Addressing non-CO_2 effects of aviation

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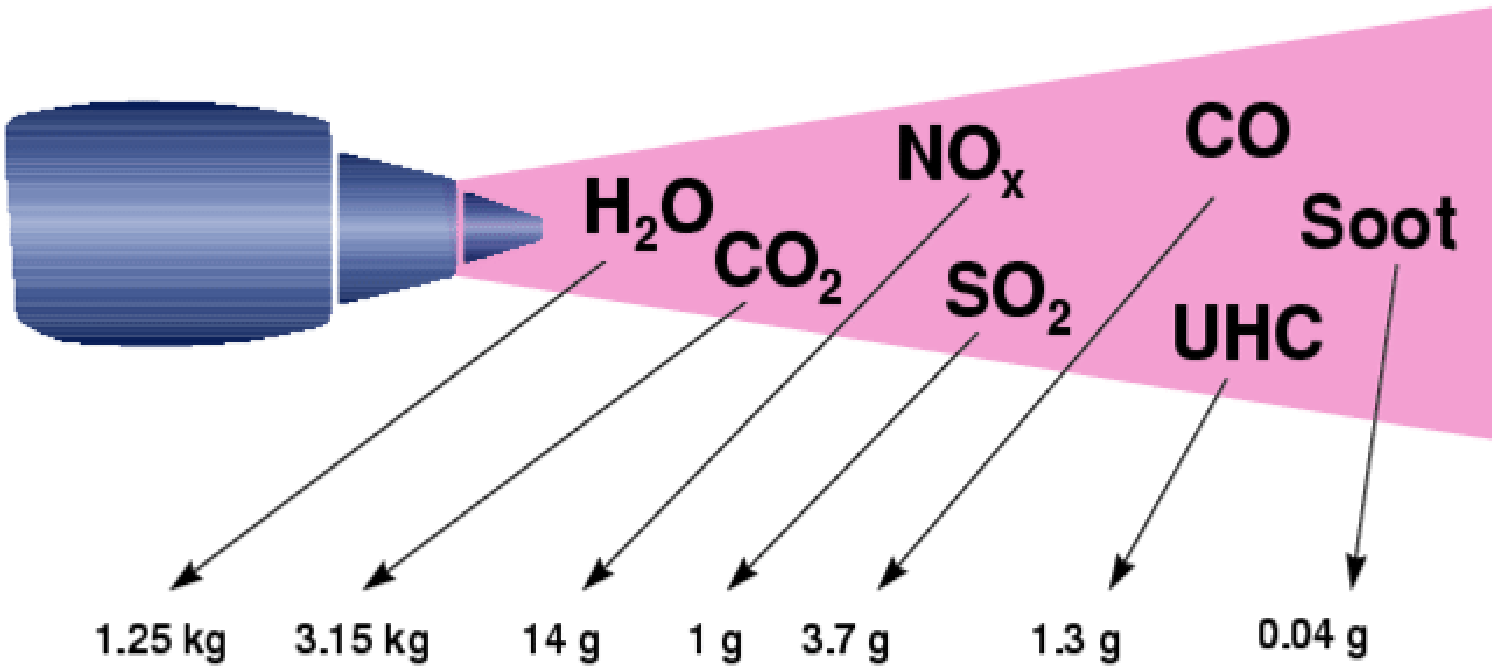
Air traffic emissions at cruise

Combustion products
- depending on operating conditions
- at cruise altitude

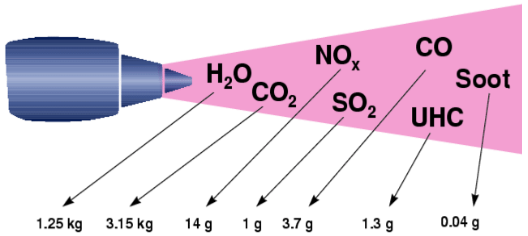


(per kg kerosene)

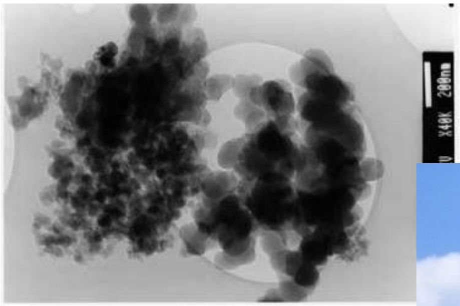
IPCC (1999)

Climate impacts via non-CO_2 effects

IPCC (1999)



Air chemistry
ozone
methane



Popovicheva et al. (2004)

Aerosols
and effects on clouds

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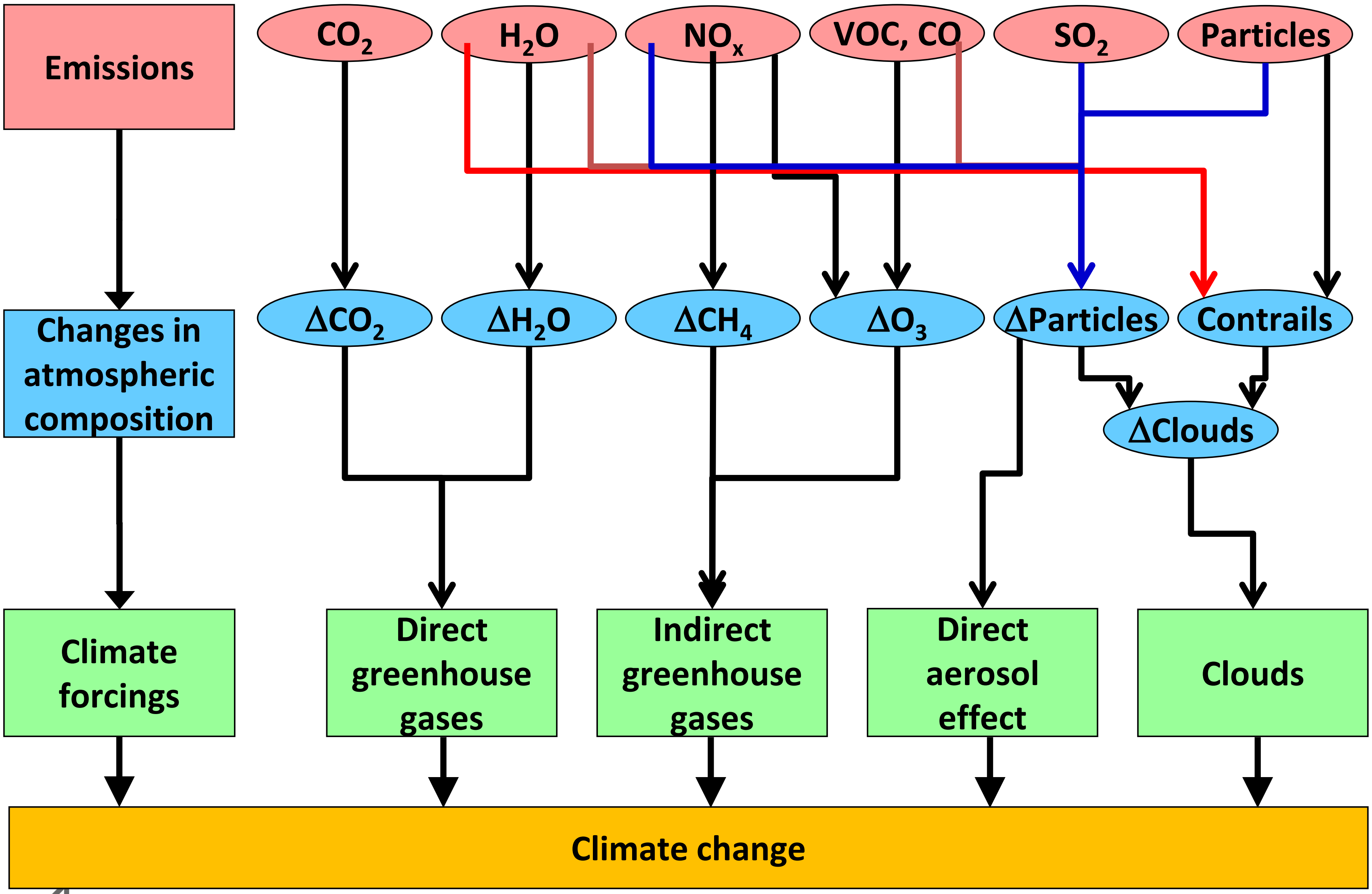
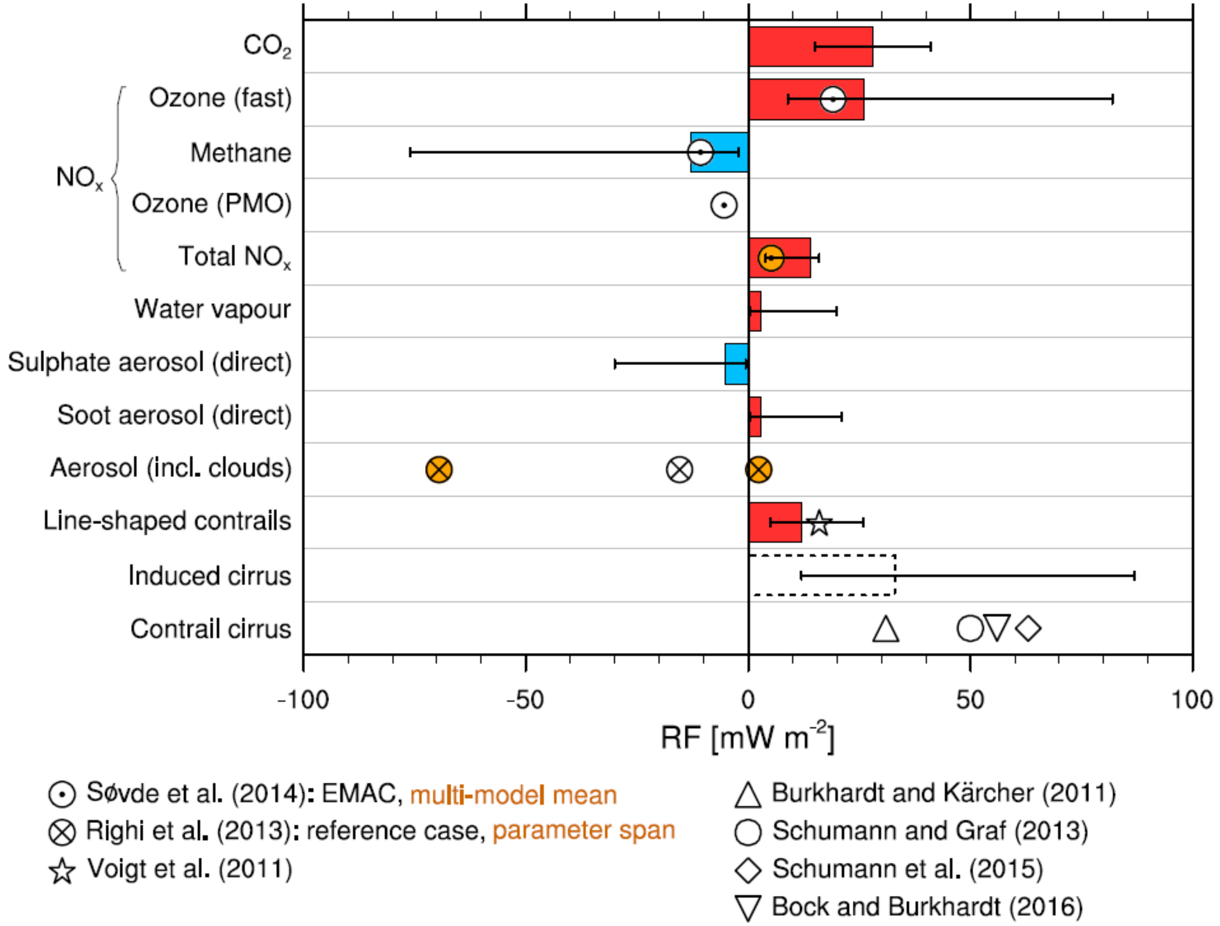
Atmospheric effects of aviation



Radiative Forcing in 2005 from historical aviation emission



Carbon Dioxide, NO_x emissions, and contrail cirrus are main contributors to aviation induced RF.

