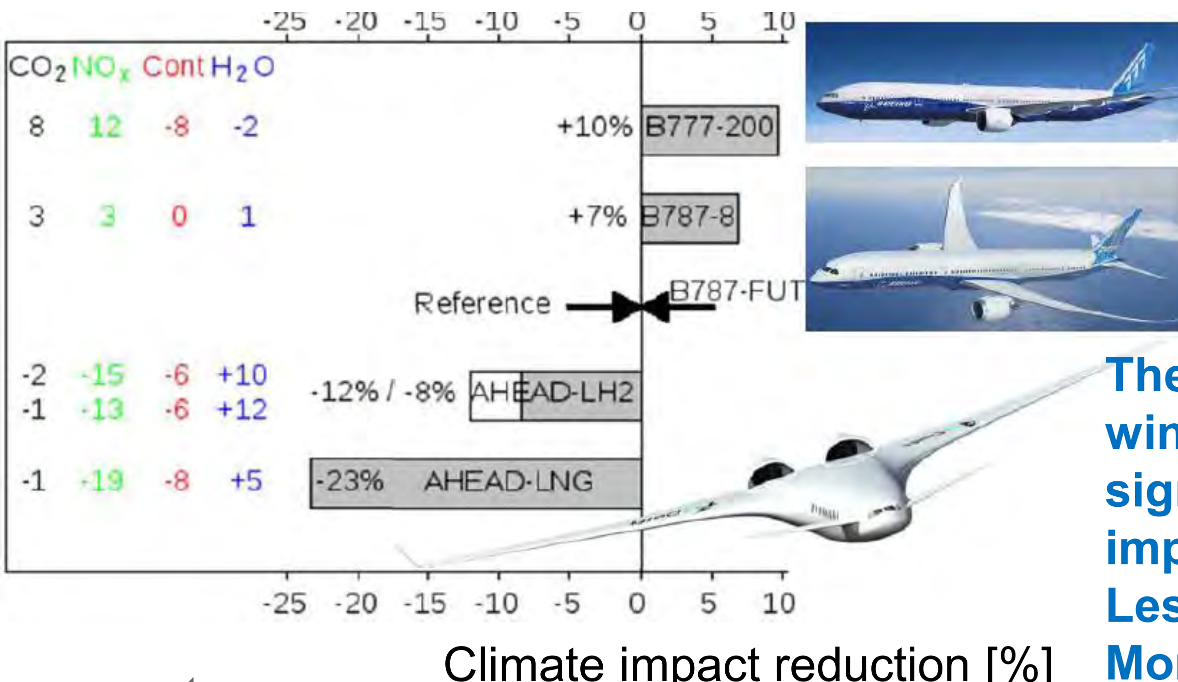
Poster
Grewe et al.

Climate impact from AHEAD MF-BWB

Poster
Grewe et al.

How large is the reduction in long-term climate change from the introduction of a MF-BWB in comparison to a future conventional aircraft?

- Consider a fleet of aircraft with Entry into service in 2050
  Full fleet in 2075
- Reference aircraft B787 including future enhancements (efficiency & biofuels)
- Average Temperature Response as Climate Indicator
- Mean change 2050 - 2150



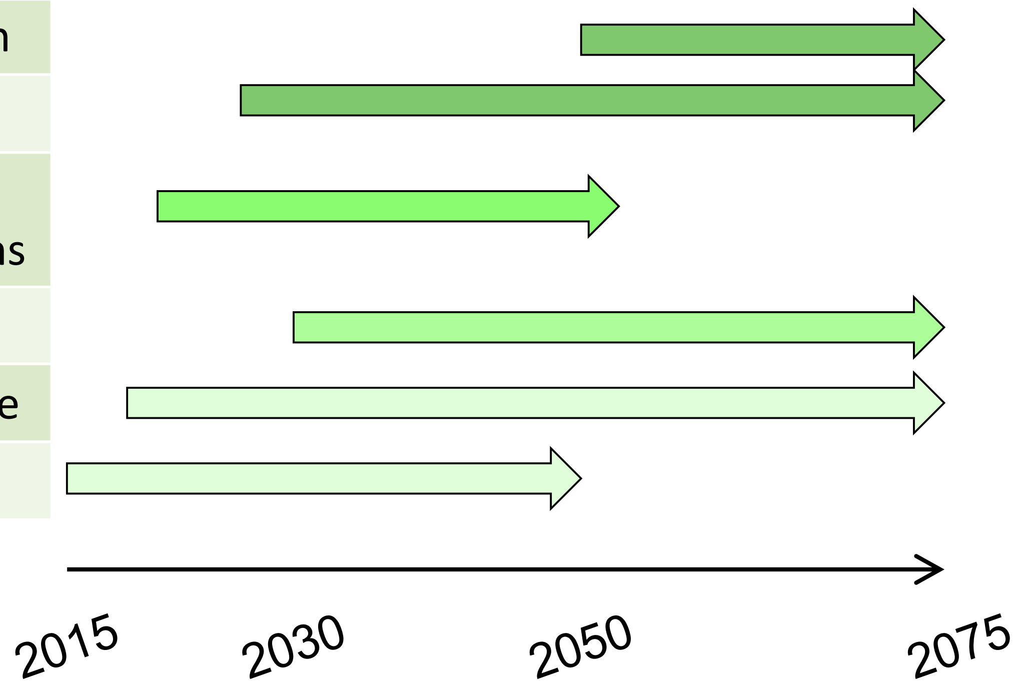
The use of a multi fuel blended wing body has the potential to significantly reduce the climate impact from aviation.
Less CO_2 NO_x Contrails
More H_2O

