Climate Impact of Aviation
CO_2 and non-CO_2 effects
and examples for mitigation options

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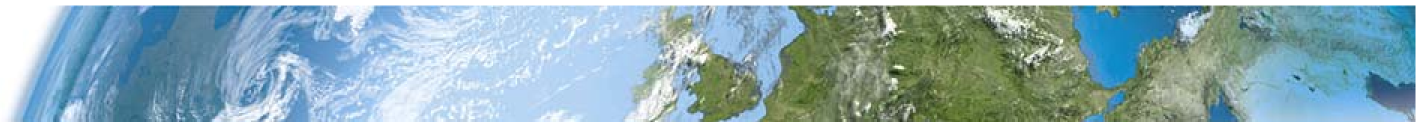
Comparison of emission of CO_2 equivalents ($TgCO_2$/year)

comprises CO_2, CH_4, NO_2, SF_6, HFCs, CFCs
(without gases from the Montreal Protocol)

Country / Type	1990	2000	2010	2015	% Change 1990-2015
Germany	1251	1043	942	902	-28% ↘
France	550	556	517	464	-16% ↘
Europe	5641	5151	4773	4307	-24% ↘
International Aviation	545	682	759	840[2014]	+54% ↗

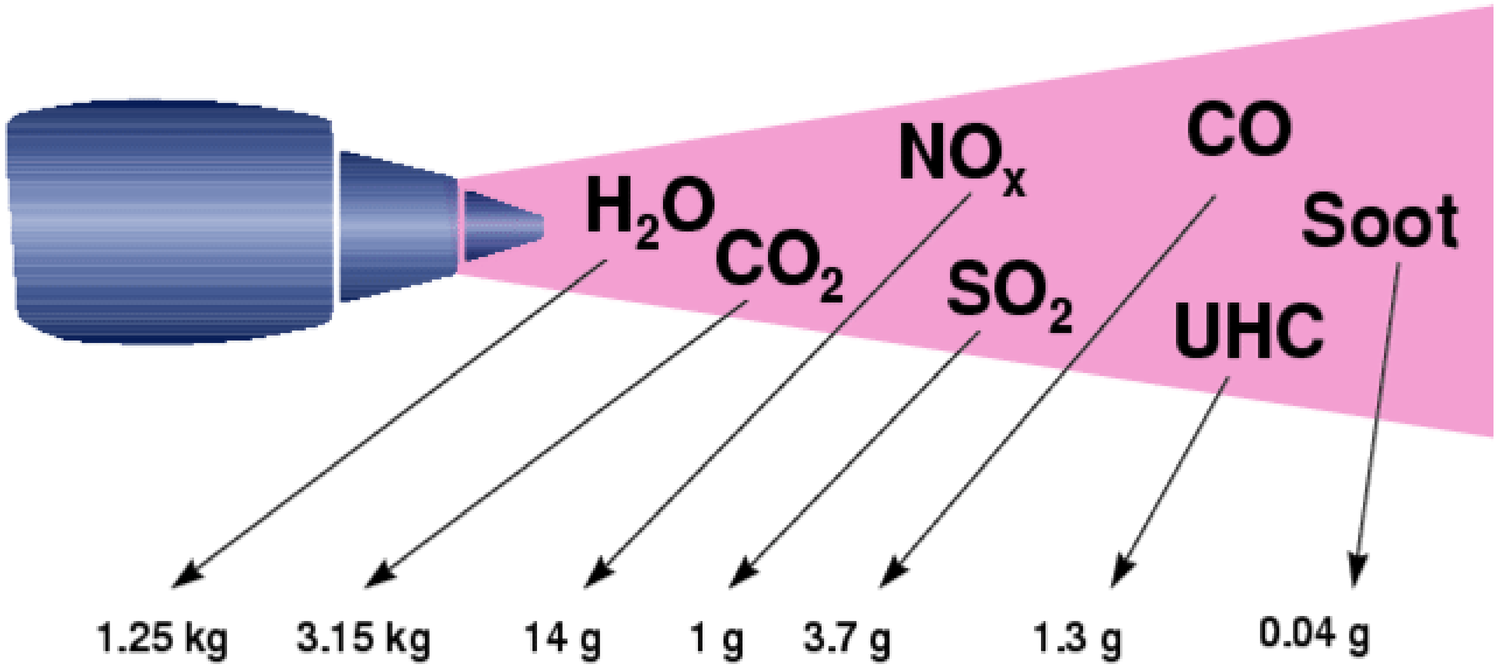
Data: unfccc.int
iea, 2016

- International Aviation
  - emits eq.CO_2 comparable to a large EU country
  - shows large increase in emissions



Air traffic emissions at cruise

Combustion products
- depending on operating conditions
- at cruise altitude

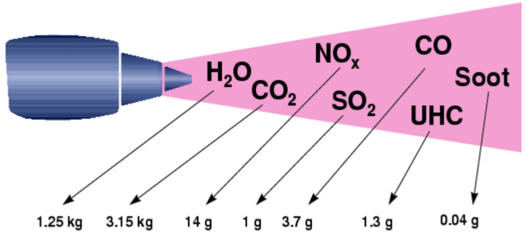


(per kg kerosene)

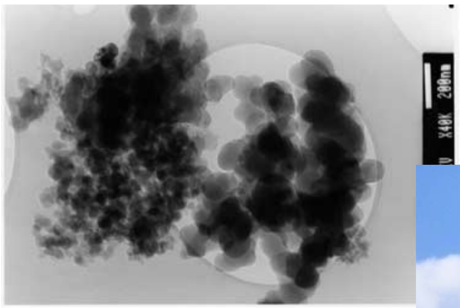
IPCC (1999)

Climate impacts via non-CO_2 effects

IPCC (1999)



