REACT4C
Mitigation potential of flying lower or higher

Matthes, S., Lim, L., Søvde, O., Dietmüller, S., Burkhardt, U., Iachetti, D., Hendricks, J., Lee, D.S., Owen, B., Pitari, Righi, M., G., Skowron

DLR, Institut für Physik der Atmosphäre, Oberpfaffenhofen

REACT4C TEAM, EU FP7 research project
An approach for a weather-dependent climate-optimized Flight Planning to mitigate Aviation climate impact

REACT4C = Reducing Aviation Climate impact by changing trajectories for the benefit of climate (2010 - 2014)

Sigrun Matthes, DLR, IPA, Oberpfaffenhofen
REACT4C Team

European Consortium DLR, Airbus, CICERO, Universities - Aquila & Manchester & Reading, Eurocontrol and UK Met Office

Funded under EU Commission 7th Framework Programme (FP7)
Main objectives of REACT4C were to explore the feasibility of adopting flight altitudes and flight routes that lead to reduced fuel consumption and emissions, and lessen the climate impact; to estimate the overall global effect of such optimized flight routing measures in terms of climate change. Impact of CO₂, NOₓ, sulphate and black carbon aerosols and contrail-cirrus are considered.
Conceptual approach
Climate cost functions

Aviation climate impact depends on geographical location, altitude and time of aircraft. Non-CO$_2$ climate impact of aviation emissions depends on fate of emissions and strongly varies with actual atmospheric chemistry and physics. Some regions are more and some less sensitive to aviation emissions, which allows to identify climate-optimized aircraft trajectories (routes).

This requires an interface between flight planning tools and climate impact information from atmospheric chemistry-climate models.

Such an interface is established with a climate-cost function (CCF).

\[ I_C = \int_{\text{flight time}} R(s(t), t, e(t)) \, dt, \]

\[ f = w_{Cm} I_C + w_{DOC} I_{DOC} \]

Climate cost function [Matthes et al., 2012]
Aviation climate impact

Overview

Climate impact of aviation emissions

- emitted compound (direct & indirect effect)
- CO₂, black carbon (soot) - direct
- NOₓ (O₃, CH₄)
- H₂O (contrail cirrus)
- soot (AIC, aviation induced cloudiness)

• Climate impact of non-CO₂ emissions depends
  • time and position of aircraft
  • actual weather conditions (processes, transport pathways, temperature, humidity)
  • background concentrations

Matthes, Jöckel et al. 2011
Aviation induced cloudiness

Formation of line-shaped contrails, contrail-cirrus, change in size of ice particles and change in natural cirrus
Contrails spread in humid air masses, they warm or cool
Radiative forcing by Contrail Cirrus from ECHAM GCM

Burkhardt and Kärcher
Main contributors:
Contrails
\( \text{CO}_2 \)
\( \text{NO}_x \)

3.5-5.0% of warming attributed to air traffic

ACARE, 2008
The findings of the IPCC point very clearly to the need to do something but there are areas of detail where more understanding is needed.

Lee et al., 2010
updated with Burkhardt & Kärcher, 2011
CARIBIC - Civil Aircraft for the regular investigation of the atmosphere based on an instrument container
**S4D module in nudged simulation**

Aircraft Measurements Intercomparison

- Module s4d allows to generate user defined data set along flight trajectory
- Aircraft measurement of scheduled air traffic is analysed (MOZAIC, CARIBIC)
- QCTM study quantifies aviation contribution to atmospheric concentrations on tracks
- Perturbation signal in NO\textsubscript{x} from aviation amounts to up to 30% on aircraft flight trajectories and varies for two weather pattern (strong zonal vs. confined jet)
Mitigation of Aviation Impact by flying lower or higher

Nitrogen oxide emissions (direct / indirect) water vapour emissions, aerosols sulfate and black carbon, contrail and contrail-cirrus
REACT4C Mitigation studies
Flying lower and flying higher

- **Mitigation option**
  - Mitigation options cause changes in total amount of emission and their spatial distribution