DLR

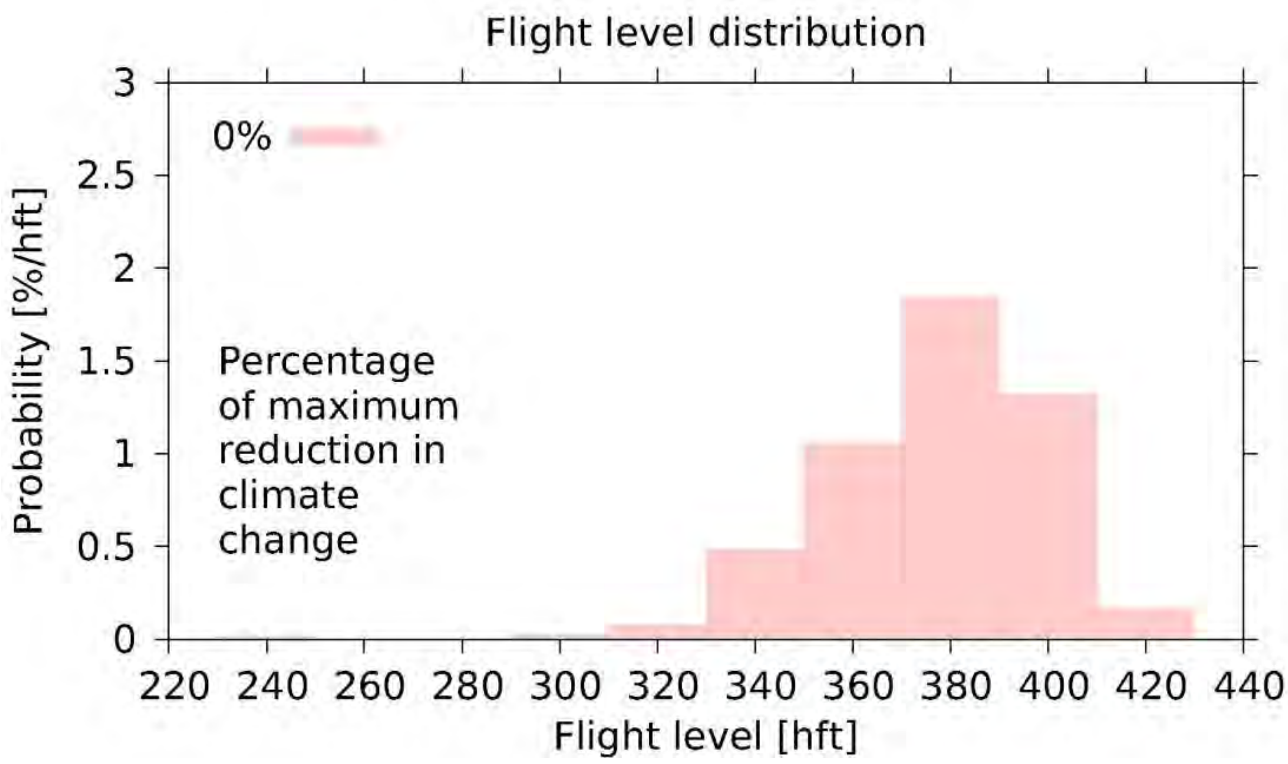
Summary

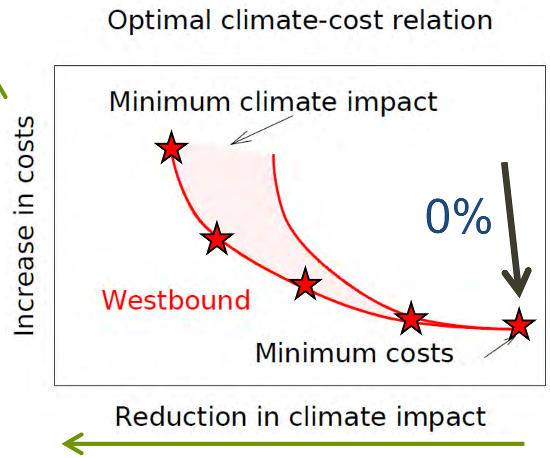
- Atmospheric uncertainties has to be key part of climate impact assessment
- We are moving from suggesting options to quantifying options
- Different options have different requirements, different type of costs, different time scales and effectiveness ⇒ Difficult to compare
- Political framework required to enable climate impact reduction

Project	Requirements
AHEAD	New Engine + Design
REACT4C	CCF + ATM
Closing Airspace	Determination of Climate Sens. Regions
CATS-New	Re-Design
ISO	Airport Infrastructure
CATS-Old	No requirements