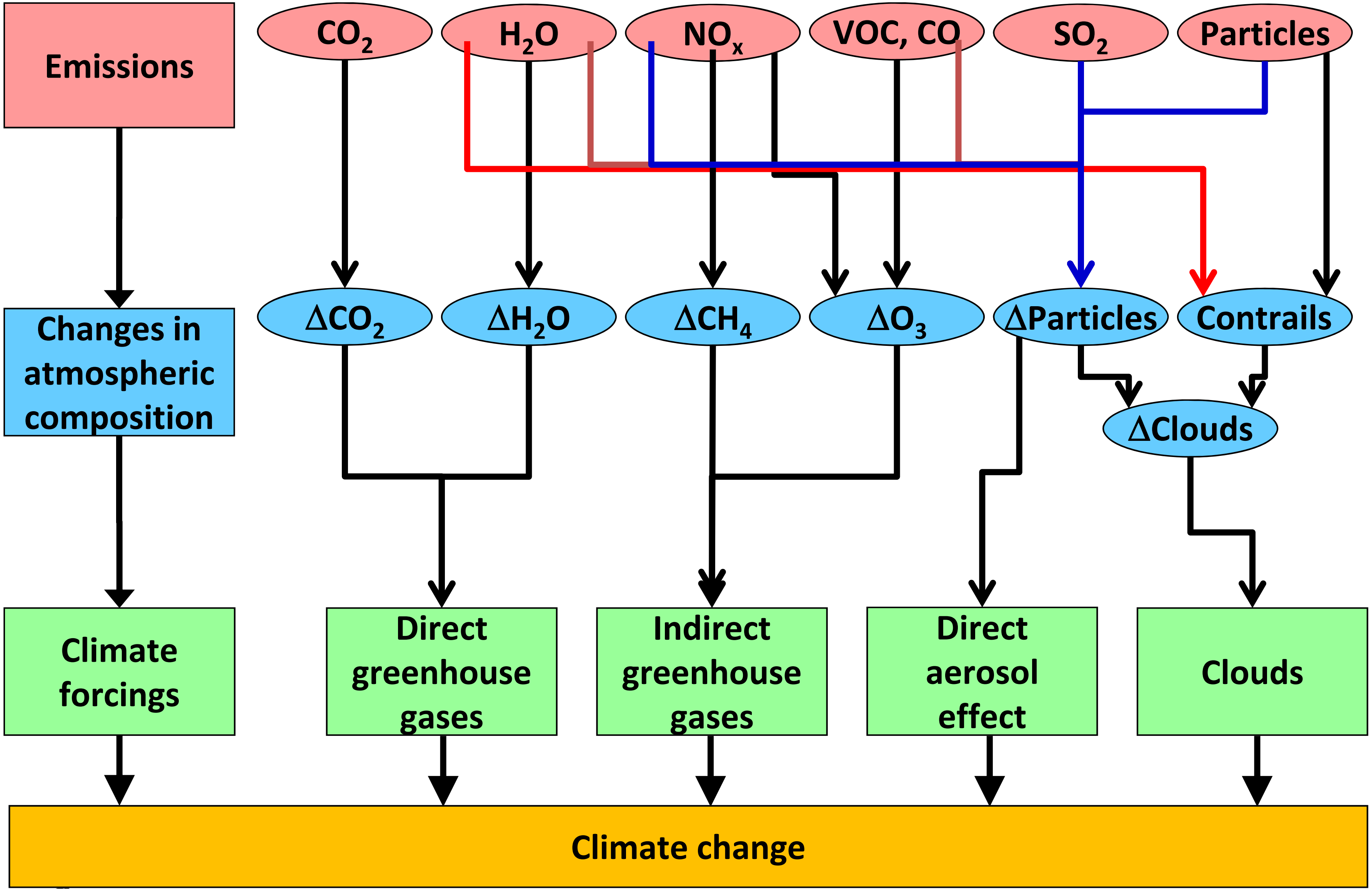
Air chemistry
ozone
methane

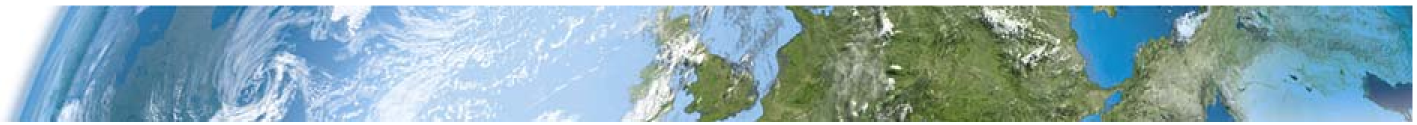


Popovicheva et al. (2004)

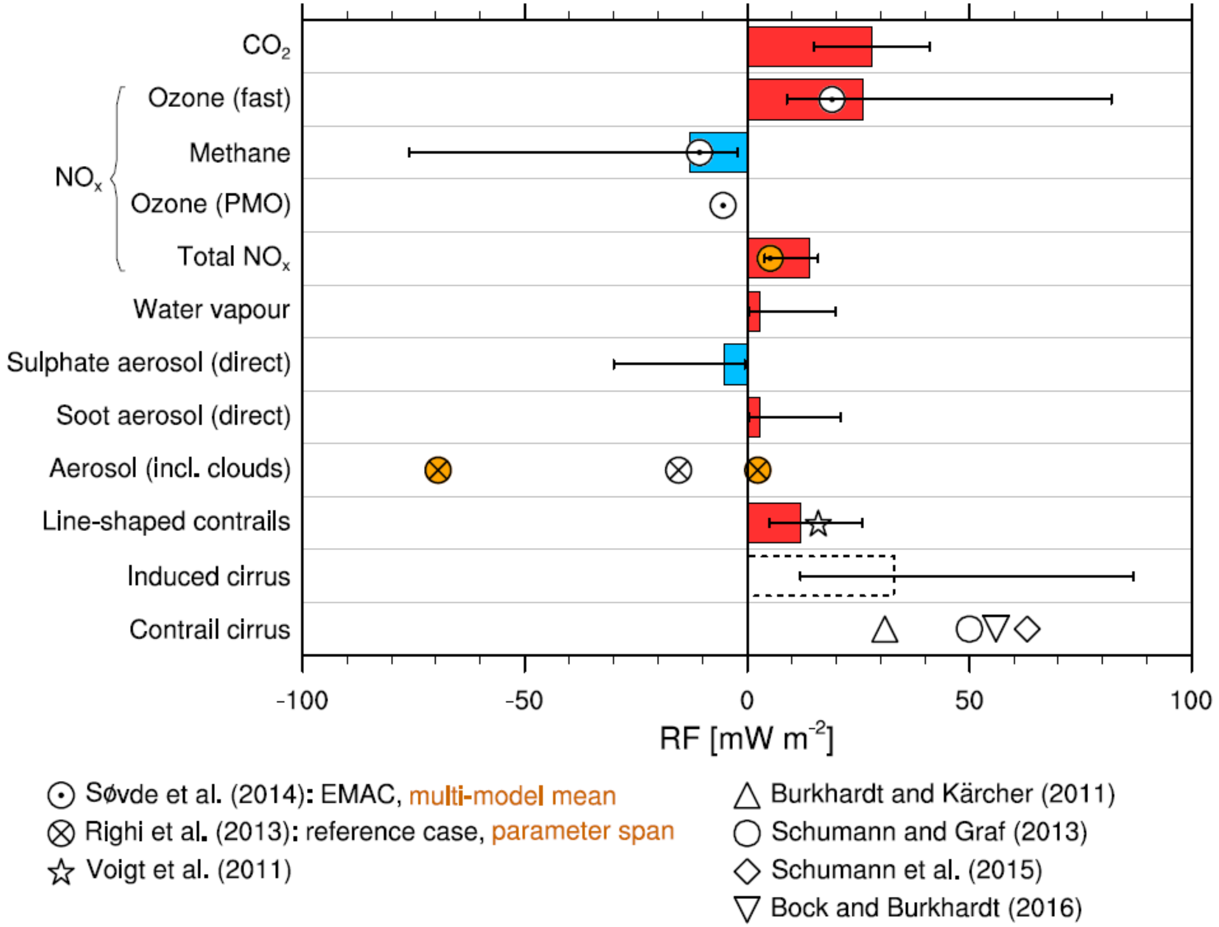
Aerosols
and effects on clouds

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

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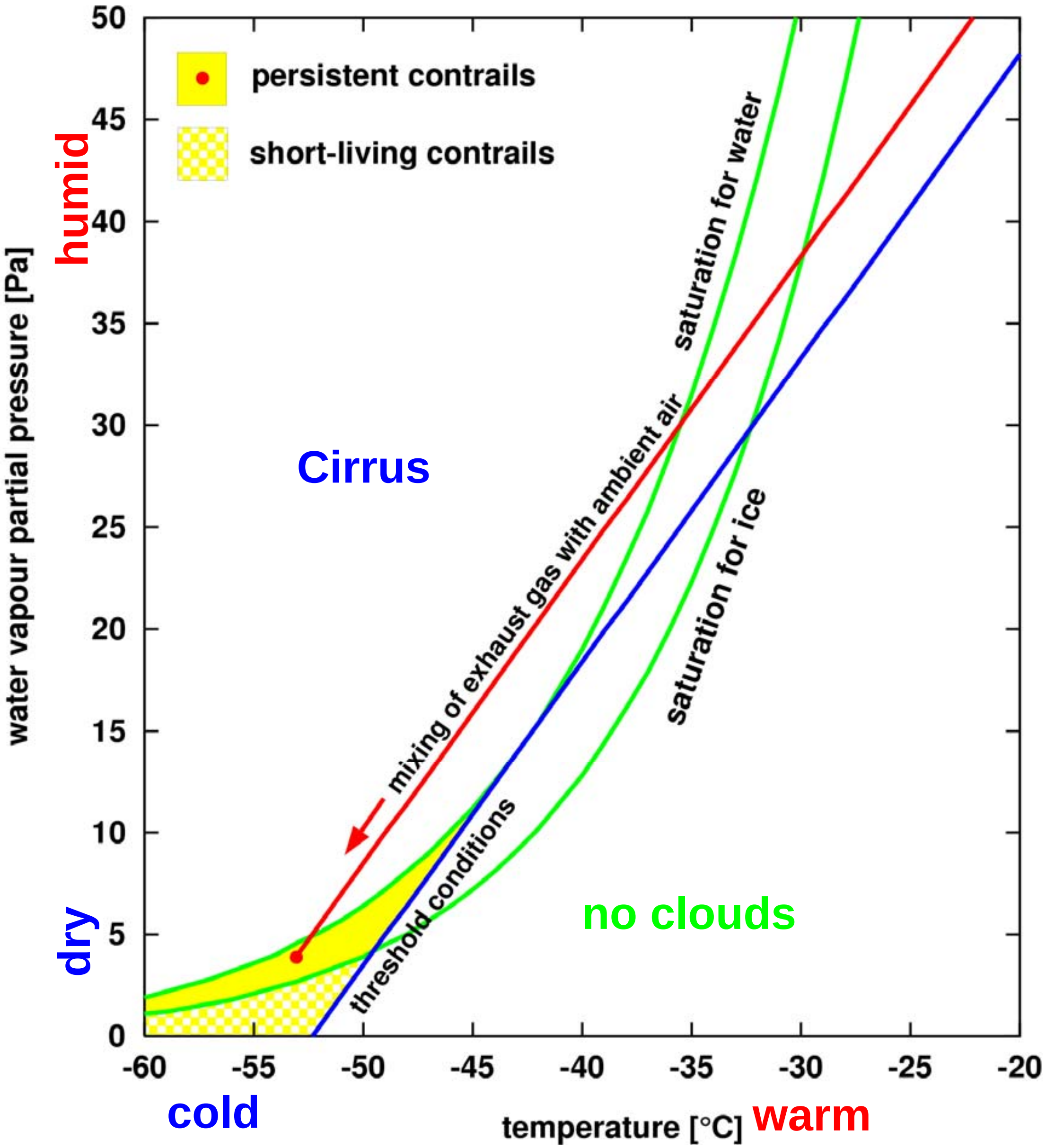
Contrails and