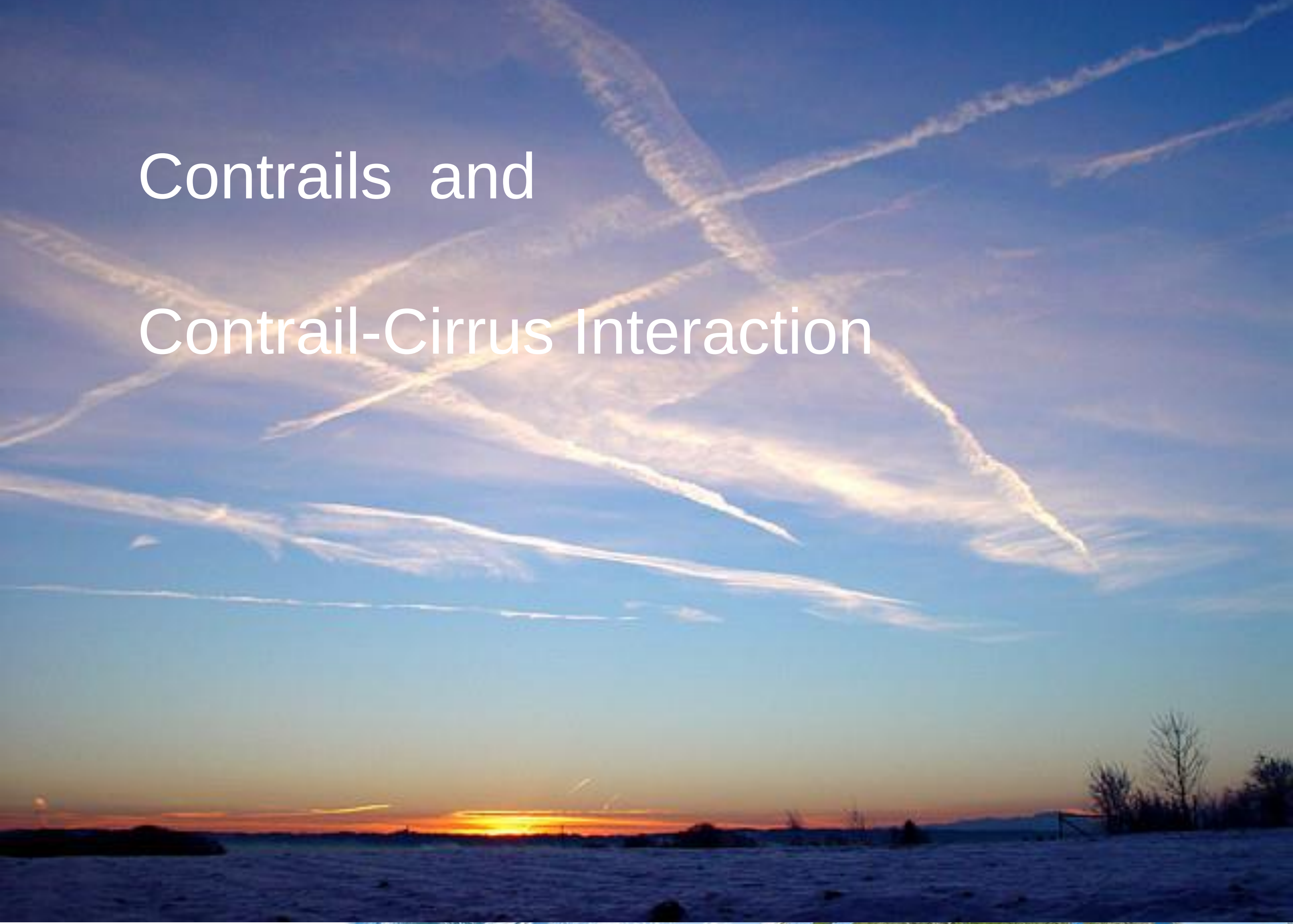
Level of Scientific Understanding (LoSU) varies between individual effects

Grewe et al. (2017)

Data are based on Lee et al (2009) with update from various more recent publications

Contrails and

Contrail-Cirrus Interaction



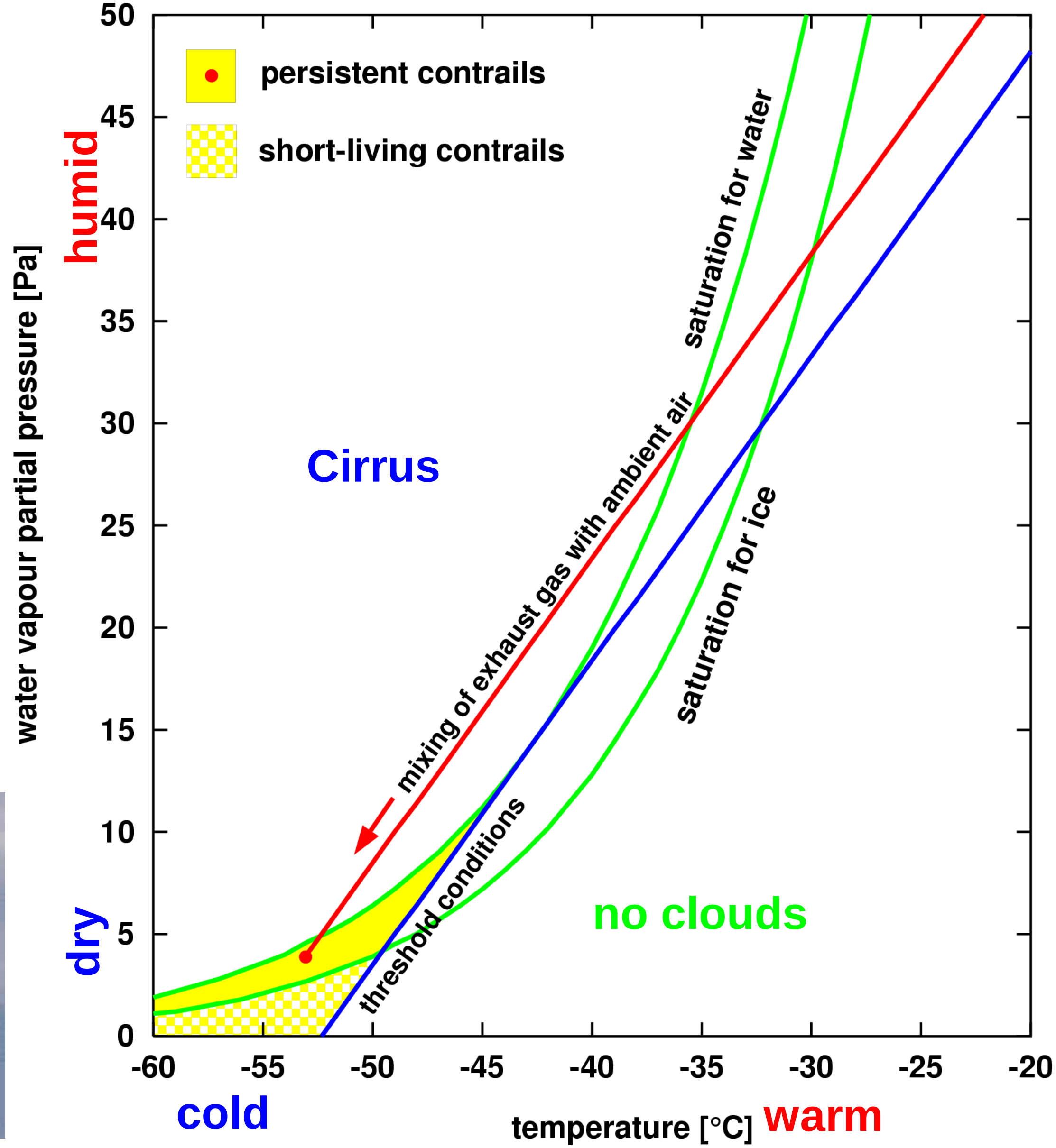
How do contrails form?