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





Grewe et al., 2014b

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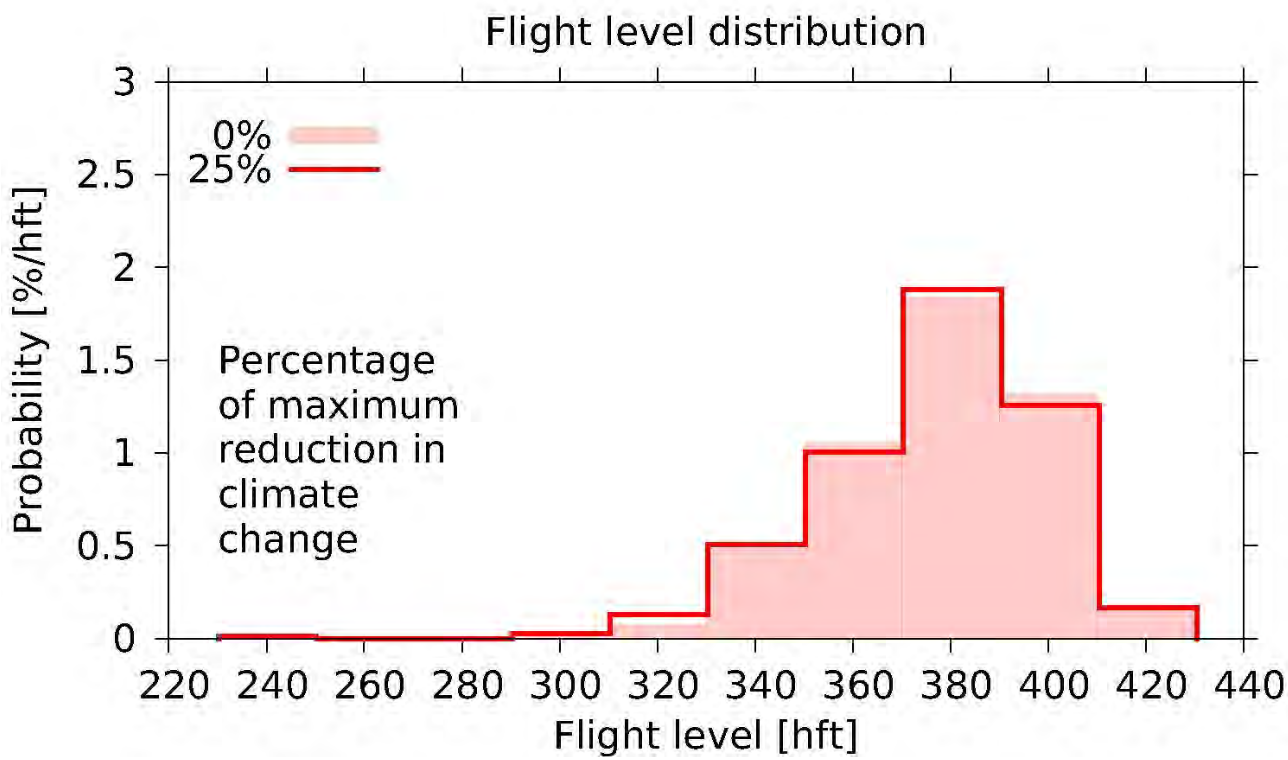
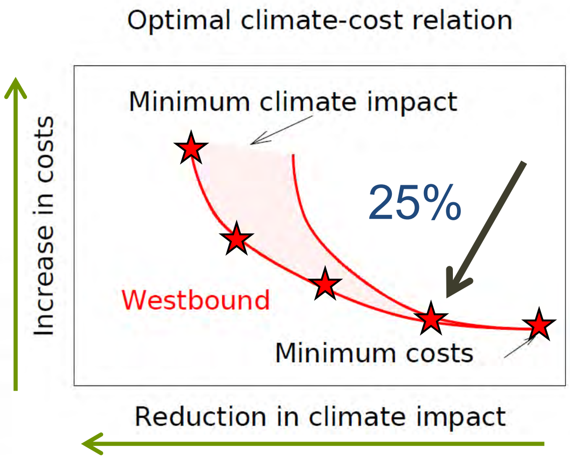
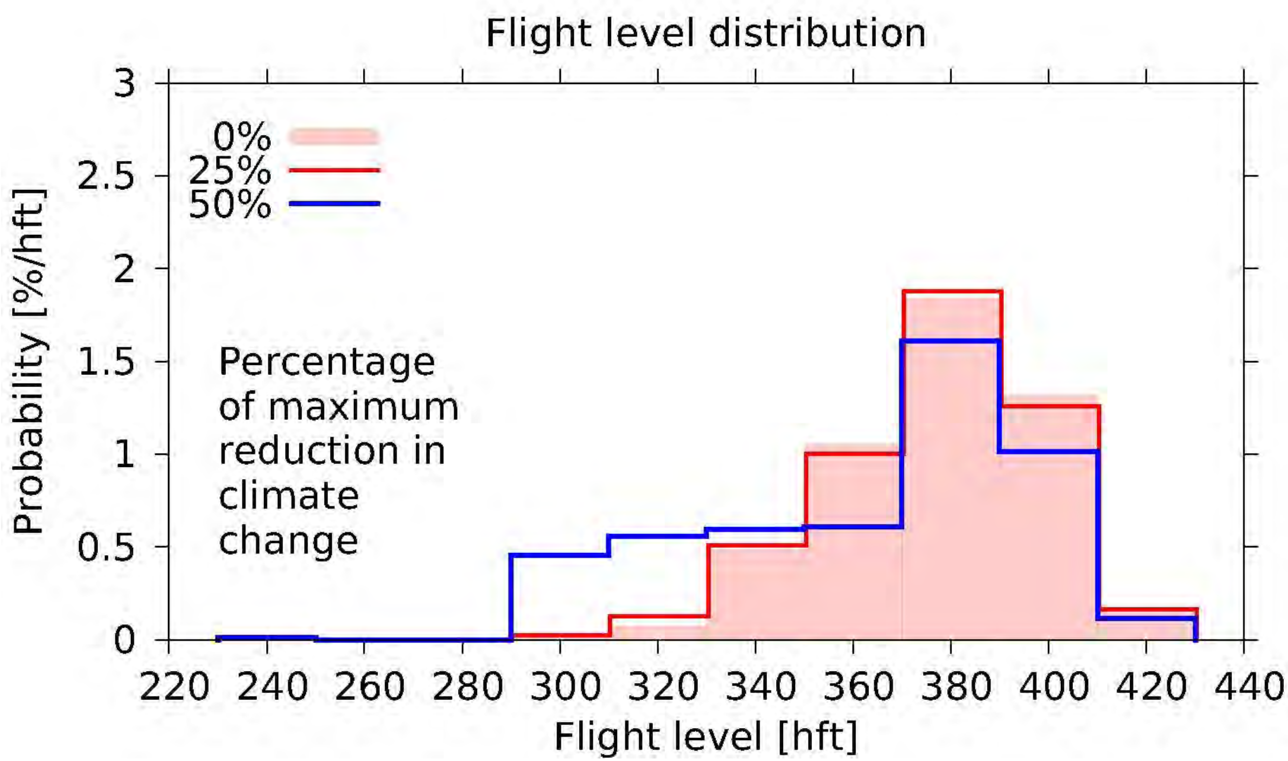