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



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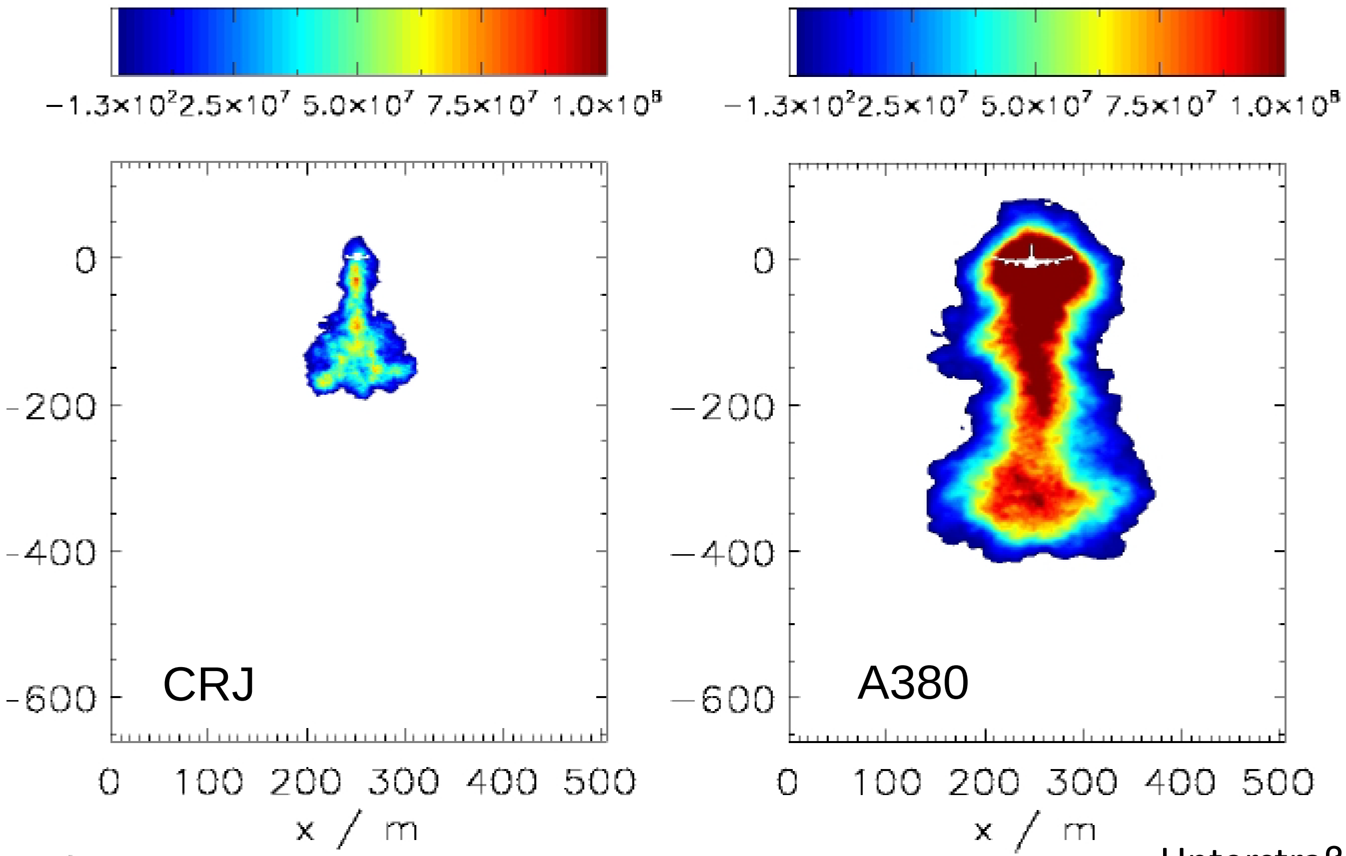
Contrail Dimension also depends on aircraft type (weight basically controlls the strenght of vortex

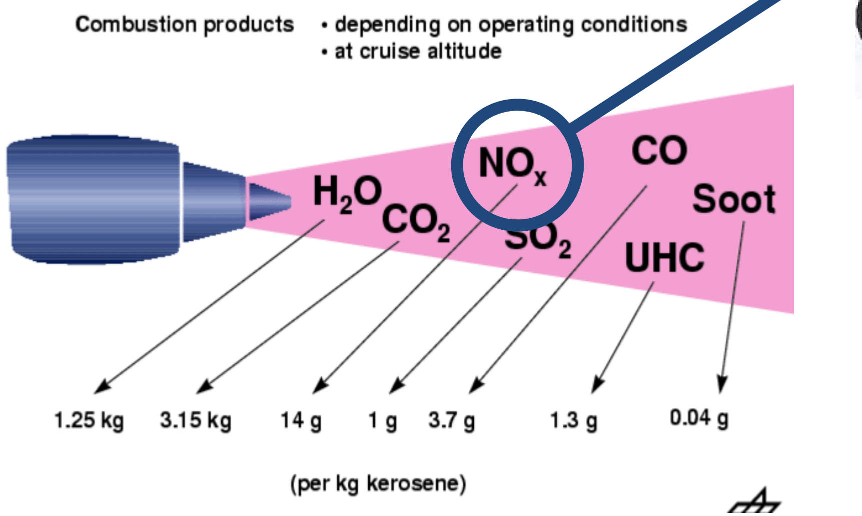
Ice crystal number concentrations



Unterstraßer et al., 2014

Chemistry

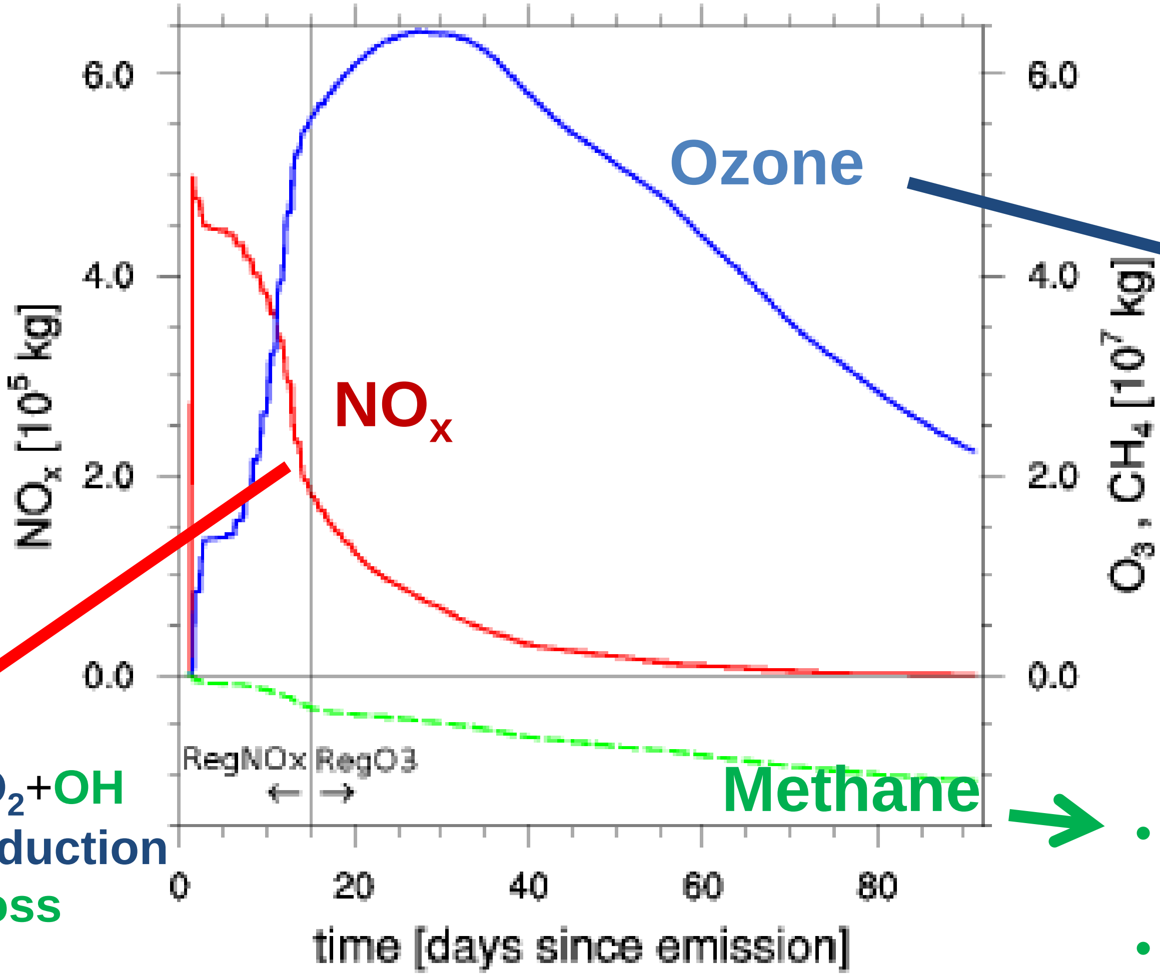
Air chemistry



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)