Formation depends on

- Atmospheric condition
  Temperature/Humidity

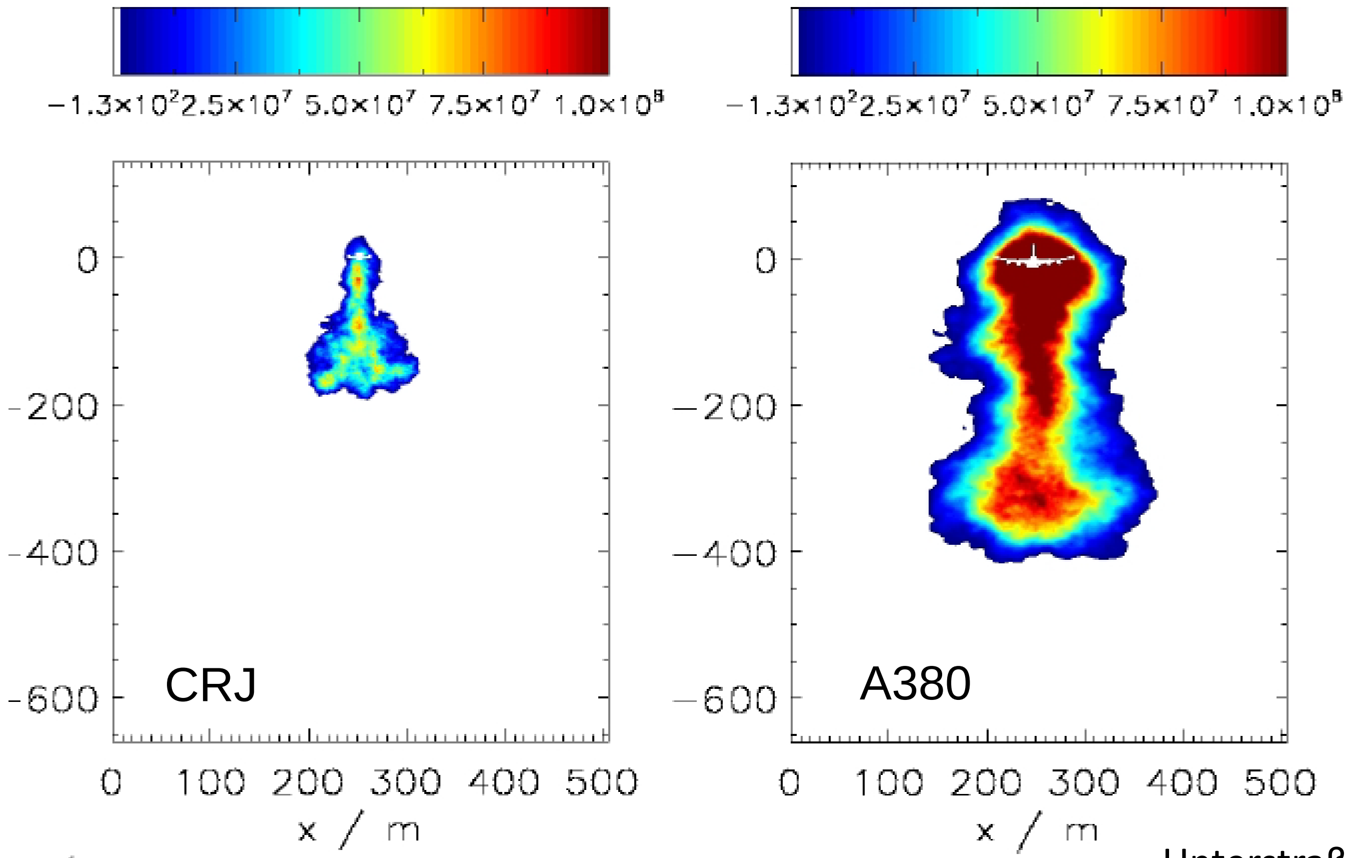
- Too dry/warm
  ⇒ No contrails

- Too humid/cold
  ⇒ Cirrus already exists



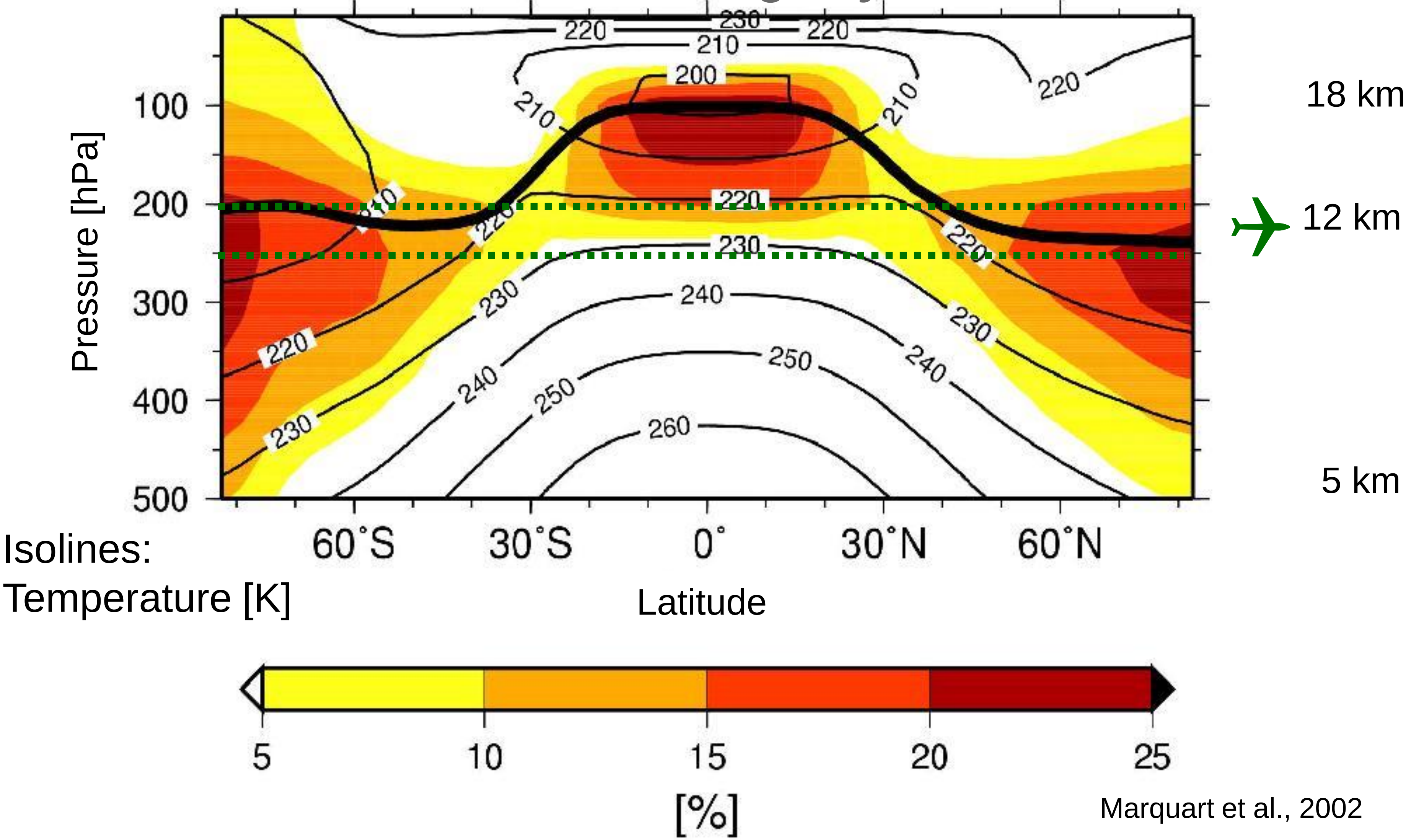
Contrail Dimension also depends on aircraft type (weight basically controlls the strenght of vortex

Ice crystal number concentrations



Unterstraßer et al., 2014

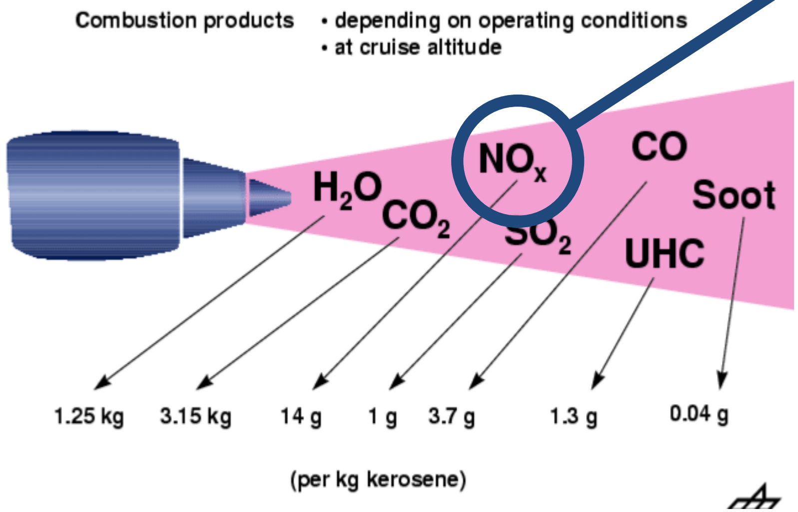
Where can contrails form? Potential contrail coverage = Maximum coverage by contrails



Marquart et al., 2002

Chemistry

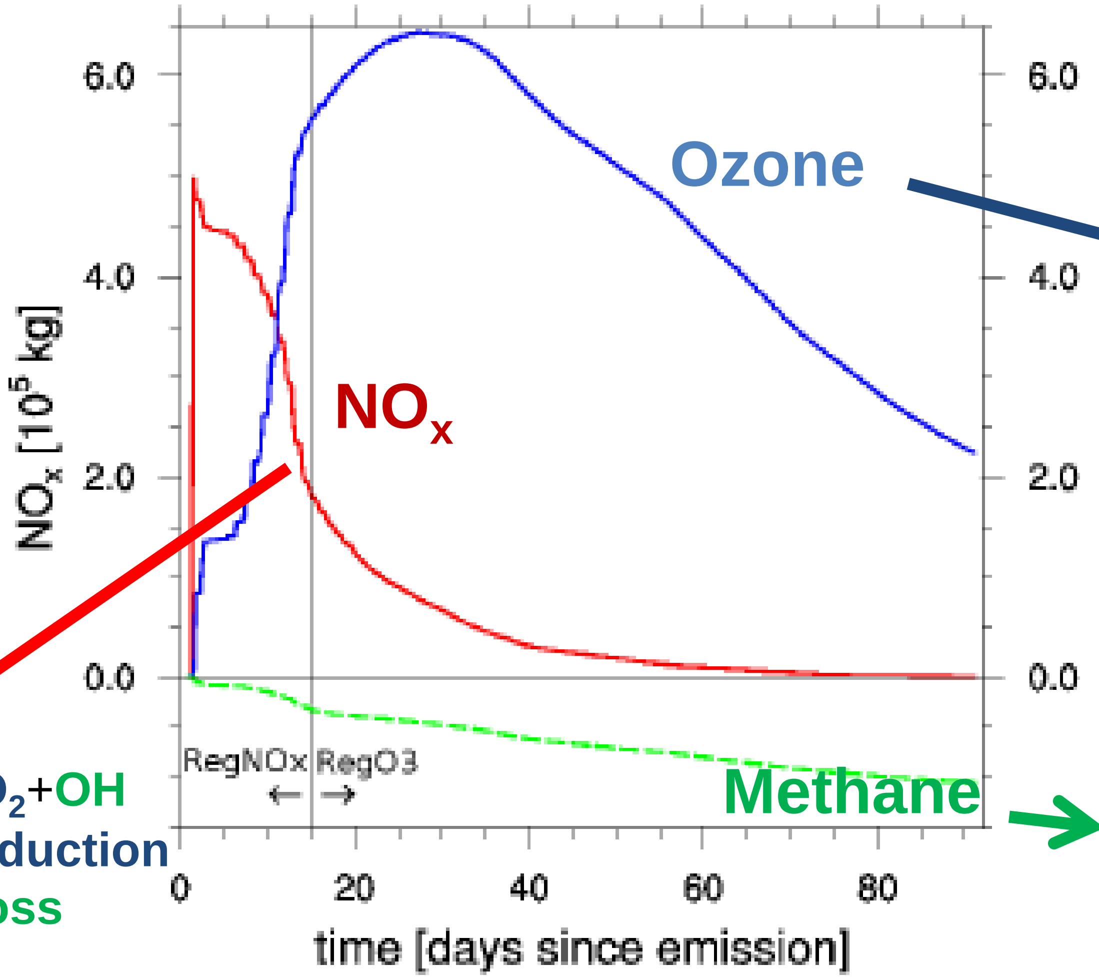
Air chemistry



Produces ozone

Destroys methane

Chemical regimes for methane loss



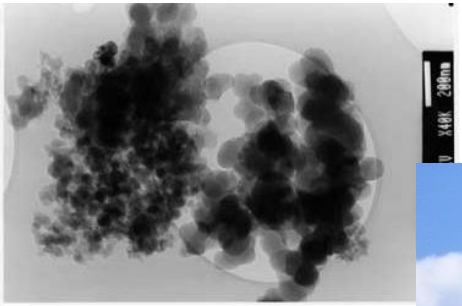
O_3+hv →O+O_2
O+H_2O →2 **OH**
- **Methane loss**

NO+HO_2→**NO_2**+**OH**
- **Ozone production**
- **Methane loss**

- **Reduced ozone production**
- **Stratospheric water vapour**

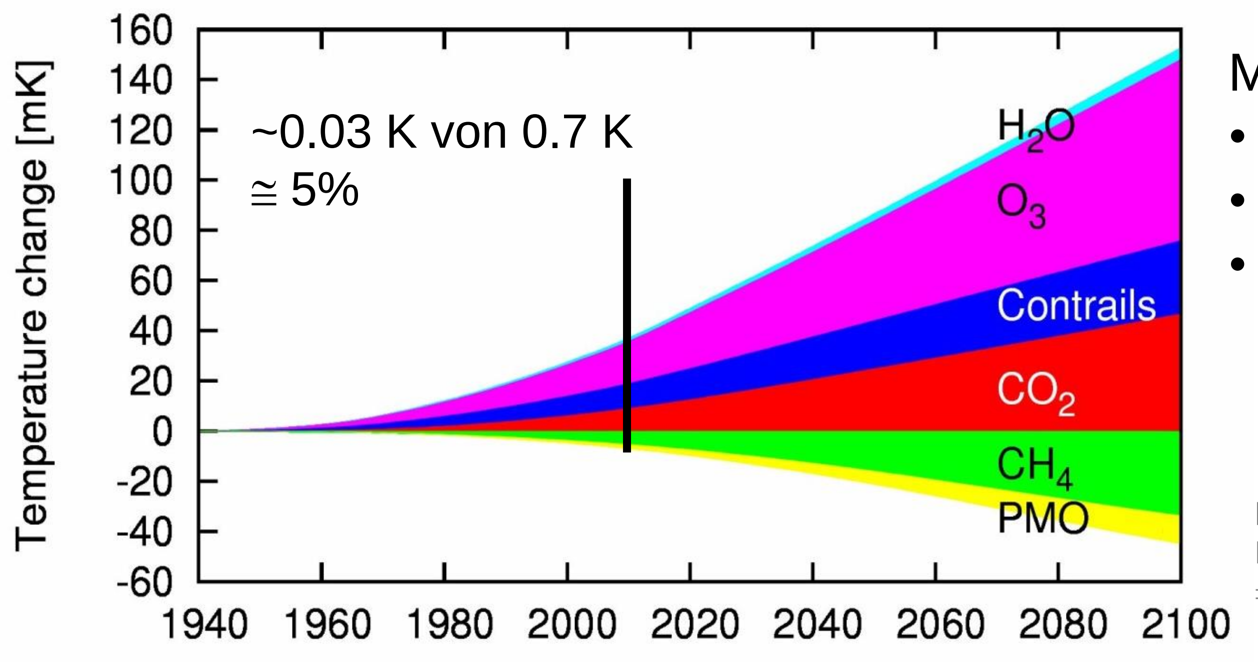
Grewe et al. (2017)

Aerosols impact on clouds is still uncertain !



- **Two potential effects are identified**
  - Impact on ice clouds (cirrus)
  - Impact on low level tropical clouds
- **All results depend on the initial characteristics of soot and sulphur emissions:**
  - Additional cirrus forms only if the emitted soot has the ability to act as good ice nucleii.
  - Low level clouds are altered by sulphate droplet only if the fuel contains enough sulphur and a large number of very small particles are emitted.
- **Both effects, if they occur, potentially cool!**
- **Currently poor understanding!**

Aviation´s impact on global mean 2m-temperature



Main contributors :

- CO_2
- Contrails
- NO_x (O_3 and CH_4)

PMO=„Primary mode ozone“
Results from less CH_4
$\Rightarrow$ less HO_2 $\Rightarrow$ less O_3 production

Air traffic contributes to climate change by roughly 5%.