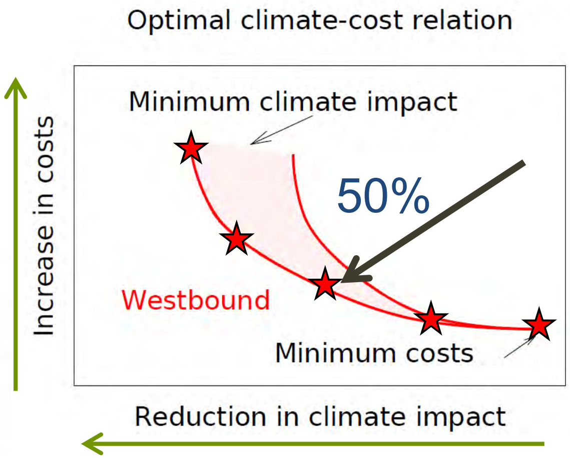


Only small changes in flight altitude

Grewe et al., 2014b

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

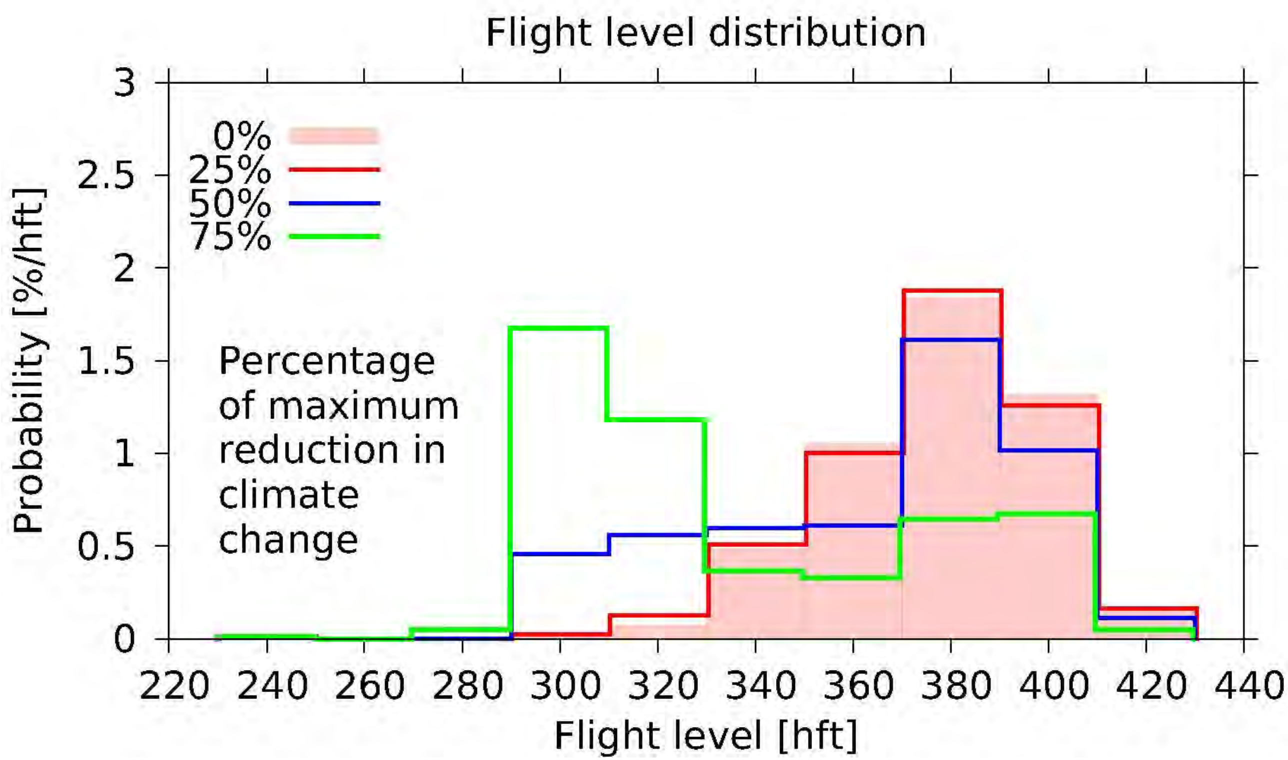


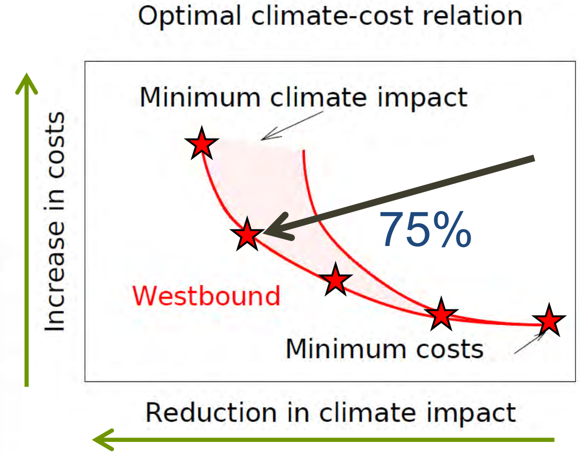


Some flights are shifted to lower flight altitudes

Grewe et al., 2014b

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

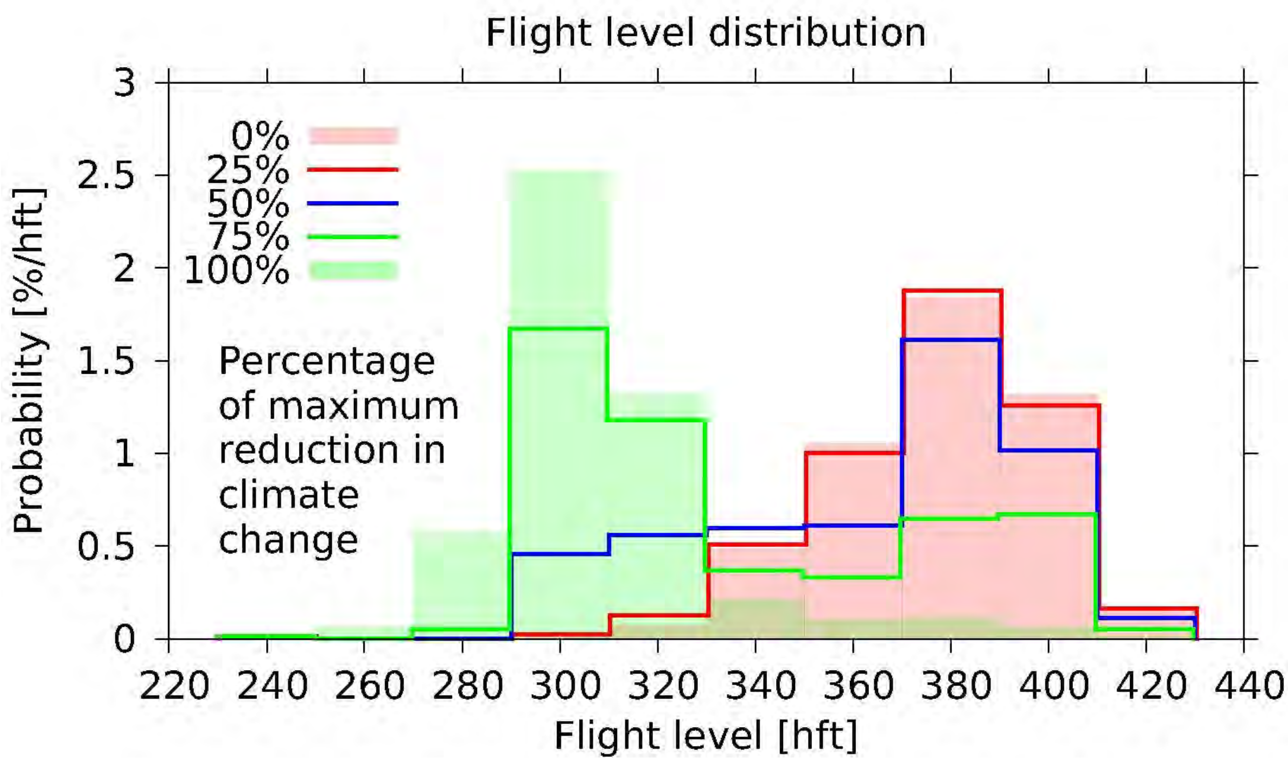