Radiative Forcing from aviation NO_x Emission [mW/m2]

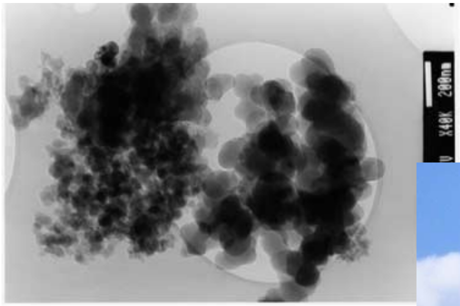
Methane has a perturbation lifetime of 12 years
Here a steady-state is assumed: Methane responses immediately to NO_x emission
Mhyre et al. (2011) (QUANTIFY): Taking the lifetime into account, delays the impact

	Lee et al. 2009	Additional Processes	Methane Lifetime
NO_x→Ozone	26.3	26.3	26.3
NO_x→Methane	-12.5	-12.5	-8.1
Methane→Ozone		~ -4.0	~ -2.6
Methane→H_2O		~-2.5	~-1.6
Total	13.8	7.3	14.0

Summary:
- New processes (Methane→Ozone/H_2O) reduce NOx RF
- Appropriate consideration of methane lifetime enhance NOx RF
- EI-NOx generally increases
- Fuel consumption increases

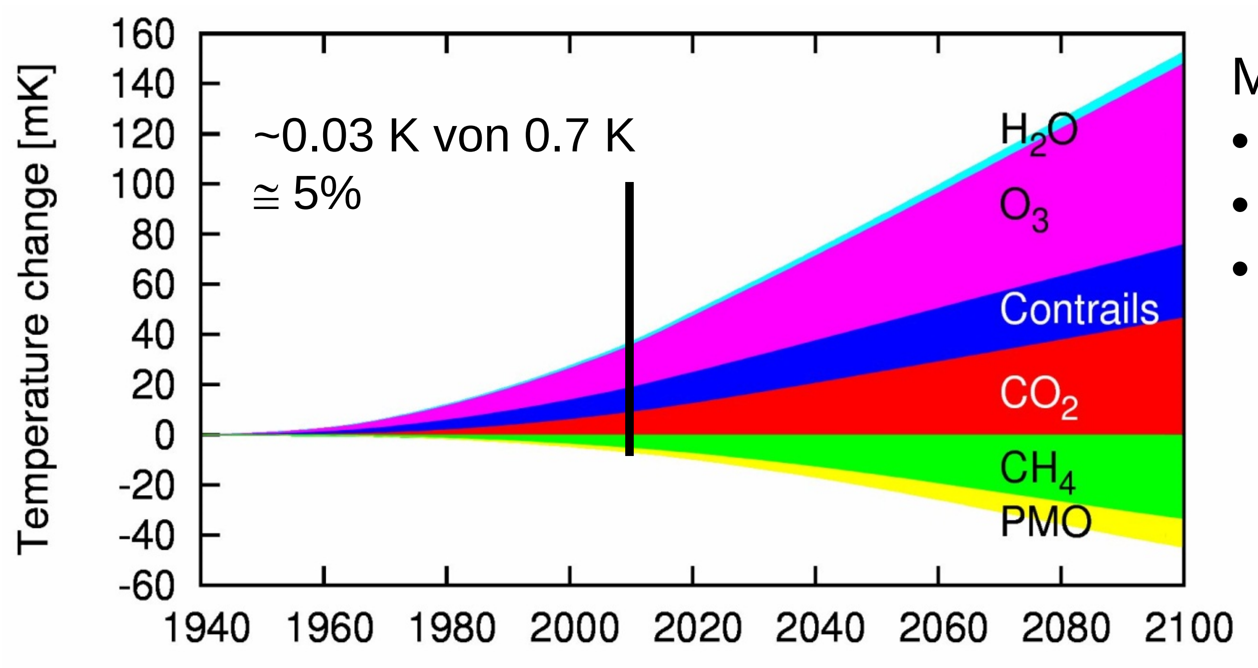
NO_x emissions are relevant

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!

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%.

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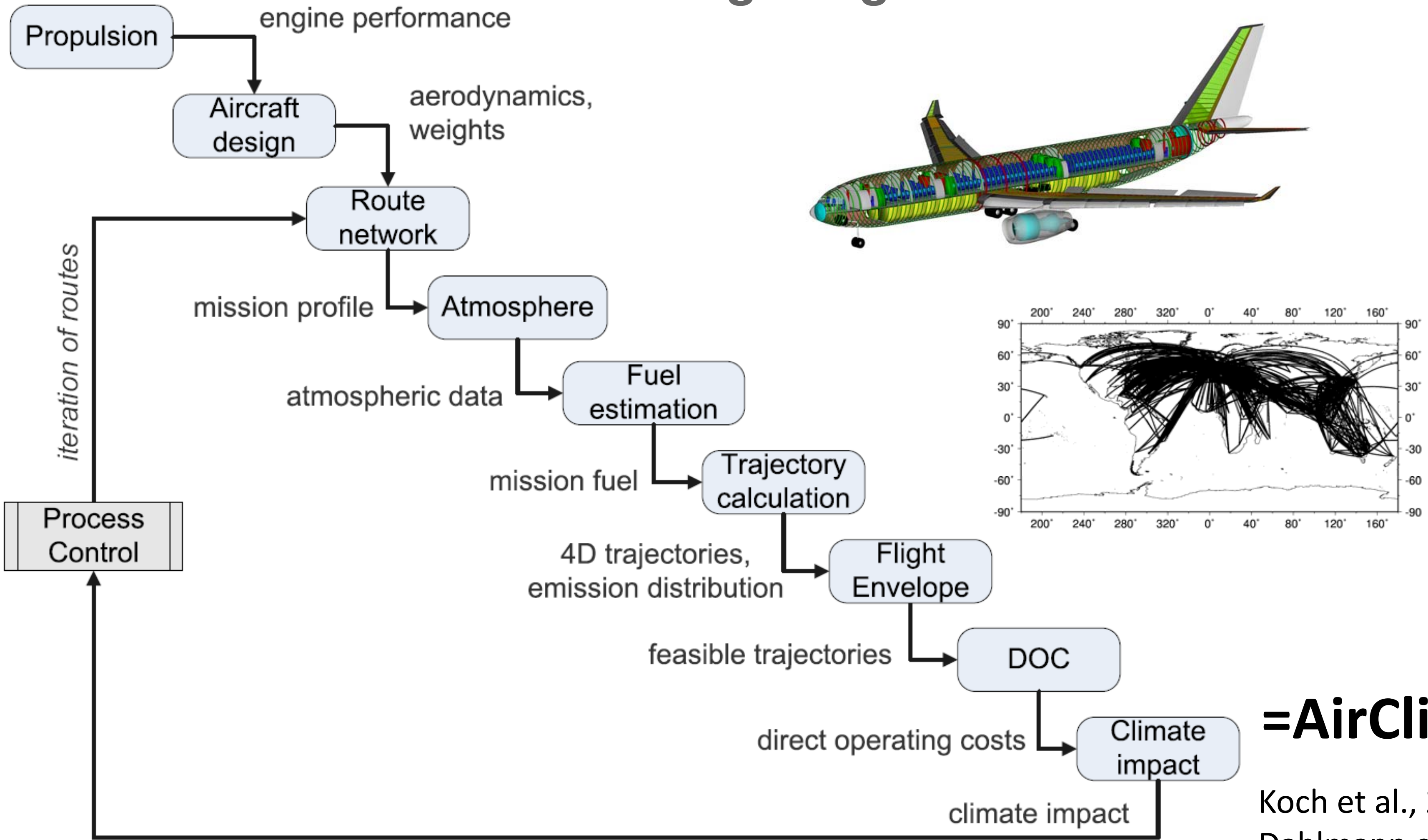
Mitigating the climate impact of aviation: Some recent studies