- **Assessment of mitigation potential by estimating changes in RF**
  - Methods are required which provide a robust measure and metric

- **Generation of scenarios flying higher and flying lower**
  - Alternative emission scenario (FAST, provided by MMU)
  - Set of state-of-the-art global atmosphere-climate models investigate changing atmospheric impact and climate impact of alternative routing
Modelling intercomparison: Weather pattern analysis

Variability aviation ozone

Aviation ozone perturbation (July)

- Five **models** participating
- Updated (mitigation) **a/c emission inventory**, identical emission sets
- Harmonised parameterisations (e.g. lightning NO$_x$)
- Additional **diagnostics** (ozone production rates – diagtrac (ozone production & destruction channels))
Aviation climate impact - NOx

- Detailed study on atmospheric impact of nitrogen oxide emissions (NO\textsubscript{X}) and inventories
- Short term ozone & long-term CH\textsubscript{4} & O\textsubscript{3}
- Multi-model estimate for uncertainty analysis
- Five CTM models participating for evaluating

<table>
<thead>
<tr>
<th></th>
<th>Net [mW/m\textsuperscript{2}]</th>
<th>Range [mW/m\textsuperscript{2}]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>O\textsubscript{3} short – CH\textsubscript{4}</td>
<td>10.5</td>
<td>19.2/-8.7</td>
<td>this study</td>
</tr>
<tr>
<td>CTM2</td>
<td>12.1</td>
<td>21.1/-9.0</td>
<td></td>
</tr>
<tr>
<td>CTM3</td>
<td>13.0</td>
<td>22.4/-9.4</td>
<td></td>
</tr>
<tr>
<td>EMAC2</td>
<td>7.8</td>
<td>18.5/-10.7</td>
<td></td>
</tr>
<tr>
<td>ULAQ</td>
<td>10.2</td>
<td>17.4/-7.2</td>
<td></td>
</tr>
<tr>
<td>MOZART</td>
<td>9.3</td>
<td>16.1/-7.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>14.0</td>
<td>24.8/-10.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-1.9 – 24.0</td>
<td>Olsen et al., 2013</td>
<td></td>
</tr>
</tbody>
</table>

| Long term O\textsubscript{3} | -4.34 | -5.4 – -3.6 | this study |
|                            | -6.6  | -17.0 – -1.9 | Holmes et al., 2011 |

| O\textsubscript{3} s+PM +CH\textsubscript{4} | 6.1  | 2.4 – 8.3 | this study |
|                                            | 4.5  | -1.8 – 12.0 | Holmes et al., 2011 |

- REACT4C Basecase 2006 (Inventory)
- Multi-model mean 6.1 mW/m\textsuperscript{2} (O\textsubscript{3}s, CH\textsubscript{4}, PMO)
- Holmes et al., 2011 results correspond well
- Olsen et al., 2013 present considerable higher O\textsubscript{3}s
Mitigation of aviation NO\textsubscript{x} impact

- **Mitigation options**
  - Aviation aims to reduce its climate impact and investigates mitigation options
  - Mitigation options cause changes in emission and their spatial distribution

- **Assessment of mitigation options**
  - Methods are required which provide a robust measure and metric

- **Case study on aviation NO\textsubscript{x} emissions**
  - Set of chemistry-transport-models (chemistry-climate) provides estimates
  - In Olson et al., 2013 scenario is not robust with a “mitigation” from -48.5 to 8.9 mW/m\textsuperscript{2}
  - REACT4C: Assessment of mitigation options are robust (Sovde et al., 2013)