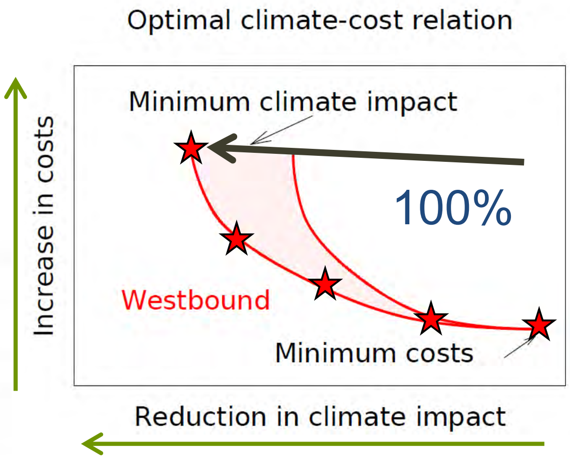


Many flights shifted from FL380 to FL300

Grewe et al., 2014b

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

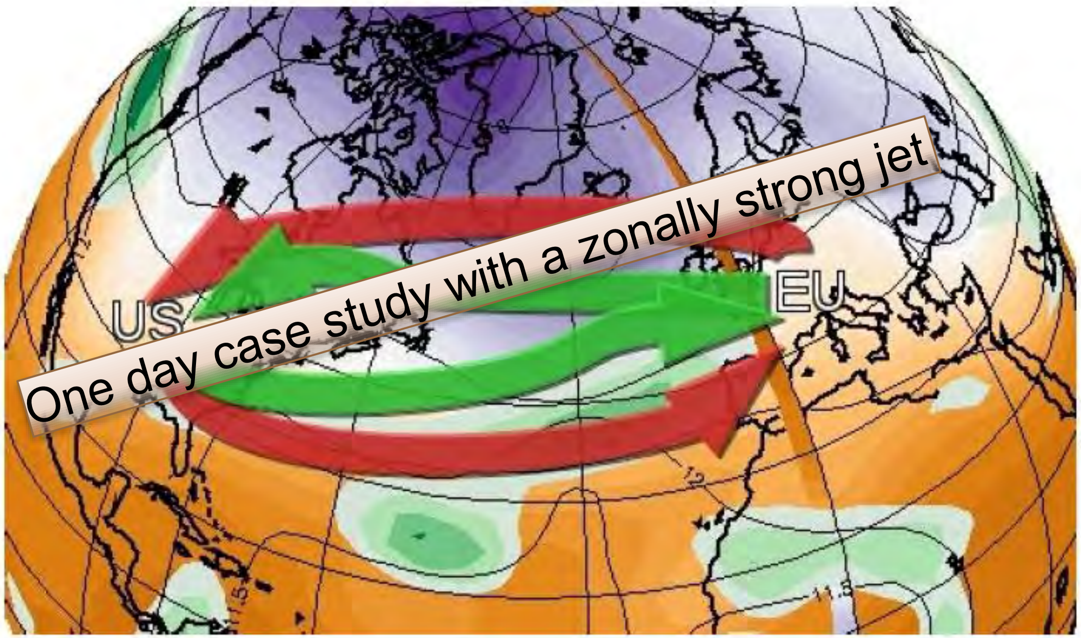


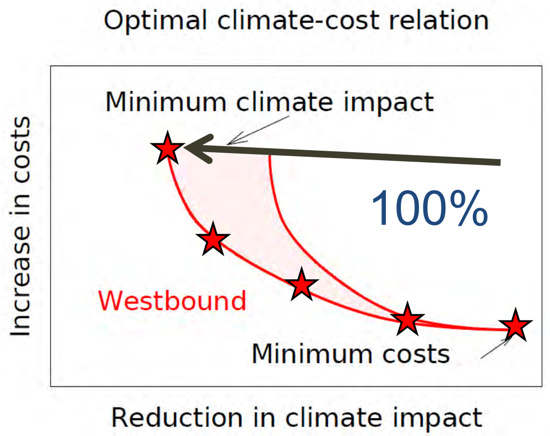


Main flight altitude: FL 300

Grewe et al., 2014b

How is the air traffic modified? Lateral changes

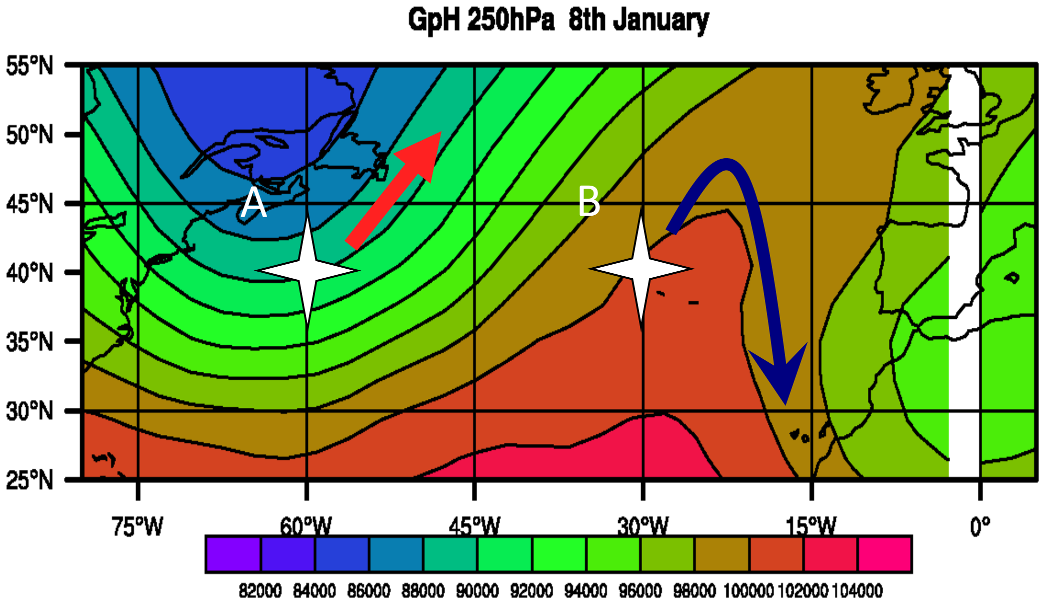




More confined air traffic.