- **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

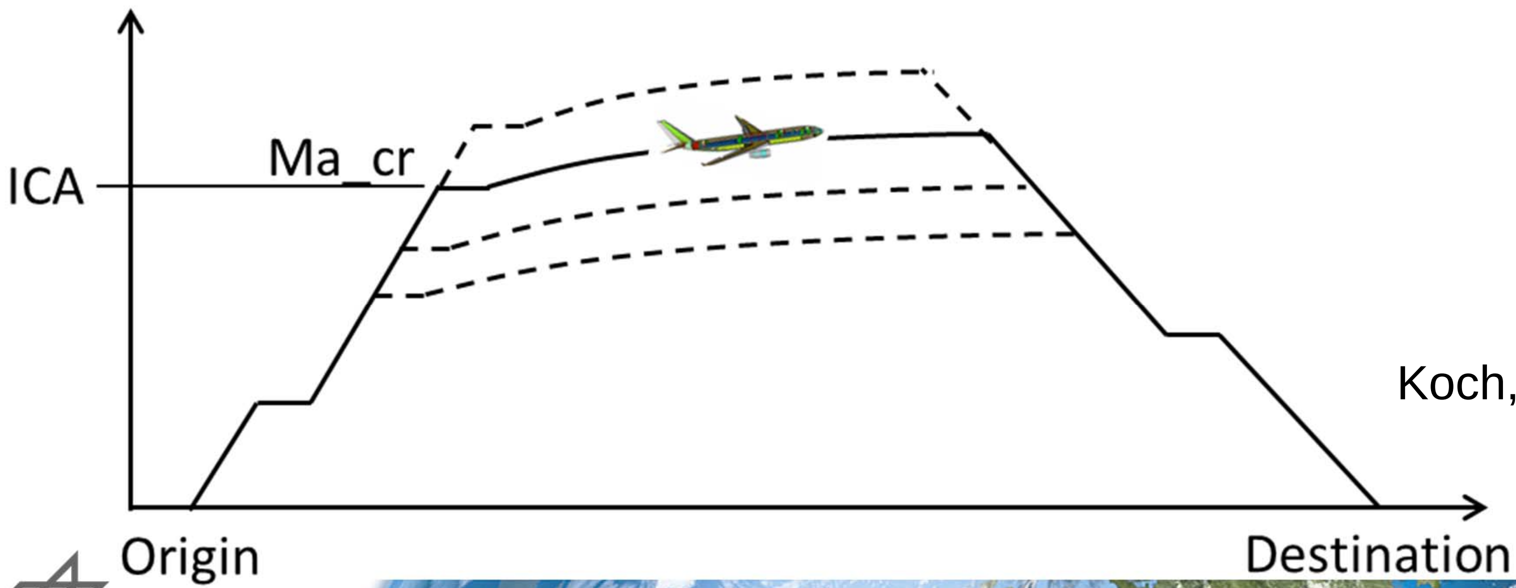


=AirClim

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**

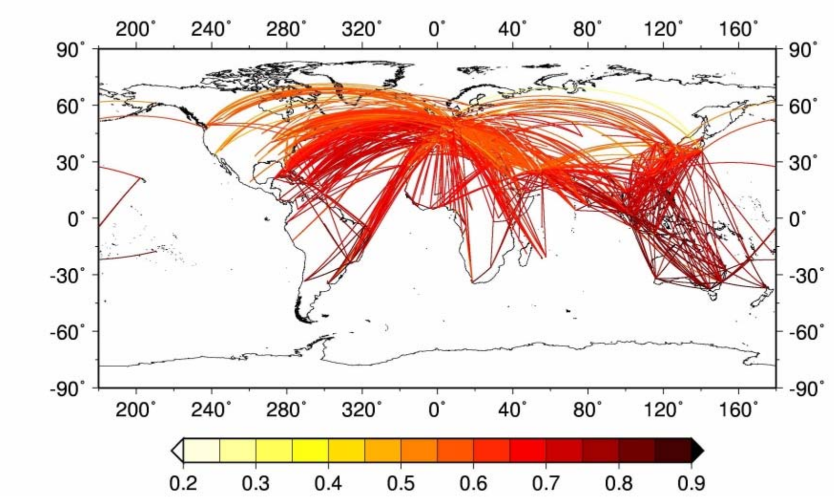


Koch, 2013

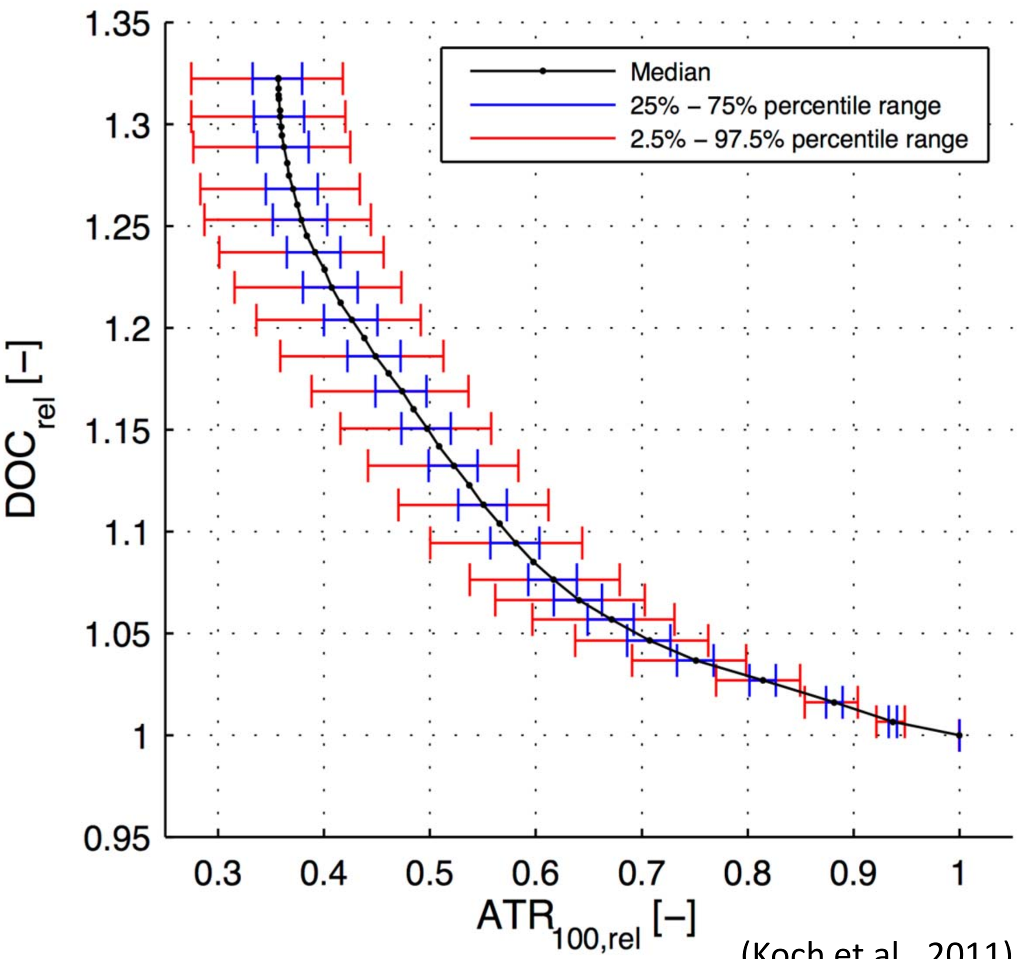
A330: Potential of a climate change reduction: CATS-results

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)