Mitigating the climate impact of aviation: Some recent studies

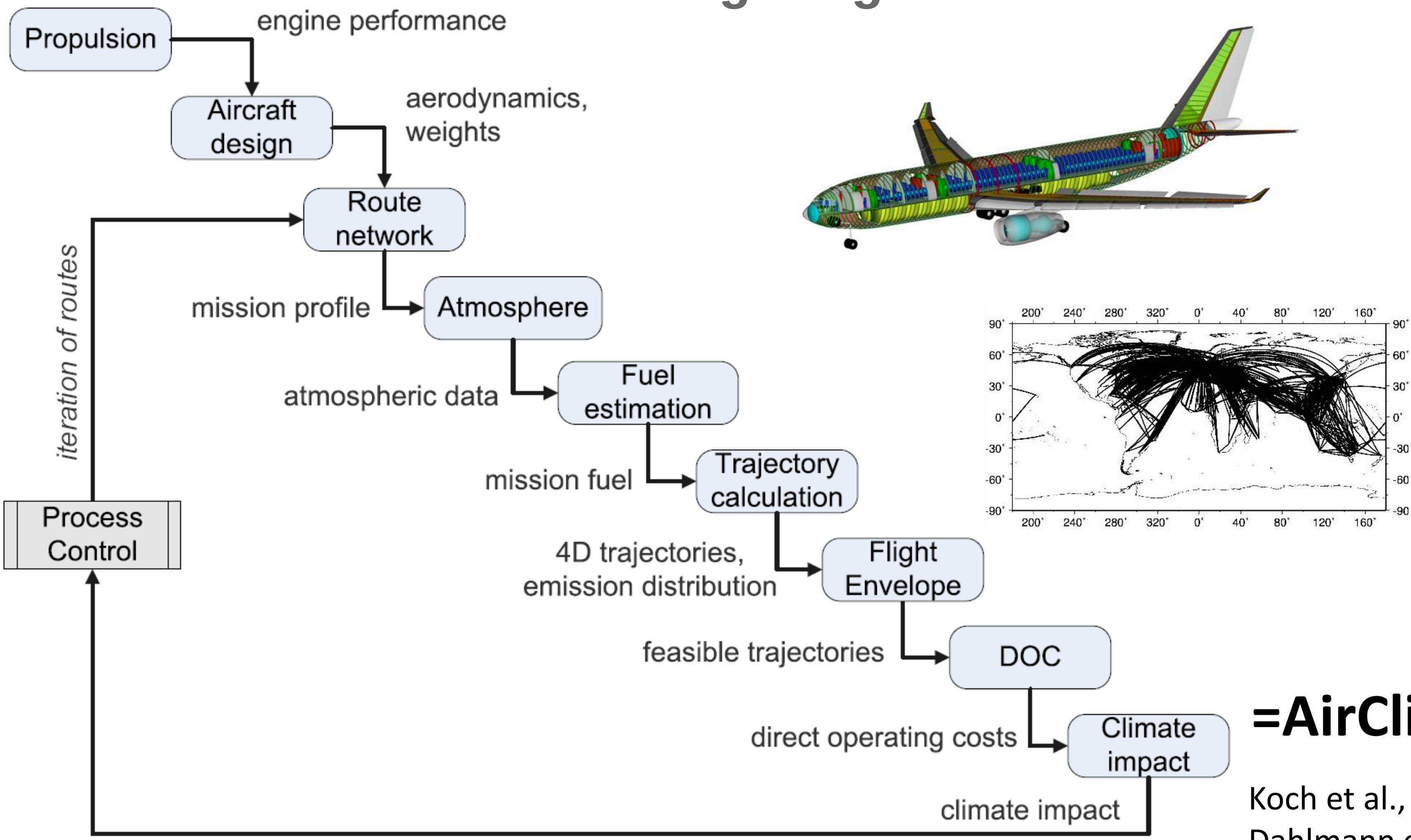
- **Technological Measures:**
  - Fuel efficiency
  - Emission reduction
  - Alternative fuels

- **Operational Measures:**
  - Avoiding climate sensitive regions
  - Intermediate Stop Operations
  - Climate restricted airspaces

- **Economical Measures**
  - Market-Based Measures
  - Carbon off-setting
  - Climate – Charged Areas

DLR-Project CATS: Climate Compatible Air Transport System

Focus on a long-range aircraft

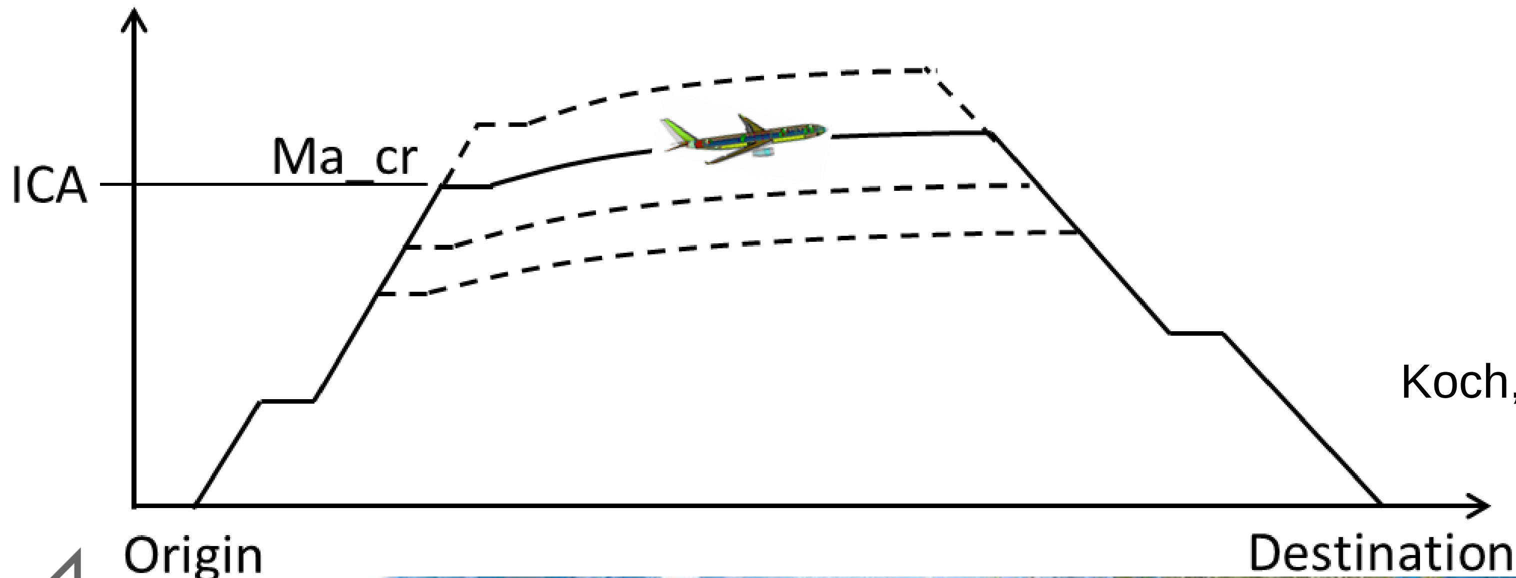


=AirClim

Koch et al., 2011
Dahlmann et al. 2016

CATS-optimisation approach

- **Variation of initial cruise altitude and speed**
- **Optimal relation between costs and climate**
- **Definition of new design point**
- **Optimisation of the new aircraft for this new design point**



Koch, 2013

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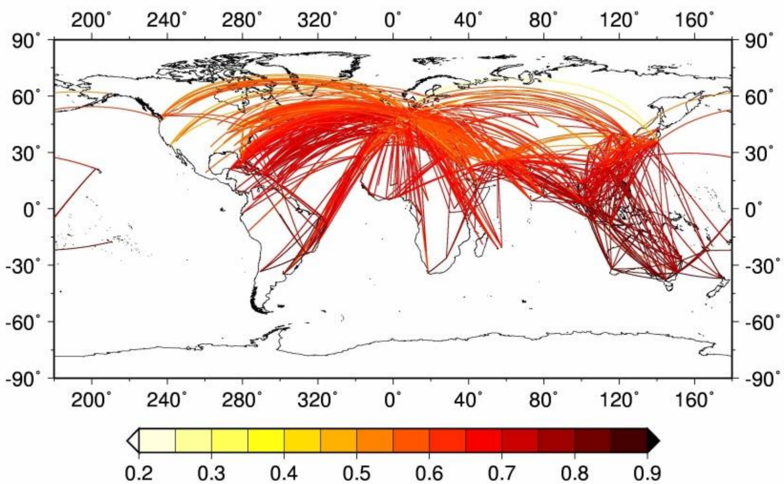
A330: Potential of a climate change reduction: CATS-results

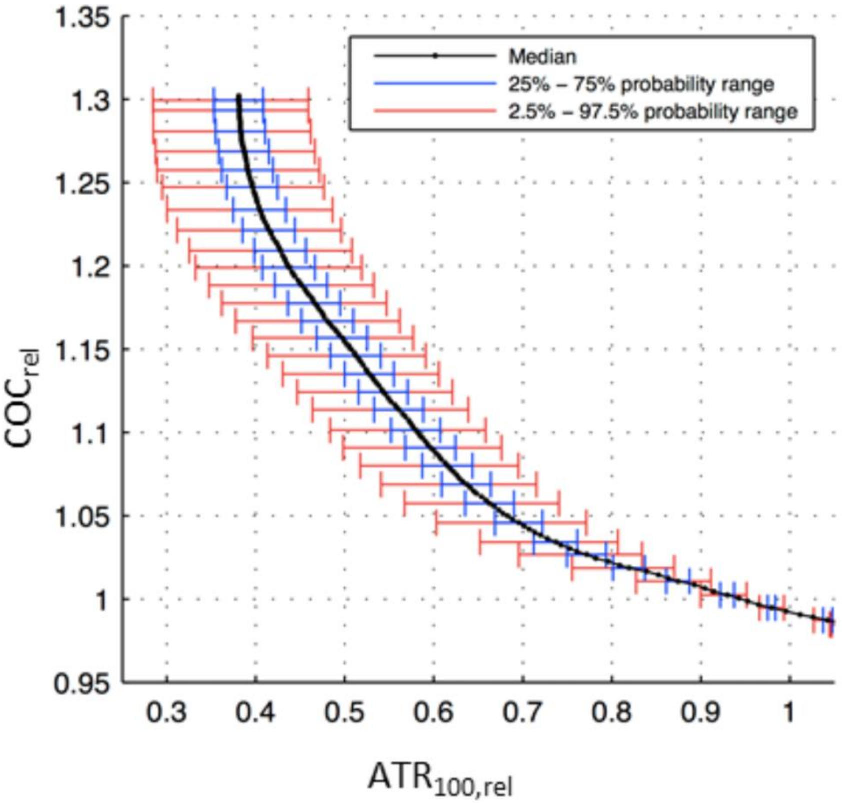
Variation in speed an cruise altitude

30% Reduction in climate change
with 5% increase in costs

64% Reduction in climate change
with 32% increase in costs
(w/o adaption of aircraft)



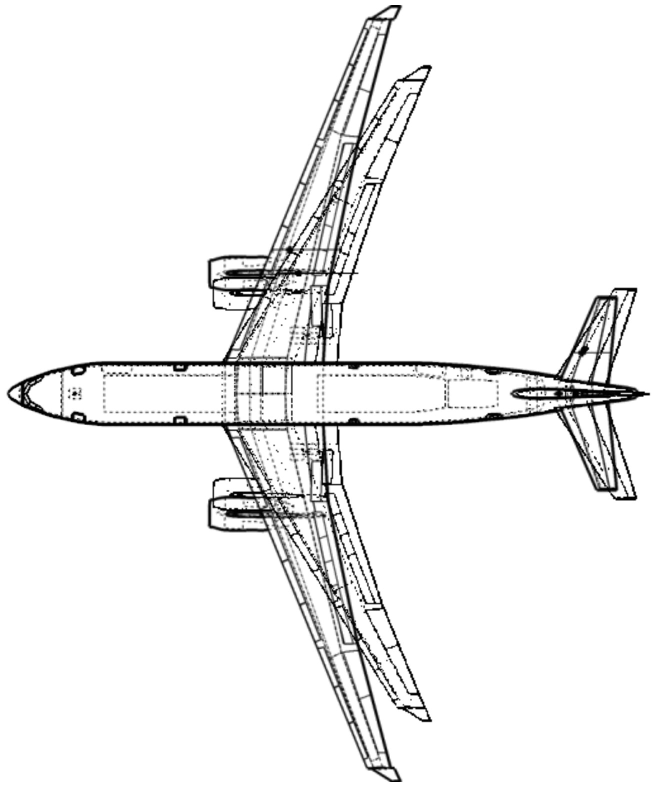
(Dahlmann, 2012)