Grewe et al., 2014b

Different weather situations: Evolution of aircraft NO_x

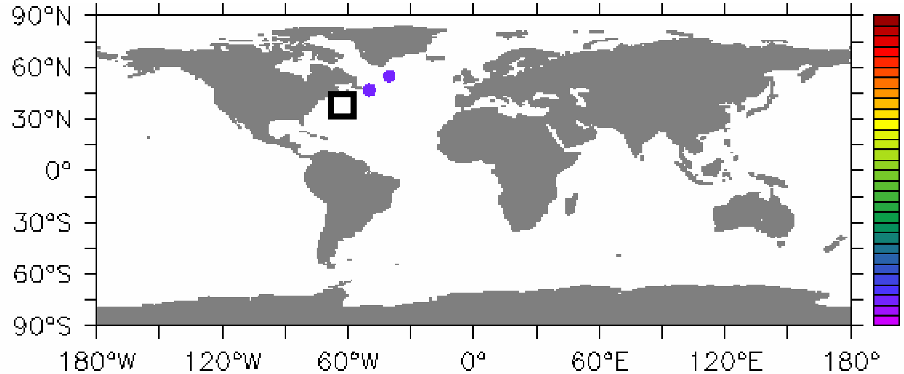


Weather type #3 "Weak and tilted jet"

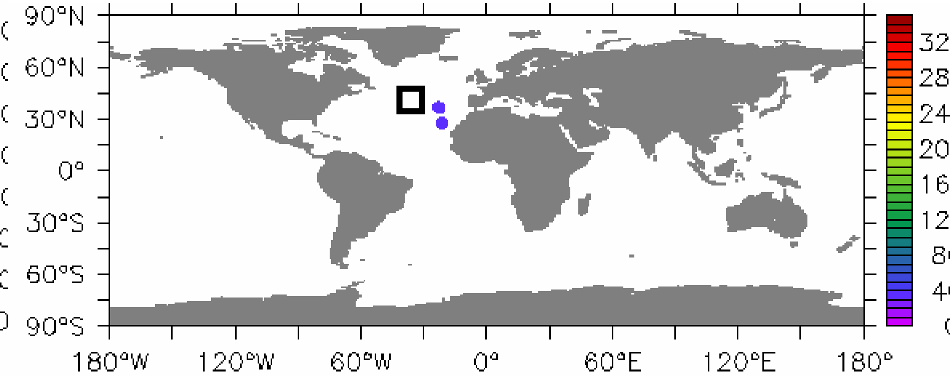
What happens if an aircraft emits NO_x at location A compared to location B?

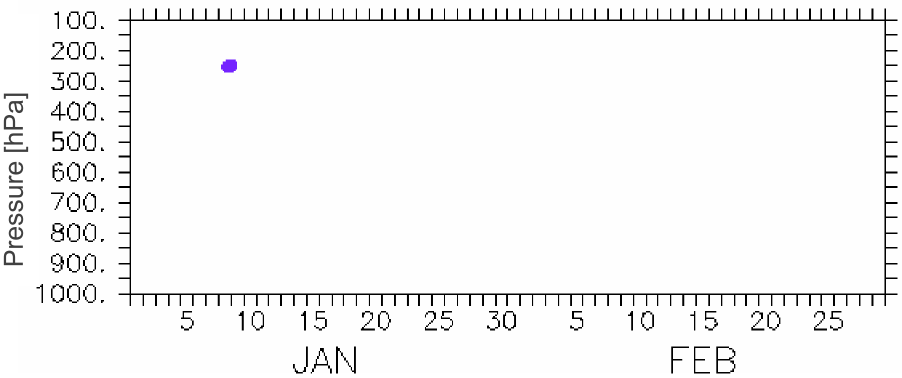
Evolution of O_3 [ppt] following a NO_x pulse