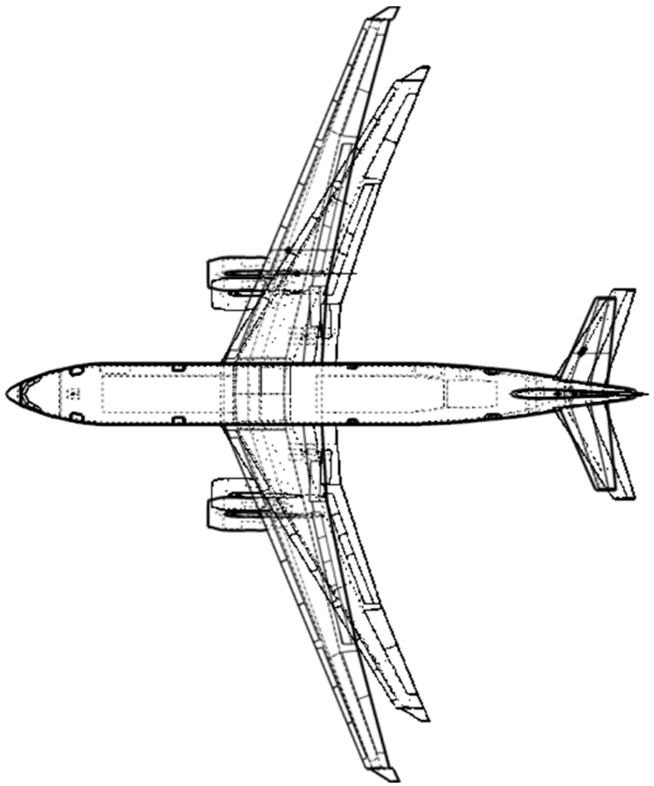
(Dahlmann, 2012)



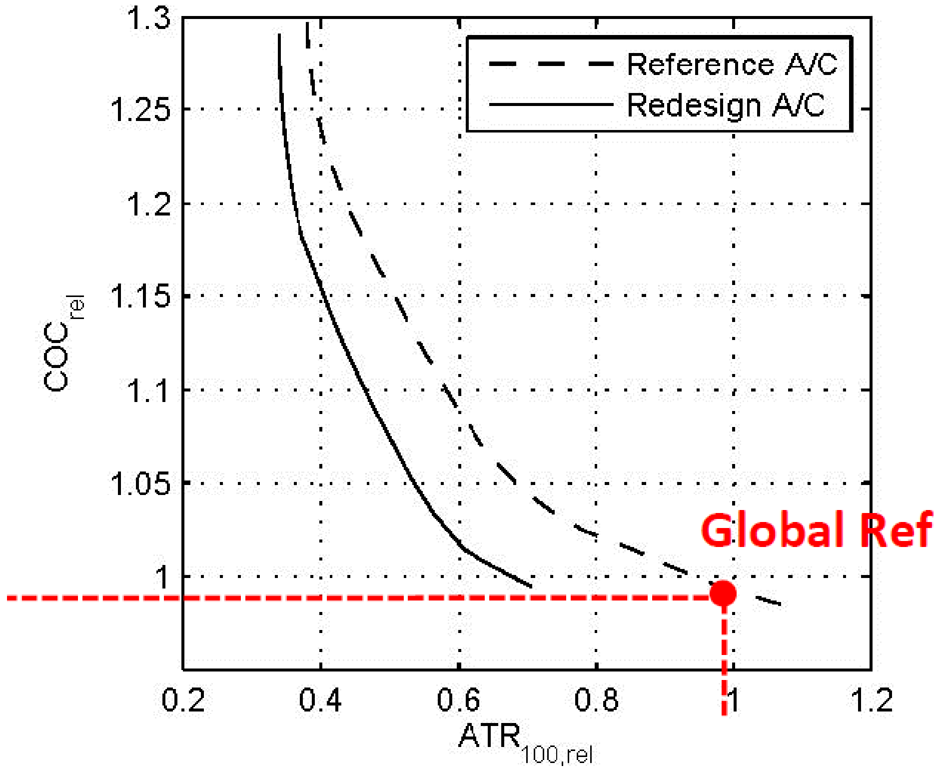
(Koch et al., 2011)

CATS Final results

Cumulative potential for all routes operated by redesigned A/C



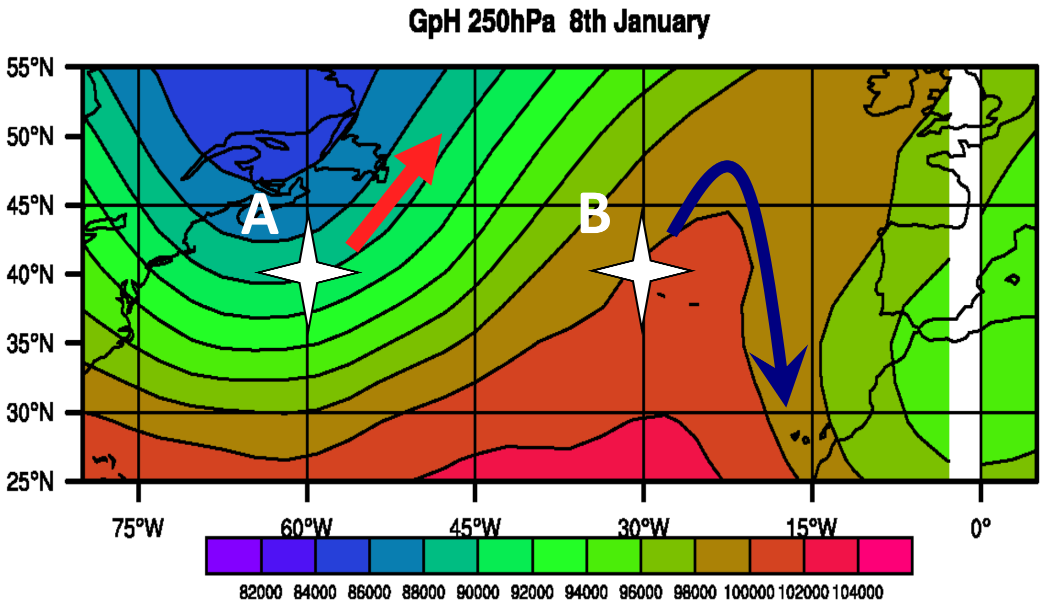
Max Mach 0.775 / Max Altitude 10500m



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

Koch (2012)

Different weather situations: Evolution of aircraft NO_x

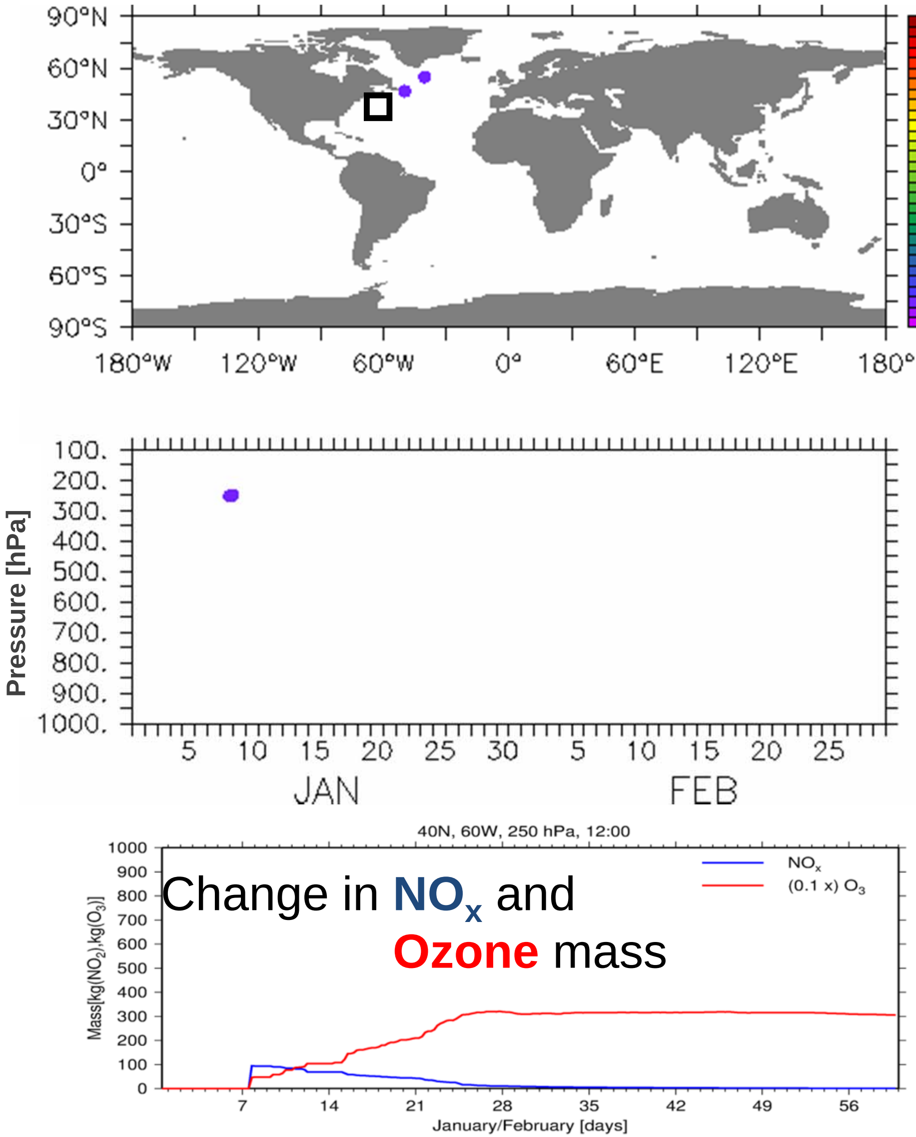


Weather type #3 "Weak and tilted jet"