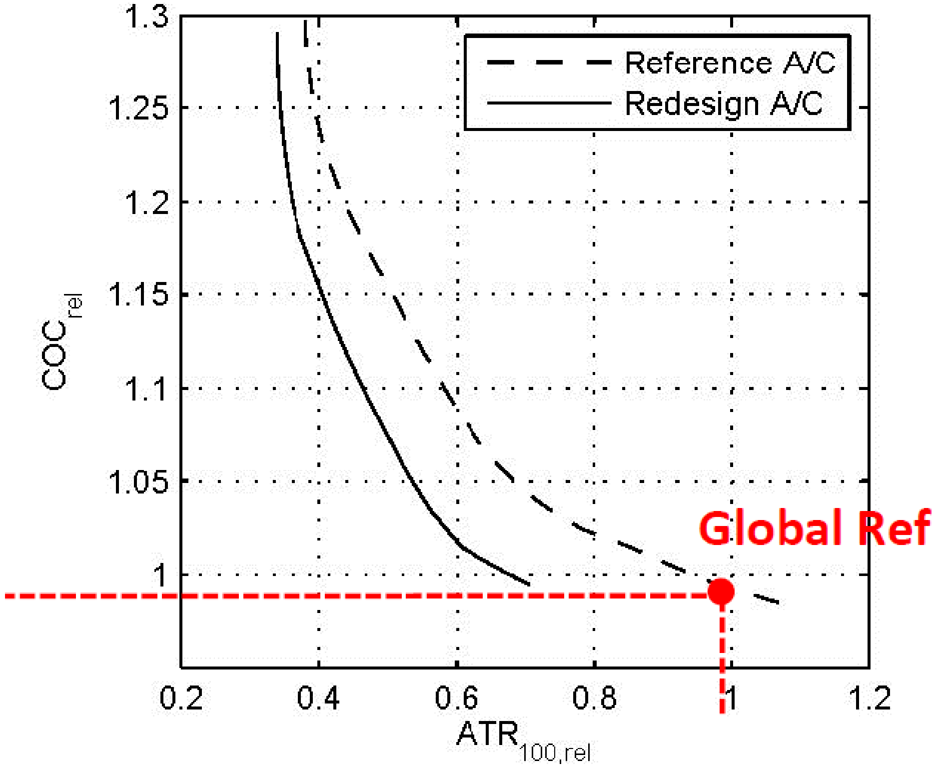
(Koch et al., 2011; Dahlmann et al, 2016)

CATS Final results

Cumulative potential for all routes operated by redesigned A/C



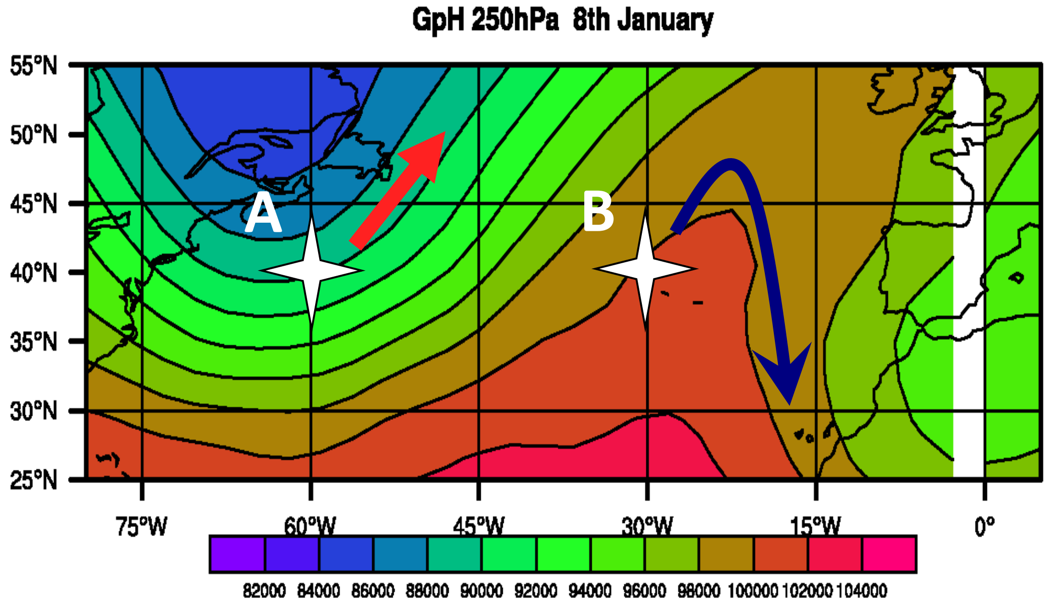
Max Mach 0.775 / Max Altitude 10500m



Redesigned A/C considerably improves climate impact mitigation potential and cost penalty

Koch (2012)

Different weather situations:
Evolution of aircraft NO_x

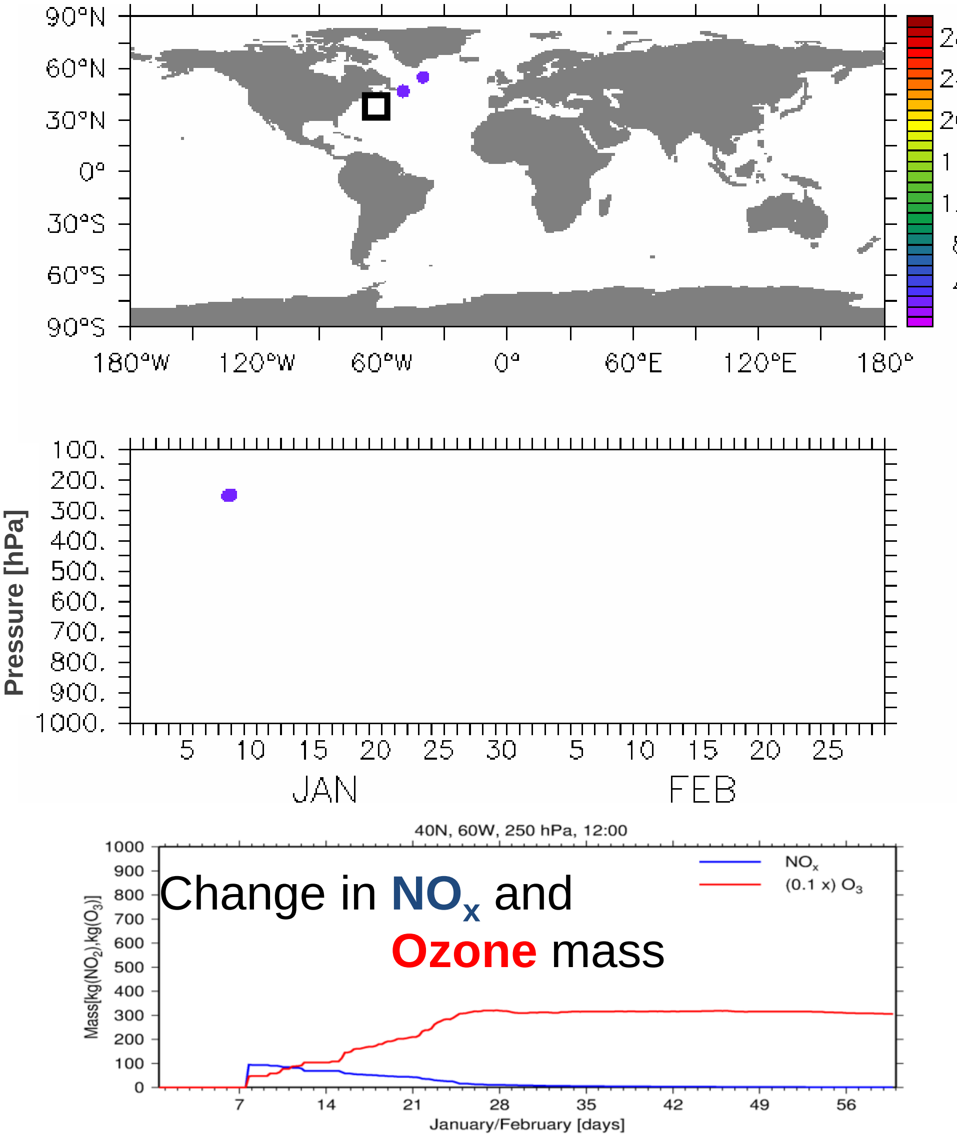


Weather type #3
"Weak and
tilted jet"

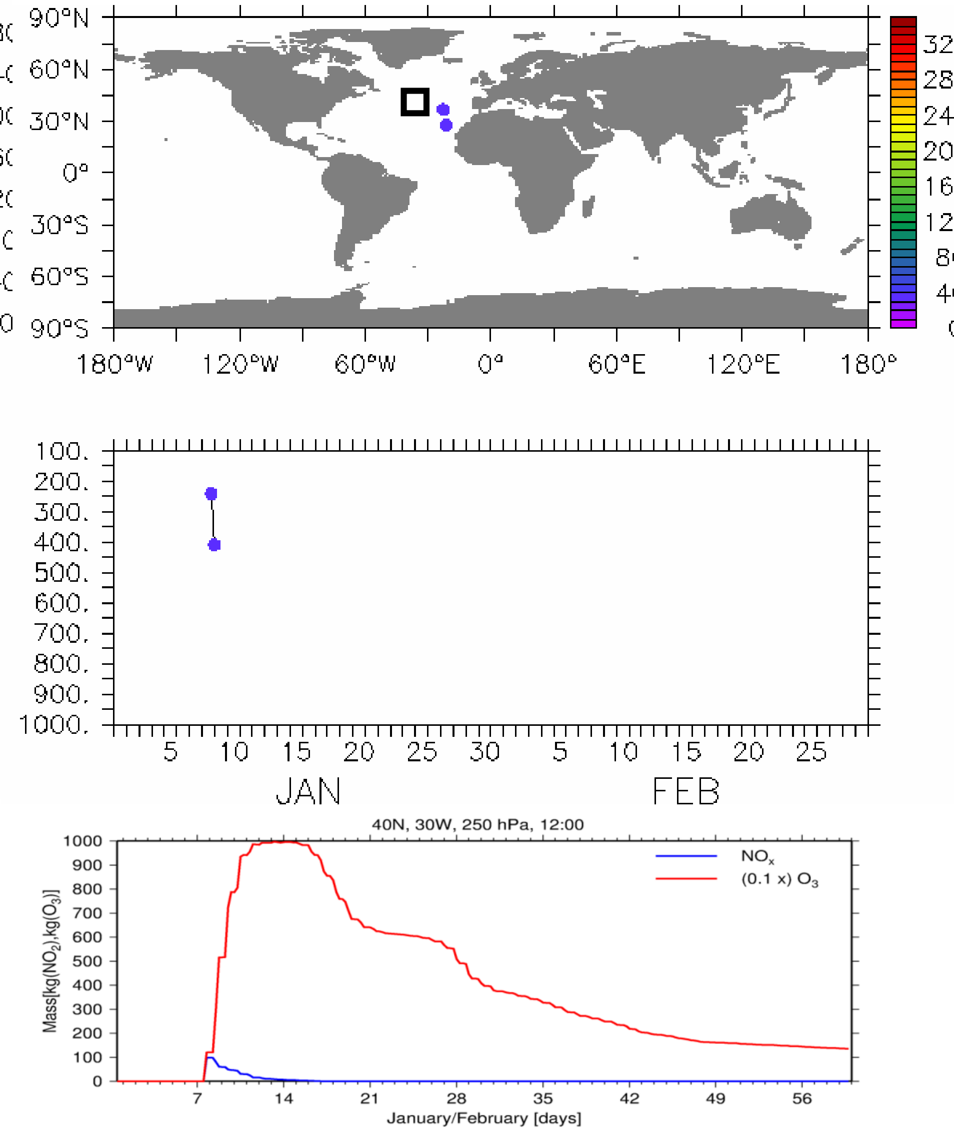
What happens if an aircraft emits NO_x at location A compared to location B?