### Mitigation cases

<table>
<thead>
<tr>
<th>Mitigation cases</th>
<th>O\textsubscript{3}</th>
<th>CH\textsubscript{4}</th>
<th>O\textsubscript{3} s + CH\textsubscript{4}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flying higher</td>
<td>1.5 (0.3-2.8)</td>
<td>0.1 (0.1-0.2)</td>
<td>1.6 (0.5-2.8)</td>
</tr>
<tr>
<td>Flying lower</td>
<td>-1.3 –(2.2-0.5)</td>
<td>-0.2 –(2.2-0.5)</td>
<td>-1.5 –(2.3-0.6)</td>
</tr>
</tbody>
</table>
Radiative forcing of alternative routing
Nitrogen oxide emissions (direct / indirect) water vapour emissions, aerosols sulfate and black carbon, contrail and contrail-cirrus

Result from Multi-model study involving nine atmospheric models [Figure L. Lim]
Mitigation potential of alternative routing
Radiative Forcing

• Results from multi-model study show
  • “flying higher” reduces CO$_2$ impact, but increases non-CO$_2$ climate impacts,
  • “flying lower” increases CO$_2$ impact but reduces climate impact of non-CO$_2$ impacts at the same time.

Result from Multi-model study involving nine atmospheric models
Summary & Conclusion

- **Aviation climate impact of alternative routing**
  - Alternative emission scenarios used to calculate climate impacts of aviation with set of state-of-the-art **models**
  - Climate impact of CO2 and non-CO2 impacts have opposite sign, resulting in non-CO2 representing a trade-off on CO2 benefits when flying higher.
  - Emission scenario was constructed as generic mitigation strategy, which means e.g. routing strategy was not adapted to synoptical situation

- **Quantitative estimates of mitigation potential of alternative flight altitudes were provided for nitrogen oxides, water vapour, soot and sulfate aerosol, contrail and contrail cirrus was quantified**

- **Assessment of aviation climate impact:**
  - Results show need for comprehensive assessments of mitigation strategies to evaluate individual effects, their uncertainty and trade-offs
    - Which processes dominates **overall climate impact**?
    - Which effects to be studied with **mitigation options**?
Thank you
Assessment of climate metrics

- CO₂ (and other "Kyoto" gases) can easily be included in an emission trading scheme.

- Large uncertainty exists with respect to the climate impact of non-CO₂ emissions from aviation.

- In general, radiative forcing at a certain time is no good measure for the expected climate change. Therefore, the RFI is not suitable for emission trading.

- Multiplying CO₂ emissions by any simple multiplication factor would weaken incentives to reduce the total climate impact beyond a reduction of the fuel consumption.

- Eventually, it might become possible to include non-CO₂ effects by their individual contributions to climate change.

- Often emissions have further effects beyond climate change, e.g., impact on air quality (trade-offs & interdependencies).
Alternative metrics
Temperature perturbation of sustained emissions

- Changing cruise altitude changes the radiative forcings and our results suggest that in a sustained emission scenario, contrail cirrus have a larger impact on temperature than does the change in CO$_2$ due to fuel changes. Also changes originating from NO$_x$ are larger than the CO$_2$ changes.

- However, the total temperature change for sustained BASE emissions is about 0.07 K after 100 years of emissions, so the overall temperature reduction when flying lower is less than 10%. Flying higher gives less than 5% increase in temperature after 100 years compared to the base case.
Variations of aviation impact on atmospheric ozone in North Atlantic weather patterns (QCTM)

- Climate-optimal trajectories are taking advantage of spatial variation of atmospheric response to aircraft emissions

QCTM EMAC2 study to investigate relationship between atmospheric response and weather pattern

Weather pattern analysis performed in EMAC

Pattern probability is evaluated vs. ERA (more or less reproduced) (Irvine et al.)

Perturbation signal $O_3$ and $NO_x$ shown for two weather pattern (strong zonal vs. confined jet)

Aviation induced concentration change ($O_3$ & $NO_x$)
### Inventories

<table>
<thead>
<tr>
<th></th>
<th>absolute amounts</th>
<th>relative changes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel [Tg C]</td>
<td>CO₂</td>
</tr>
<tr>
<td>Base Case</td>
<td>178.3</td>
<td>563.4</td>
</tr>
<tr>
<td>Minus 2000 ft flying lower</td>
<td>180.7</td>
<td>571.0</td>
</tr>
<tr>
<td>Plus 2000 flying higher ft</td>
<td>176.8</td>
<td>2.35</td>
</tr>
</tbody>
</table>

Perturbations of the altitudes flown up by 2000ft and down by 2000ft show an increase in fuel usage for the lower altitude flying (by about 1.3%) and a very small increase in flying 2000ft above the determined flight altitudes in the base case inventory. The perturbations from REACT4C and TradeOff are shown in Table 3.