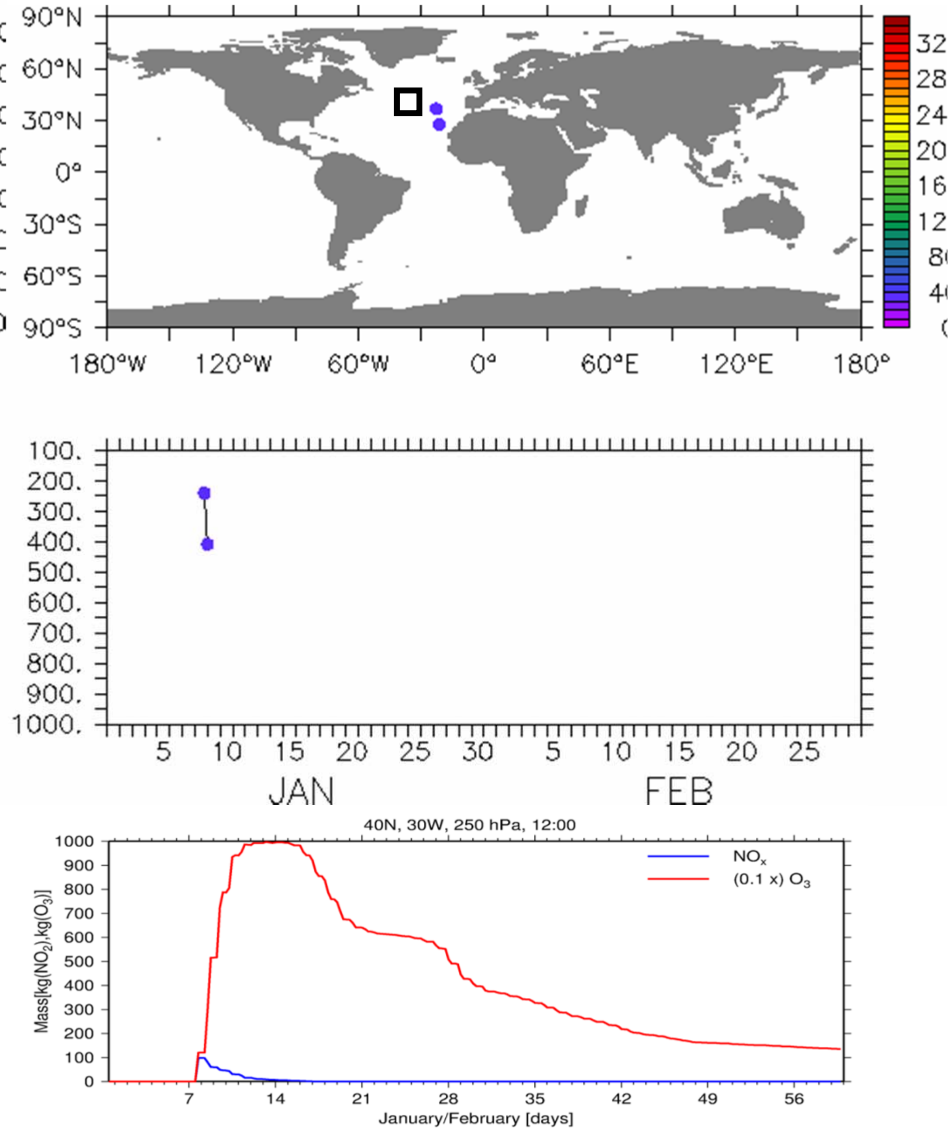
What happens if an aircraft emits NO_x at location A compared to location B?

Evolution of O_3 [ppt] following a NO_x pulse

A: 250hPa, 40°N, 60°W, 12 UTC



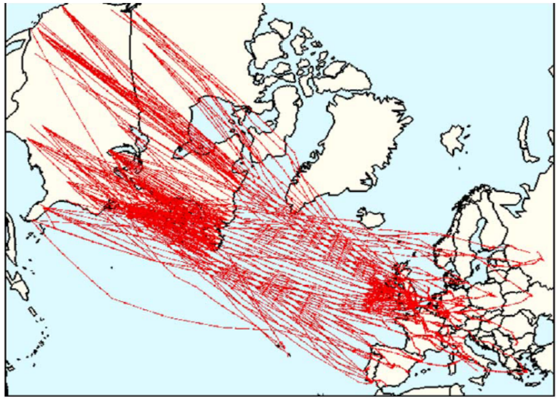
B: 250hPa, 40°N, 30°W, 12 UTC



Avoiding climate sensitive regions: The approach

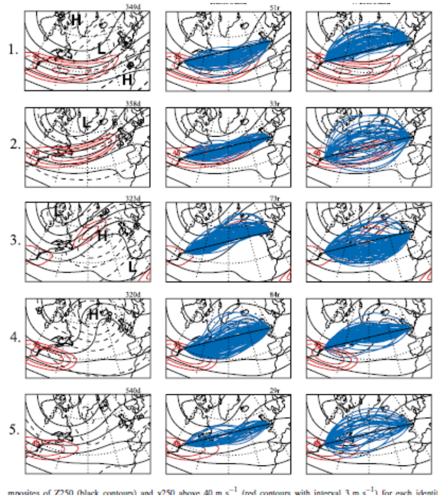
Traffic scenario:

Roughly 800 North Atlantic Flights



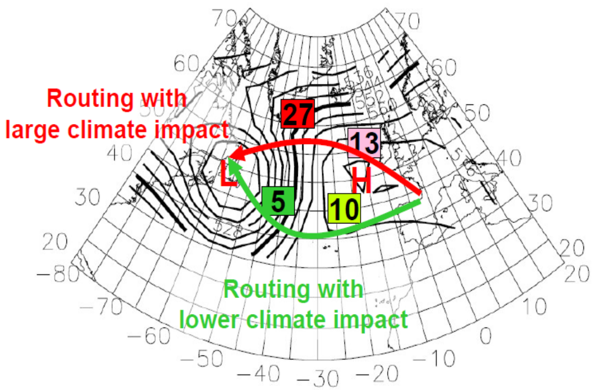
Respresentative weather situations

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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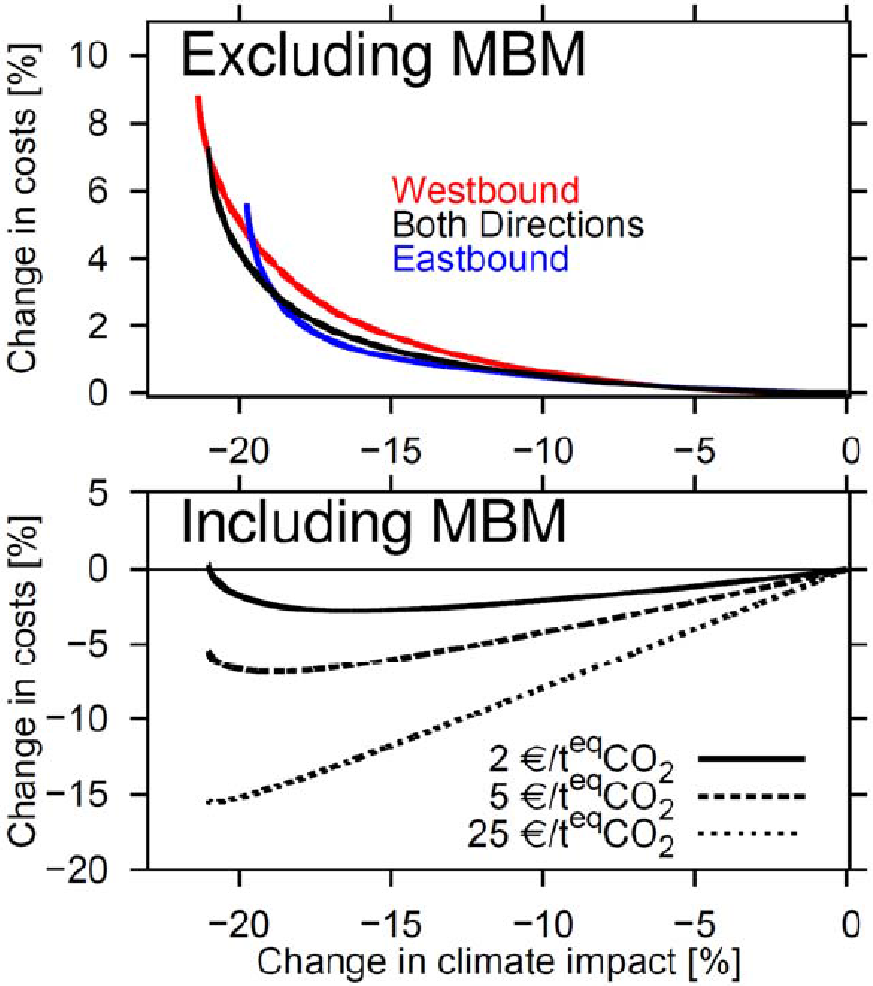
Climatology based on 8 representative weather pattern