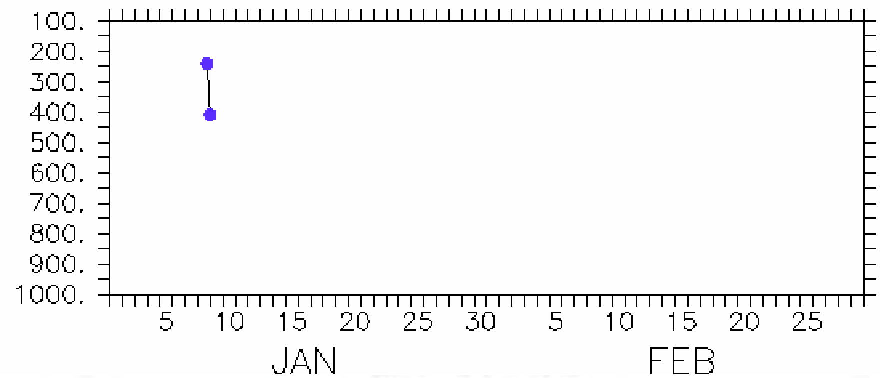
A: 250hPa, 40°N, 60°W, 12 UTC

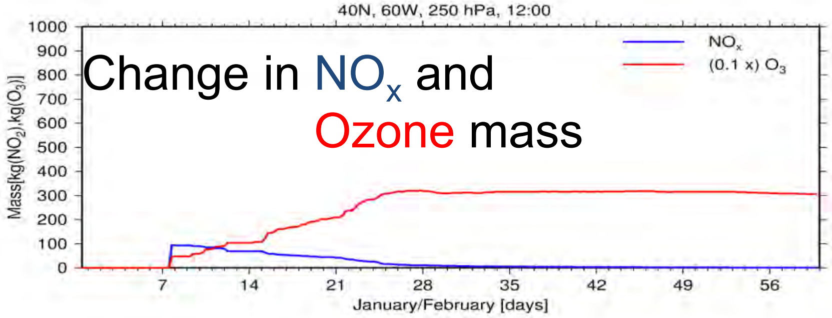


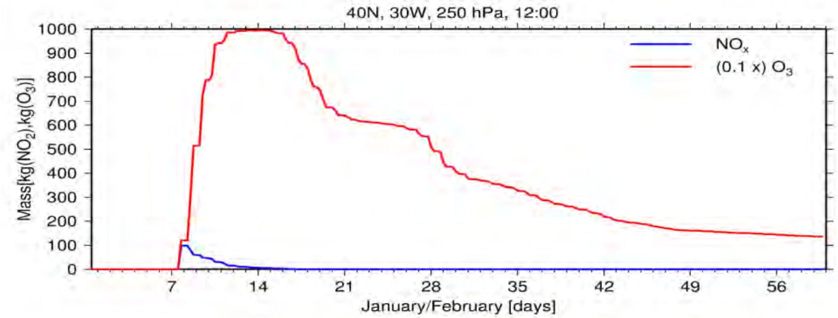
B: 250hPa, 40°N, 30°W, 12 UTC



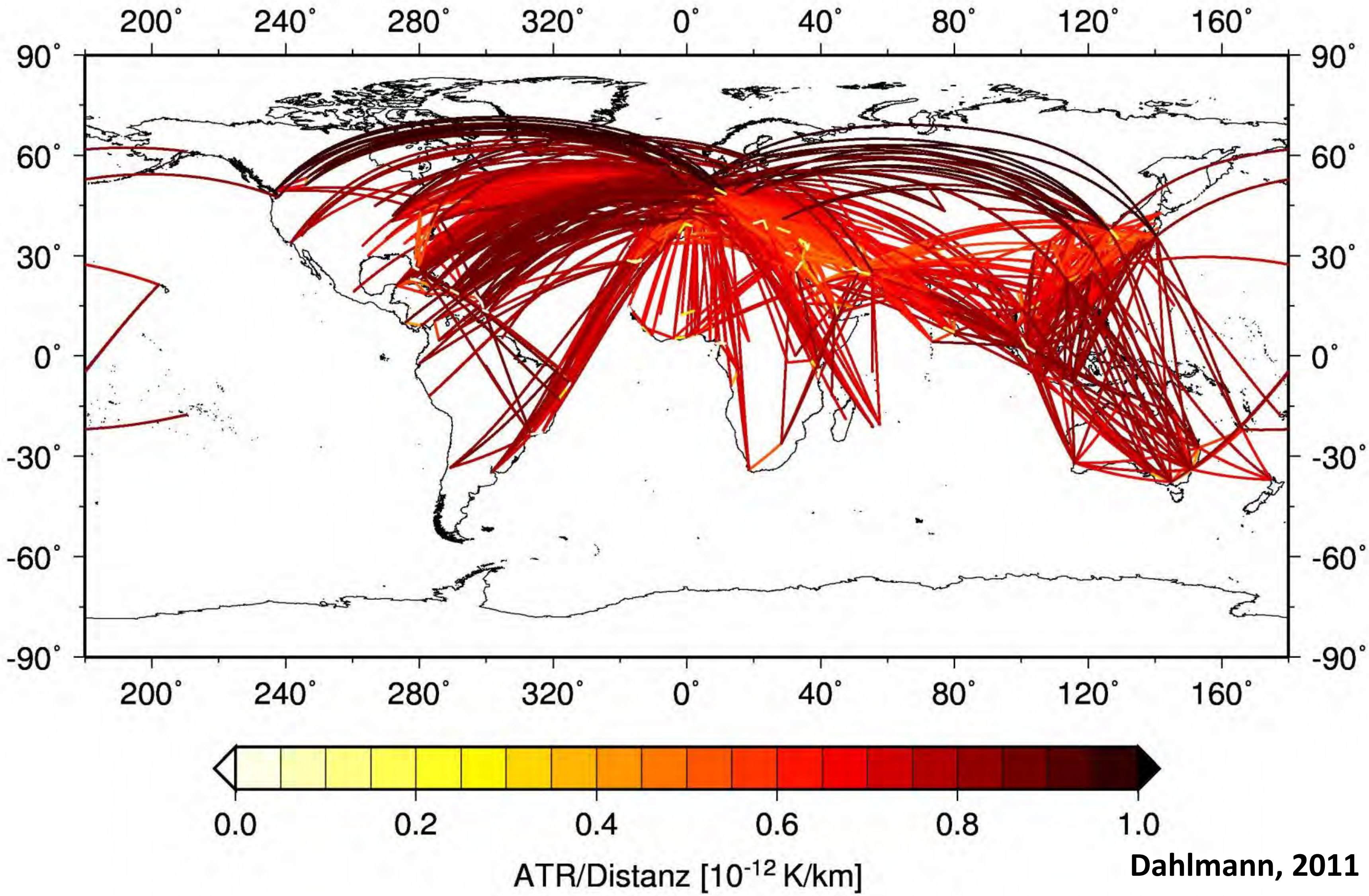








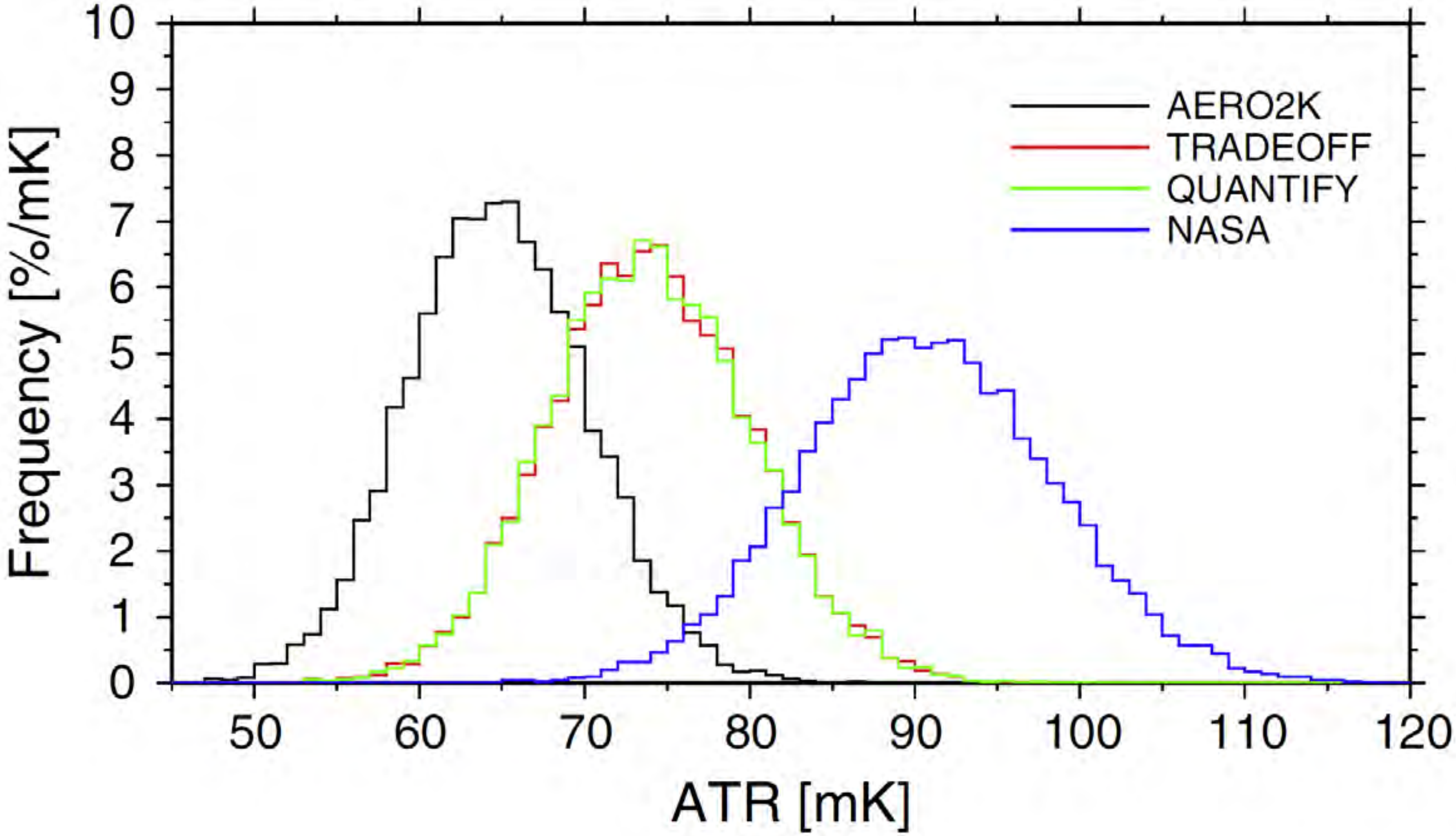
Route network and specific "Global warming" [K/km] induced by individual routes for an A330



