Unlocking greater near-term efficiency, while transitioning to the next generation of planes
“There is no quick fix”

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Addressing non-CO₂ effects of aviation

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Air traffic emissions at cruise

Combustion products - depending on operating conditions - at cruise altitude

- $\text{H}_2\text{O}$
- $\text{CO}_2$
- $\text{NO}_x$
- $\text{CO}$
- Soot
- $\text{SO}_2$
- $\text{UHC}$

1.25 kg 3.15 kg 14 g 1 g 3.7 g 1.3 g 0.04 g

(per kg kerosene)

IPCC (1999)
Climate impacts via non-CO₂ effects

Aerosols and effects on clouds

Contrails

Air chemistry ozone methane

Popovicheva et al. (2004)
Atmospheric effects of aviation

Emissions

Changes in atmospheric composition

Climate forcings

Direct greenhouse gases

Indirect greenhouse gases

Direct aerosol effect

Clouds

Climate change

CO₂

H₂O

NOₓ

VOC, CO

SO₂

Particles

ΔCO₂

ΔH₂O

ΔCH₄

ΔO₃

ΔParticles

ΔContrails

ΔClouds

DLR.de • Chart 4 • ICSA Aviation Decarbonization Forum 12 Feb 2019 • V. Grewe • Non-CO₂ effects of Aviation
Radiative Forcing in 2005 from historical aviation emission

Carbon Dioxide, NO\textsubscript{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

\( \text{LoSU} \)
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 controls the strength 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

5 km
12 km
18 km

Isolines:
Temperature [K]

Pressure [hPa]

Marquart et al., 2002

[5 10 15 20 25]

[5]
Chemistry

Air chemistry

Produces ozone

Destroys methane
Chemical regimes for methane loss

\[ \text{NO} + \text{HO}_2 \rightarrow \text{NO}_2 + \text{OH} \]

\[ \text{O}_3 + \text{hv} \rightarrow \text{O} + \text{O}_2 \]
\[ \text{O} + \text{H}_2\text{O} \rightarrow 2 \text{OH} \]

- Ozone production
- Methane loss

\[ \text{NO}_x \]

- 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 nuclei.
  - 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

~0.03 K von 0.7 K
≈ 5%

Main contributors:
- CO$_2$
- Contrails
- NO$_x$ (O$_3$ and CH$_4$)

PMO = "Primary mode ozone"
Results from less CH$_4$
⇒ less HO$_2$ ⇒ 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

Propulsion
Aircraft design
Route network

Aircraft design
Aerodynamics, weights

Mission profile
Atmosphere

Atmosphere
Fuel estimation

Fuel estimation
Trajectory calculation

Trajectory calculation
Flight envelope

Flight envelope
4D trajectories, emission distribution

4D trajectories, emission distribution
Feasible trajectories

Feasible trajectories
DOC

DOC
Climate impact

Climate impact
Direct operating costs

Direct operating costs
Climate impact

Climate impact

=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)

(Koch et al., 2011; Dahlmann et al., 2016)
CATS Final results

Cumulative potential for all routes operated by redesigned A/C

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

Koch (2012)
What happens if an aircraft emits NO$_x$ at location A compared to location B?

Weather type #3
"Weak and tilted jet"
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

Change in NO$_x$ and Ozone mass
Avoiding climate sensitive regions: The approach

Traffic scenario:
Roughly 800 North Atlantic Flights

Representative weather situations
Climatology based on Irvine et al. (2013)

Climate-Change Functions
Contrails, O₃, CH₄, H₂O, CO₂

Traffic optimisation:
With respect to costs and climate
Climatology based on 8 representative weather pattern

- Very flat Pareto-Front  
  \[ \Rightarrow \text{Large benefits at low costs} \]

- 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

Aeronautics Research

MET information services

SWIM

Standard MET

Temperature

Wind

Humidity

Vorticity

Air Traffic

Demand

Objective function

BADA data

ATC

Regulations

Aircraft trajectory optimisation

Trajectory performance data

Fuel efficiency

Flight time

Cost efficiency

Trajectory management

Matthes et al. (2017)
Air traffic management for environment: SESAR/H2020-Project ATM4E

Contribution of ATM4E

Matthes et al. (2017)
How to use equivalent CO₂?

**Definition:**
The amount of CO₂-emission, which leads to the same climate change as the emission of 1 kg of the regarded non-CO₂ emission.

\[
eq E_{CO₂} = \left(1 + eq\ CO₂^{Cont} + eq\ CO₂^{NO_x} + eq\ CO₂^{H₂O}\right) E_{CO₂}
\]
Ways to include non-CO$_2$-effets

Accounting for non CO$_2$-effects on a flight-by-flight basis -> Conversion into eq.CO$_2$.

- **Simple Factor:** Not recommended!
  - Depending on Distance
  - Depending on Latitude
  - Depending on Altitude

- **Climatological Climate-Change Functions**
  - Clim-C CF: Quite good in a climatological manner, e.g. for aircraft design,
  - Weather-C CF: Best option, still requires significant developments

**Work in progress:** Dahlmann et al., Niklass et al.
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
CO₂-Equivalents for individual components for one long range aircraft

\[ \text{Contrails} \]

\[ \text{H}_2\text{O} \]

\[ \text{O}_3 \]

\[ \text{CH}_4 \]

\[ \text{NO}_x = \text{O}_3 + \text{CH}_4 + \text{PMO} \]

Different color coding!

Dahlmann et al. in prep
Examples for CO₂ Equivalents

**Distance depending eq. CO₂ for NOₓ**
- Long-range 2-aisle aircraft
- with a typical flight pattern (2006)
- other aircraft might look different

Dahlmann et al. (in prep)

**NOₓ–Ozone Climate Change Function**
- Such maps might be part of the weather-forecasts
- Multiplied with emissions along a flight track and accumulated
  → equivalent CO₂

Grewe et al. (2014)
Other ways to include non-CO₂-effects

Accounting for non CO₂-effects on a flight-by-flight basis → Conversion into eq.CO₂.

- Non-CO₂ effects show a complex picture
- Various possibilities to extract equivalents for non-CO₂-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.