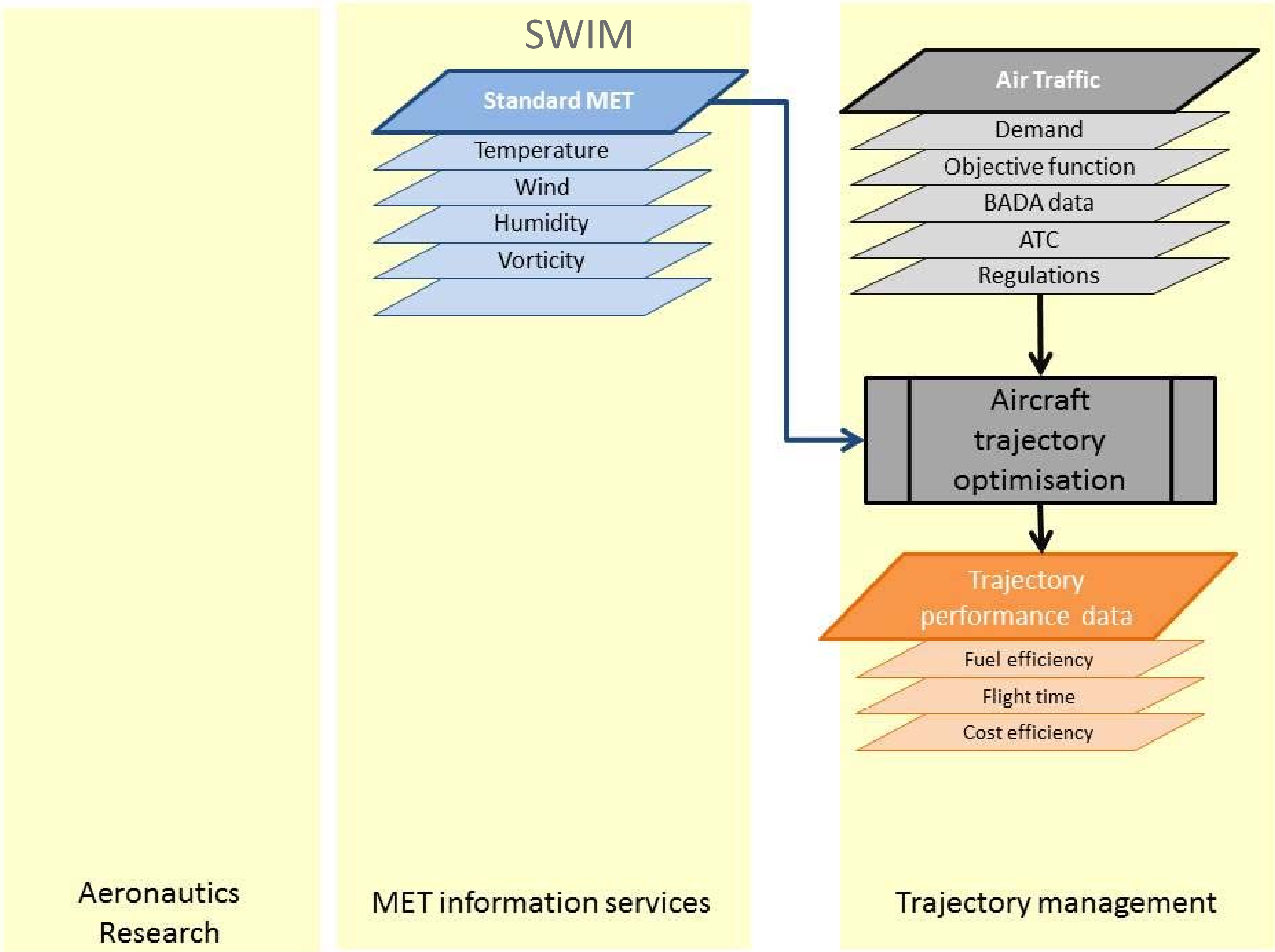
- Very flat Pareto-Front
  ⇒ Large benefits at low costs

- 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

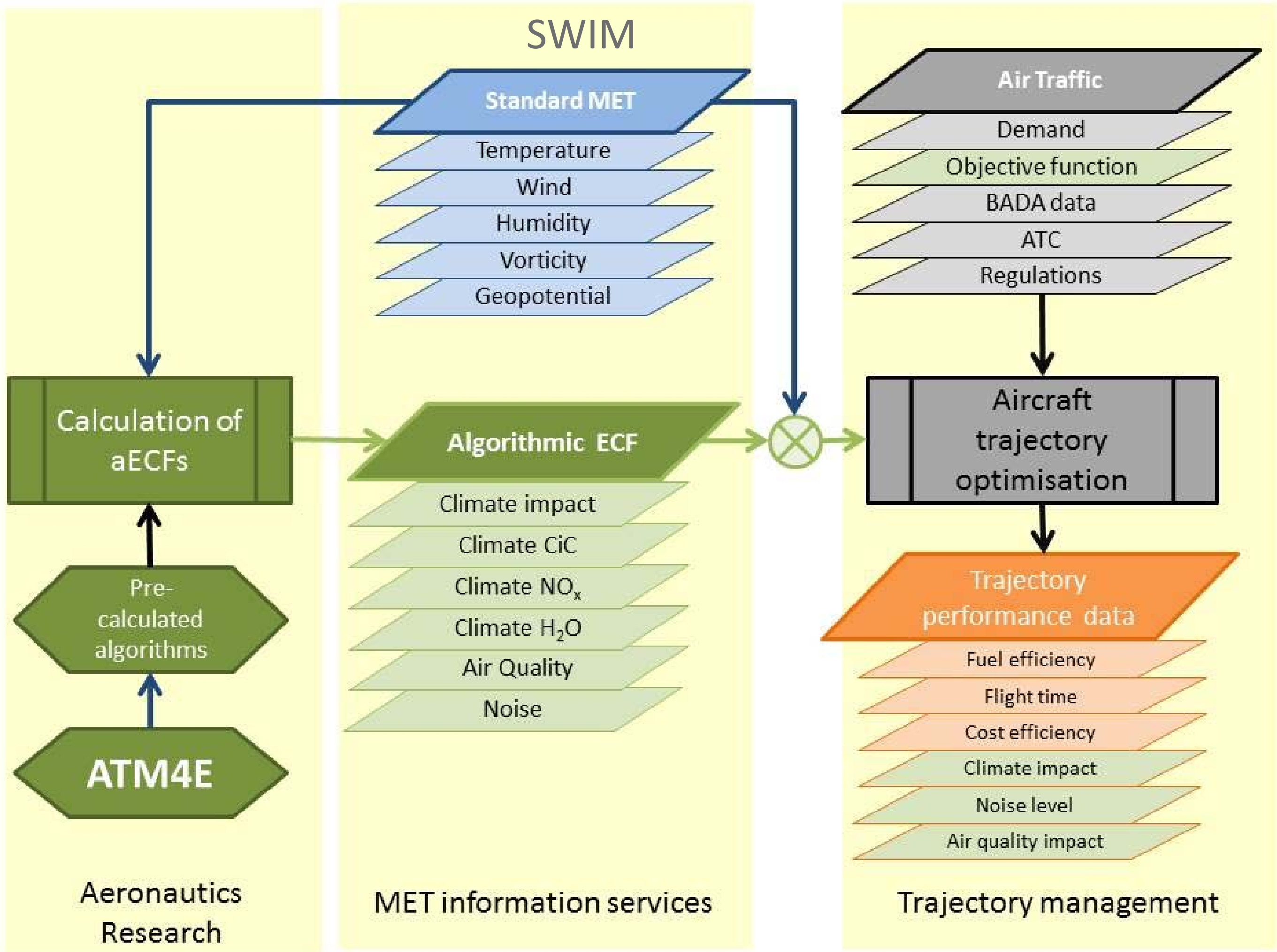
Current situation



Matthes et al. (2017)

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

Contribution of ATM4E



Matthes et al. (2017)

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,

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