Dahlmann, 2011

What can we do about the uncertainty?
An example from aviation: 4 slightly different emissions scenarios

Perform Monte-Carlo simulations: pdf of ATR



Dahlmann et al., 2016

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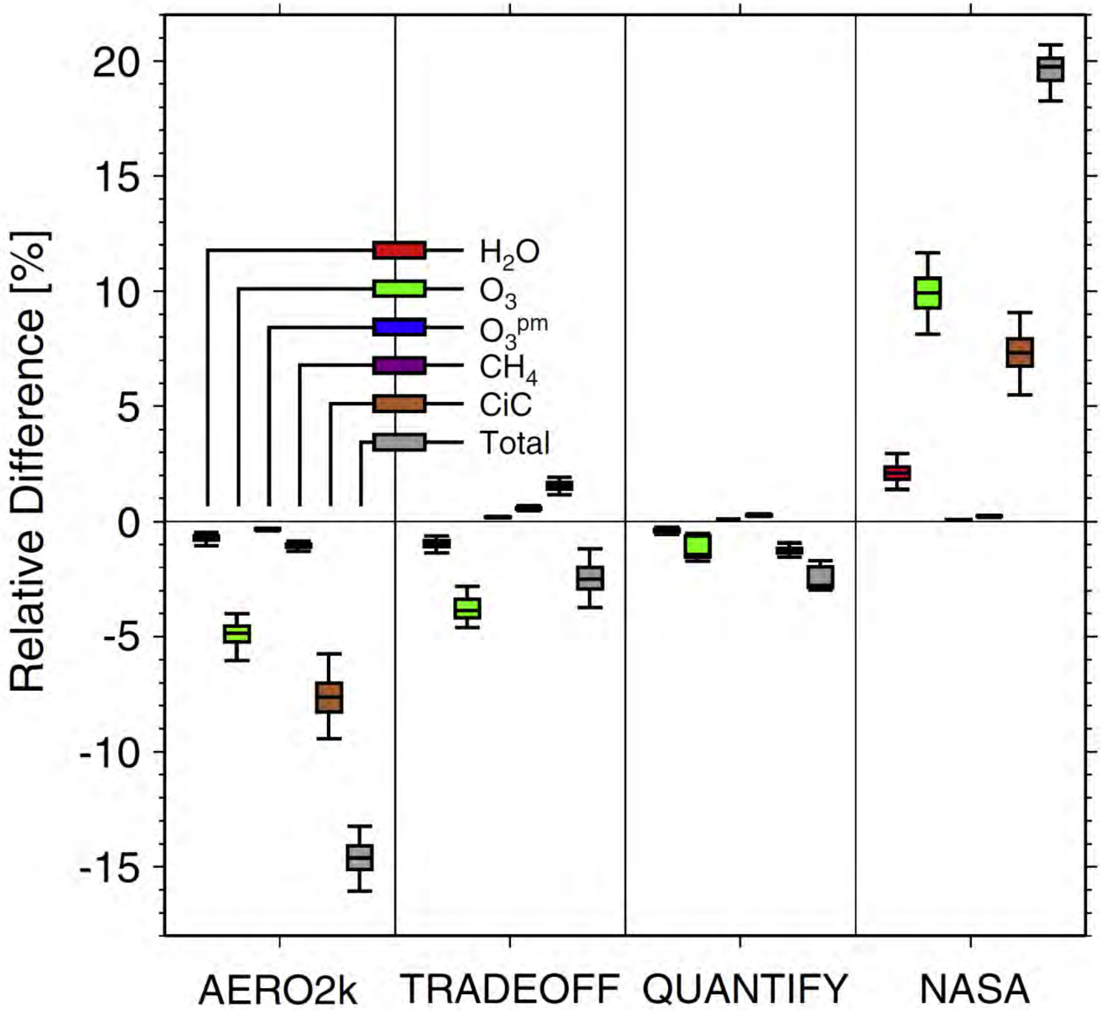

Dahlmann et al., 2016