Evolution of O_3 [ppt] following a NO_x pulse

A: 250hPa, 40°N, 60°W, 12 UTC



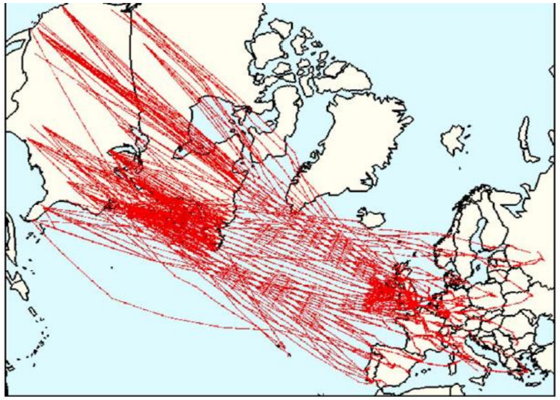
B: 250hPa, 40°N, 30°W, 12 UTC



Avoiding climate sensitive regions: The approach

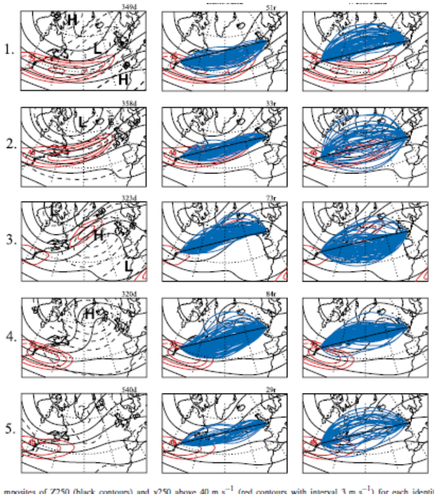
Traffic scenario:

Roughly 800 North Atlantic Flights



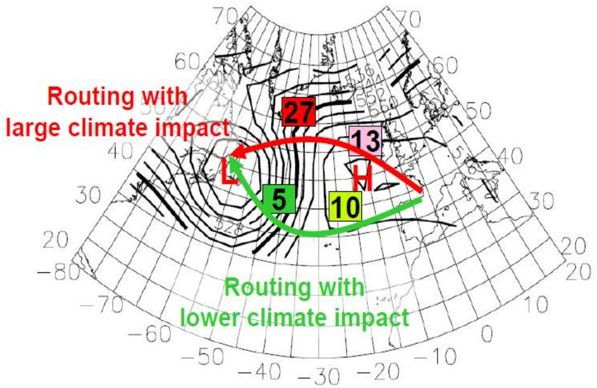
Respresentative weather situations

Climatology based on Irvine et al. (2013)



Climate-Change Functions

Contrails, O_3, CH_4, H_2O, CO_2



Traffic optimisation:

With respet to costs and climate

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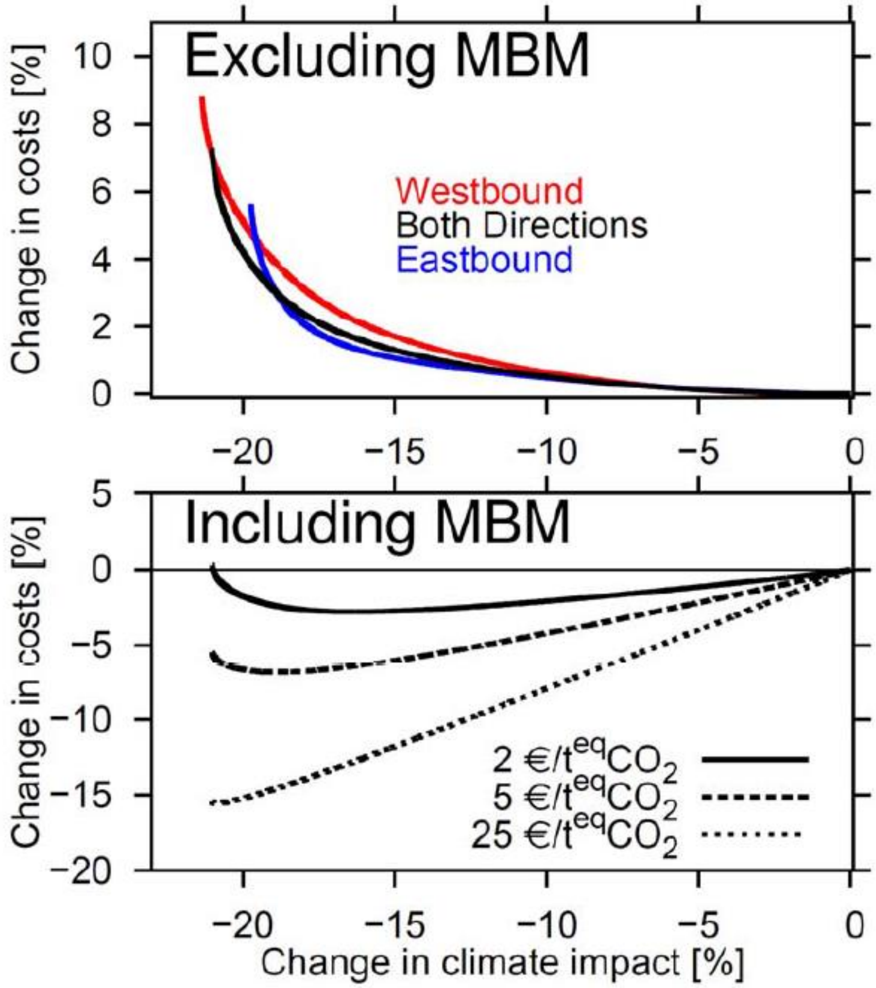
Climatology based on 8 representative weather pattern



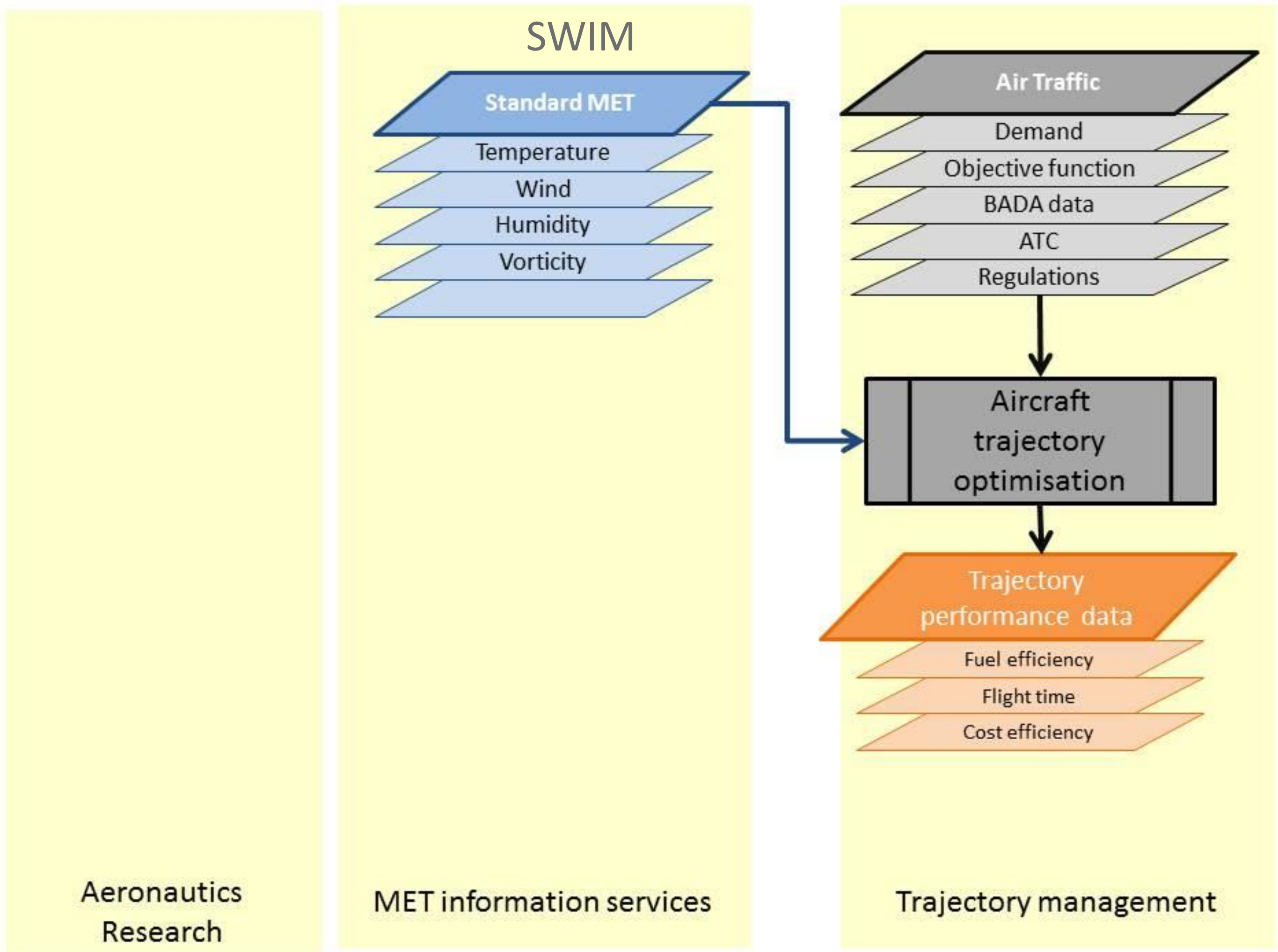
- Very flat Pareto-Front
  ⇒ Large benefits at low costs

- Market based measures would enable climate optimised routing, if non-CO_2 effects were taken into account

Grewe et al. (2017)

Air traffic management for environment: SESAR/H2020-Project ATM4E

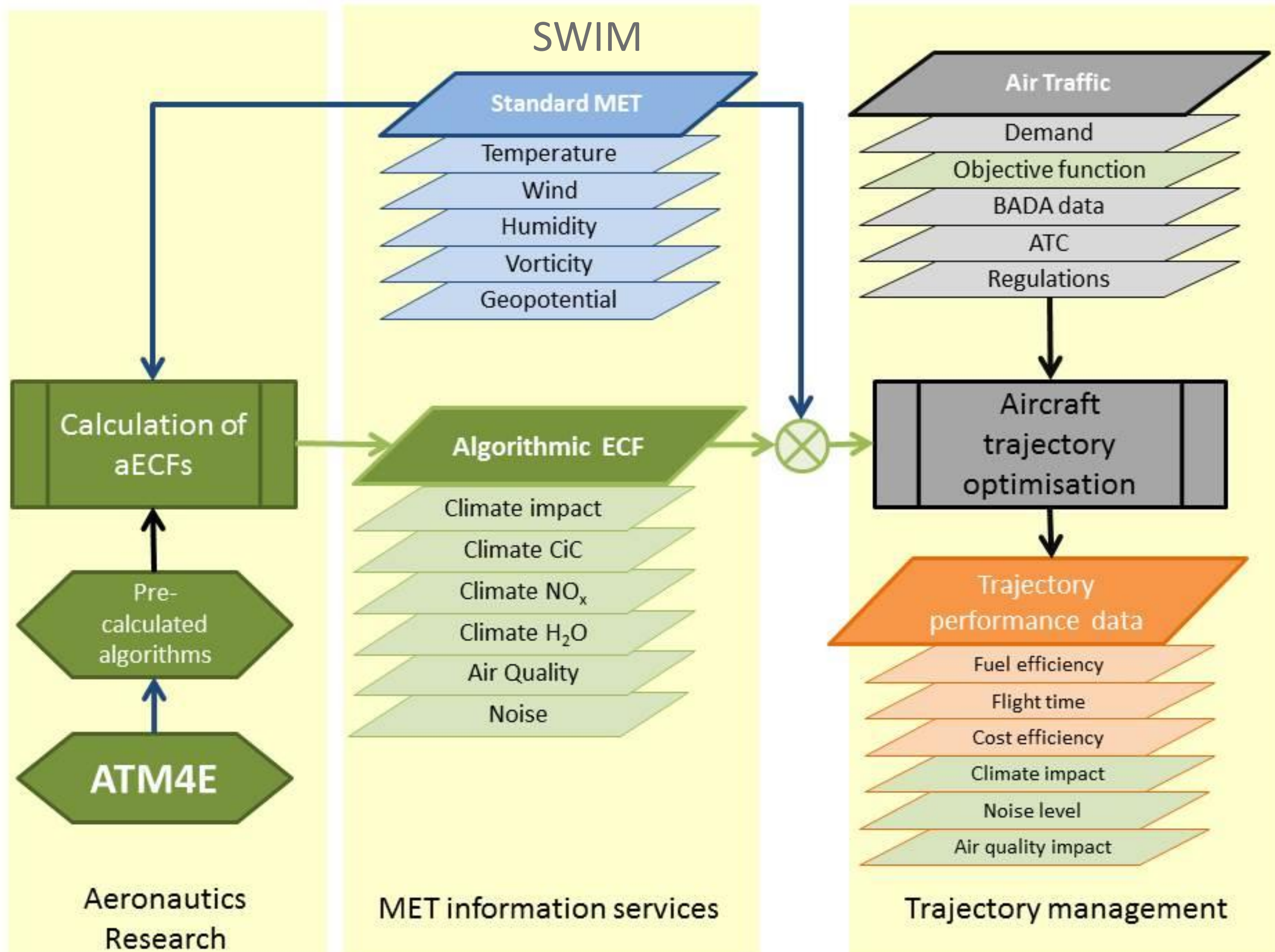
Current situation



Matthes et al. (2017)