*Table 1: Comparison of Base Case and mitigation cases flying lower (minus 2000 ft) and flying higher (plus 2000 ft) from REACT4C project, annual fuel consumption.*

A small increase (1.3%) in fuel use is shown for the minus 2000ft case when compared with the Base Case. Conversely a very small decrease (-0.8%) in fuel use is shown for the plus 2000ft case. This pattern is to be expected as generally the fuel efficiency increases with higher altitude although in reality there is a complex array of factors including aircraft weight determining the optimum altitude.
Climate cost functions

used as interface between atmospheric modelling and flight planning
Aviation climate impact – short lived ozone and long-lived methane effect

- Contribution of aviation to total ozone induces a short-lived effect
- Associated change in OH induces a long-lived methane effect

<table>
<thead>
<tr>
<th>Effect</th>
<th>Net [mW/m2]</th>
<th>SW</th>
<th>LW</th>
<th>Change „higher“</th>
<th>Change „lower“</th>
</tr>
</thead>
<tbody>
<tr>
<td>O3 short</td>
<td>16.4 / 22.4</td>
<td>3.5 / 5.3</td>
<td>12.9 / 17.1</td>
<td>0.5 / 2.9</td>
<td>-2.4 / -0.6</td>
</tr>
<tr>
<td>CH4</td>
<td>-10.7 / -7.1</td>
<td>0.1 / 0.2</td>
<td>-0.4 / -0.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Workplan Structure

Meteorology

WP 1: Definition of case studies (UREAD)
- Meteorological data
- Archetype situations

WP 2: Climate cost functions (DLR-IPA)
- Climate Cost Functions

WP 3: Environmental flight planning (EEC)
- Optimising:
  1. Flight distance
  2. Fuel consumption
  3. Emissions
  4. Climate impact

WP 4: Evaluation of mitigation effort
- Including uncertainties (CICERO)
- Optimal trajectories, emissions, radiative forcing, climate impact

WP 5: Simplified mitigation studies (MMU)

WP 6: Green aircraft
- Airbus
- Airframe
- Engine

WP 7: Recommendations for future flight concepts (DLR-IFL)
- Practical rules
- Gaps, obstacles

Modelling Chain

Mitigation Estimates

Coordination & Exploitation (DLR-IPA)

Requirements

ARAM Konference, 7-10 Jan 2013

TAC3, Prien, 2012 - Climate optimized flight planning

Sigrun Matthes, DLR et al.
Effect | Net [mW/m²] | SW | LW
--- | --- | --- | ---
O3 short | 16.4-22.4 | 18.5 | 4.5 | 12.9-17.1 | 14.0
CH4 | -10.7 / -7.1 | -10.7 | | |
O3 PMO | -5.4 / -3.6 | -5.4 | | |
H2O | -1.6 / -1.1 | | | |
Variations of impact of aviation emissions in North Atlantic weather patterns (QCTM)

• Climate-optimal trajectories are taking advantage of spatial variation of atmospheric response to aircraft emissions

Weather Pattern 1
Strong (EA pos)

Weather Pattern 4
Confined (NAO neg)

Geopotential height [m]

• QCTM EMAC2 study to investigate relationship between atmospheric response and weather pattern

• Weather pattern analysis performed in EMAC

• Pattern probability is evaluated vs. ERA (Irvine et al.)

• Perturbation signal O₃ and NOₓ shown for two weather pattern (strong zonal vs. confined jet)

Aviation induced concentration change (O₃ & NOₓ)