Air traffic management for environment: SESAR/H2020-Project ATM4E

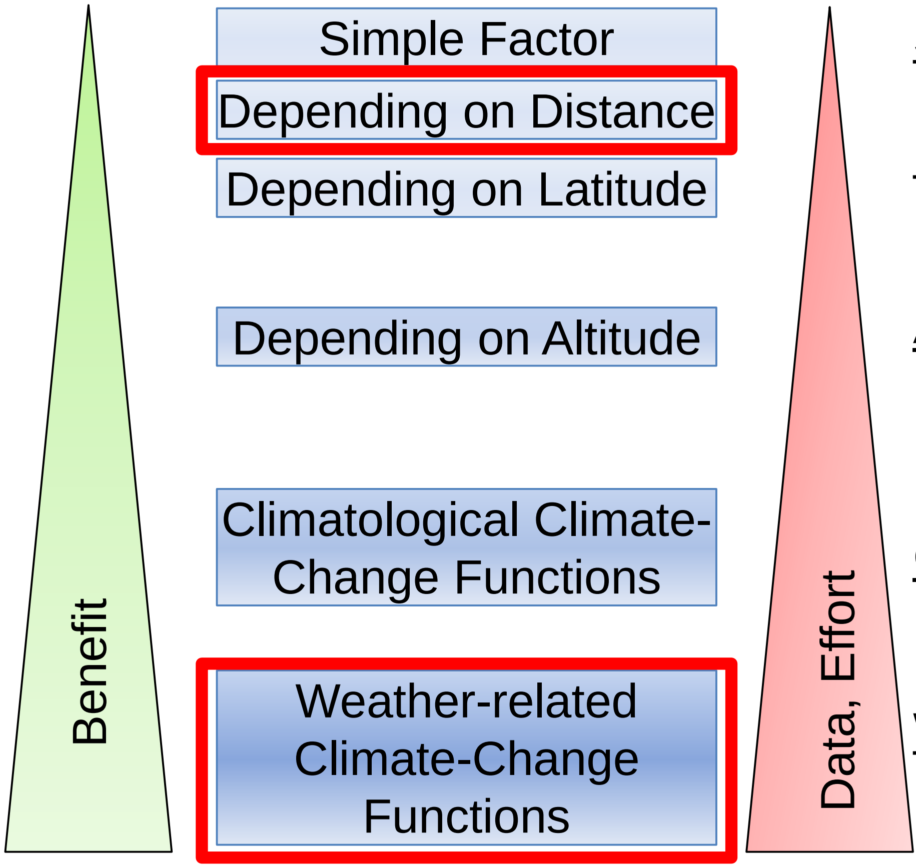
Contribution of ATM4E



Matthes et al. (2017)

Ways to include non-CO_2-effetcs

Accounting for non CO_2-effects on a flight-by-flight basis -> Conversion into eq.CO_2.



<u>Simple factor</u>: Not recommended!

<u>Distance/Latitude</u>: Has some atmospheric responses included

<u>Altitude</u>: Important factor!

<u>Clim-CCF</u>: Quite good in a climatological manner, e.g. for aircraft design, …

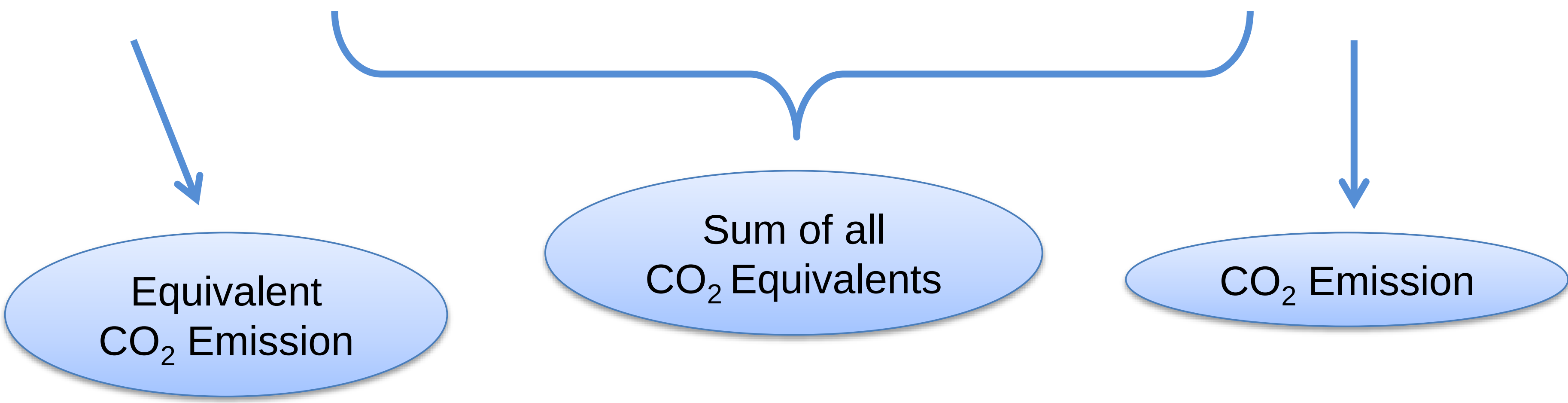
<u>Weather-CCF</u>: Best option, still requires significant developments

Work in progress: Dahlmann et al., Niklass et al.

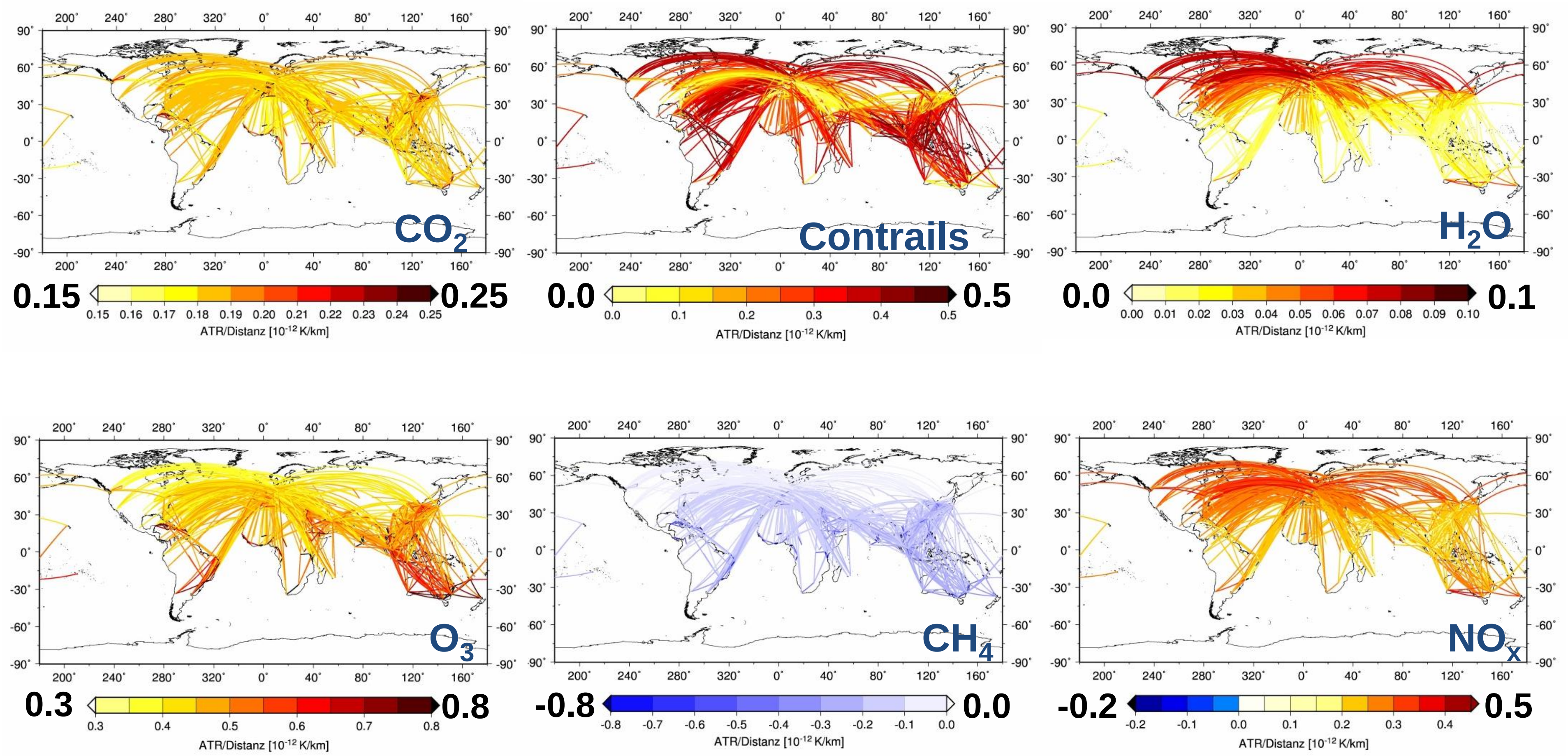
How to use equivalent CO_2?

Definition:
The amount of CO_2-emission, which leads to the same climate change as the emission of 1 kg of the regarded non-CO_2 emission.

$$^{eq}E_{CO_2} = \left(1 + ^{eq}CO_2^{Cont} + ^{eq}CO_2^{NO_x} + ^{eq}CO_2^{H_2O}\right) E_{CO_2}$$



Mean climate impact per flown distance for individual components on the basis of one long-range aircraft



Different color coding !

Dahlmann et al. in prep

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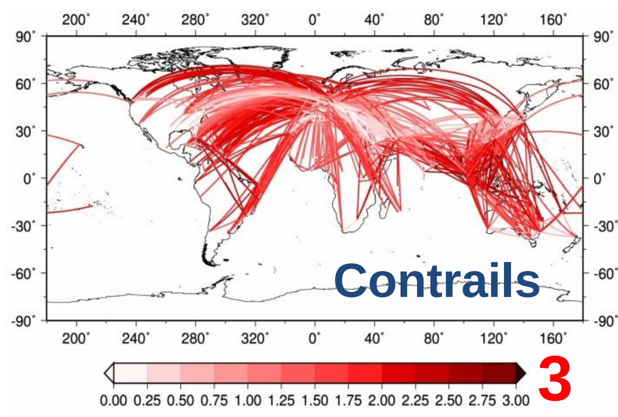
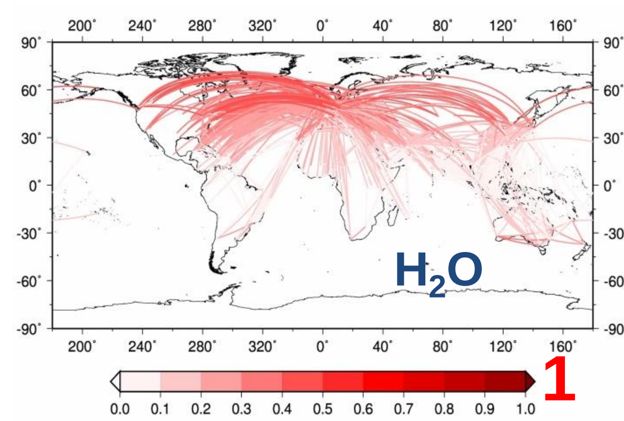
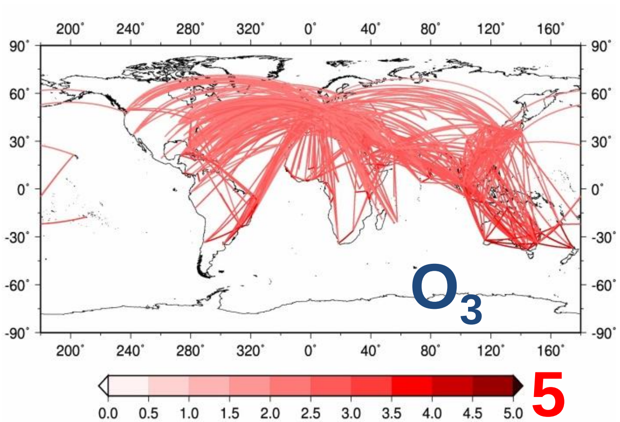
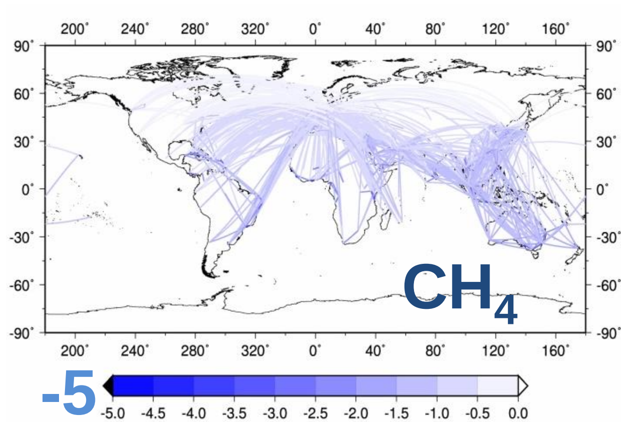
CO_2-Equivalents for individual components for one long range aircraft

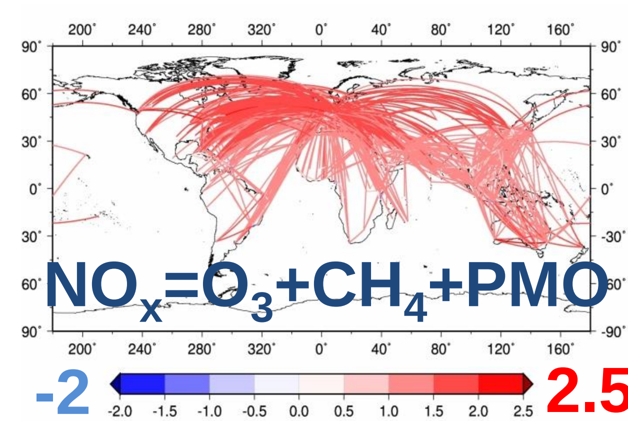
$= 1_{CO_2}$







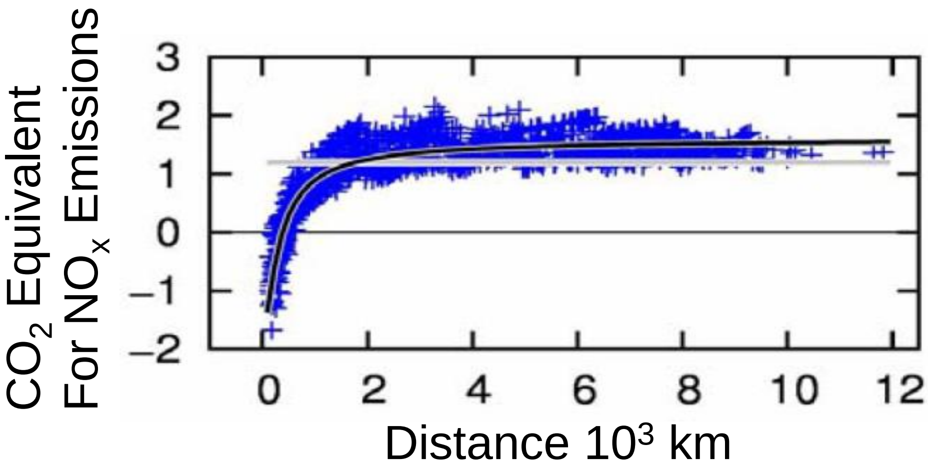




Different color coding !

Dahlmann et al. in prep

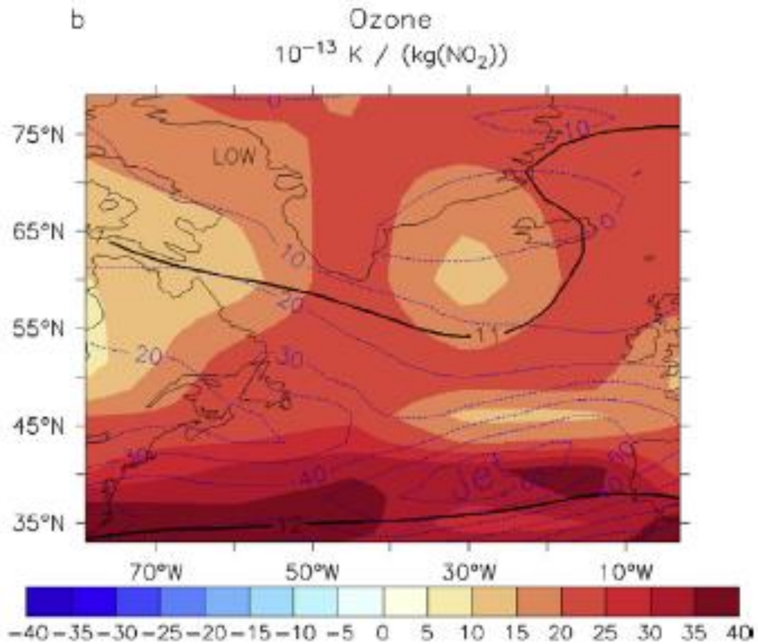
Examples for CO_2 Equivalents



Distance depending eq. CO_2 for NO_x

- Long-range 2-aisle aircraft
- with a typical flight pattern (2006)
- other aircraft might look different

Dahlmann et al. (in prep)



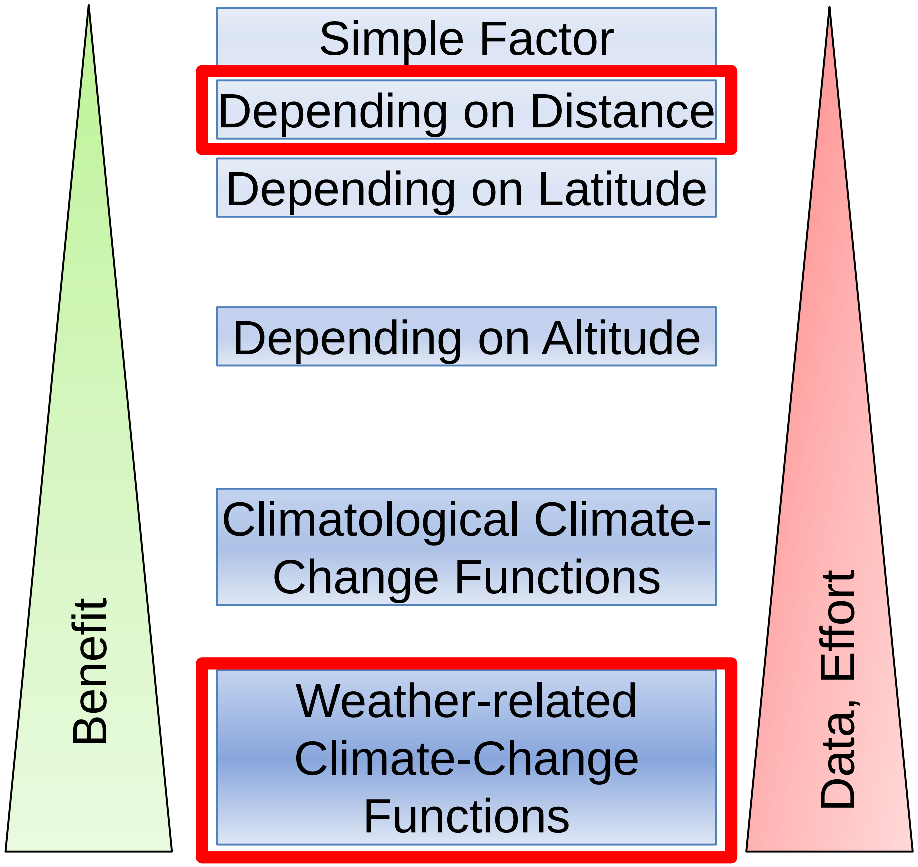
NO_x–Ozone Climate Change Function

- Such maps might be part of the weather-forecasts
- Multiplied with emissions along a flight track and accumulated
  → equivalent CO_2

Grewe et al. (2014)

Other ways to include non-CO_2-effetcs

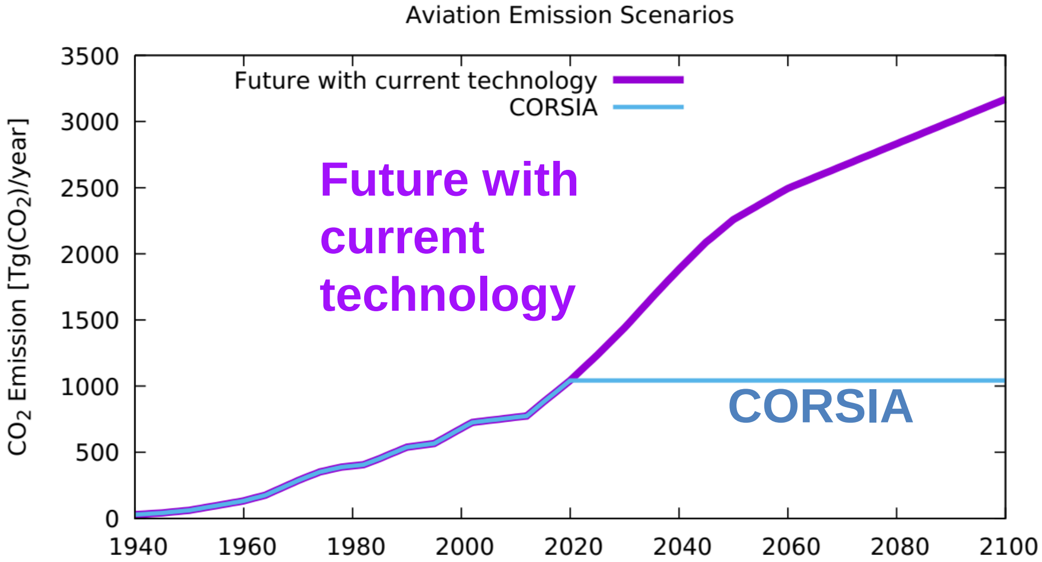
Accounting for non CO_2-effects on a flight-by-flight basis → Conversion into eq.CO_2.



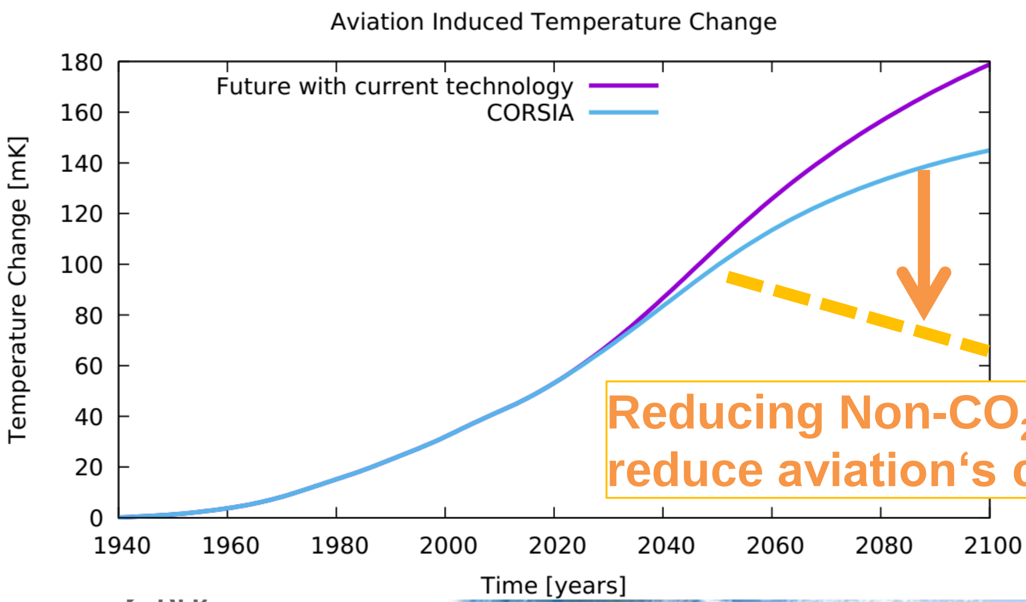
- Non-CO_2 effects show a complex picture
- Various possibilities to extract equivalents for non-CO_2-effects
- Requirements:
  - Allow for future technological advancements
  - Regional different effects
  - Altitude effects
  - Flight distance
- Tradeoff between accuracy and effort

Work in progress: Dahlmann et al., Niklass et al.

Why are non-CO_2-effects important?



- Large CO_2 emission reduction
- Large increase in Non-CO_2 effects



Small change in temperature because of

- CO_2 accumulation
- Large increase in Non-CO_2 effects

Reducing Non-CO_2 effects offer a possibility to reduce aviation's climate impact

Summary

- Enhanced knowledge on the processes related to aviation emissions.
- More than 50% of the climate impact from aviation due to non-CO_2 effects.
- Uncertainties remain, but may be better understood.
- This allows a zooming in:
  - From effects of global aviation to effects of regional emissions
  - From global climate change to regional temperature changes
- More mitigation studies, which include non-CO_2 effects.
  - Climate-sensitive areas could substantially reduce the climate impact of aviation at low cost increase.
- Outlook: Forecasting of non-CO_2 effects on a daily basis.

Thank you for your attention

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