Verification of the ozone algorithmic climate change functions for predicting the short-term NOx effects from aviation en-route

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Overview

• Motivation

• Algorithmic based climate change functions (aCCF$s$)

• Verification of the aCCF$s$

• Summary
Aviation climate impact

Climate impact of aviation emissions are both direct & indirect:

- Carbon Dioxides (CO₂)
- Nitrogen Oxides (NOx-O₃, NOx-CH₄)
- Contrail cirrus and H₂O

Climate impact of non-CO₂ emissions depends on:

- Time and flight location of aircraft
- Actual weather conditions (temperature, humidity, transport pathways)
- Background concentrations

Grewe et al., 2017, updating Lee et al., 2010 (IPCC)
Lagrangian Approach: Example evolution of $O_3$ [ppt] for a single trajectory at 2 locations (following a $NO_x$ emission pulse)

A: 250hPa, 40 N, 60W, 12 UTC

B: 250hPa, 40 N, 30W, 12 UTC

Frömming et al.
Climate-optimized trajectories

- The dependency of climate impact from aviation non-CO₂ effects on time, geographical location, altitude and weather condition provides operational measures to reduce aviation climate impact.

- Currently, during flight planning emission information is available, but no climate impact information is available.

- Climate change functions (CCFs) is such a concept to provide an interface between flight planning tools and climate impact information from atmospheric chemistry-climate models.

Fig. : Schematic of operational measures to avoid climate sensitive regions
Generation of the original climate change functions (CCFs)

- Detailed methodology of CCFs generation is described in Grewe et al., Geosci Mod Dev 2014 (10.5194/gmd-7-175-2014)

- Climate metrics are generated by following emissions from 500 points on a so-called time-region grid, and then these are interpolated to a finer resolution CCFs.

Table 2. Definition of the time-region grid.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Number</th>
<th>Unit</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitude</td>
<td>6</td>
<td>° W</td>
<td>75, 60, 45, 30, 15, 0</td>
</tr>
<tr>
<td>Latitude</td>
<td>7</td>
<td>° N</td>
<td>30, 35, 40, 45, 50, 60, 80</td>
</tr>
<tr>
<td>Pressure</td>
<td>4</td>
<td>hPa</td>
<td>400, 300, 250, 200</td>
</tr>
<tr>
<td>Time</td>
<td>3</td>
<td>UTC</td>
<td>6, 12, 18</td>
</tr>
</tbody>
</table>
Original CCFs for a single day representing winter weather pattern

- Global climate effect (here the average temperature response over 20 years) for emissions at a given location, for flights at 200 hPa (about FL380) and 12 UTC
- The figure shows the climate effect for contrails (warming and cooling) and the effect of NOx emissions on ozone (warming), and methane (cooling) and the total NOx effect (warming and cooling)
- Producing such results requires a formidable amount of computation!
- We need a “short-cut” to derive (and then verify) reliable algorithmic CCFs for real situations

Grewe et al., 2014, Atmos. Env., 10.1016/j.atmosenv.2014.05.059
From original CCFs to algorithmic CCFs

- **REACT4C**
  - Original CCFs

- Weather data at the time of emission

- Preselection of most promising candidates

- Correlation analysis

- Analysis of the candidate correlations wrt.
  - Residuals, accuracy, physical meaning, simplicity for use

- Final ATM4E algorithmic CCFs
\[ aCCFs_{NOx-O3}(T, geopot) = \begin{cases} ATR20_{NOx-O3} \\ 0 \end{cases} \]

for \( aCCFs_{NOx-O3}(T, geopot) > 0 \)

where:

- \( ATR20_{NOx-O3} = -5.2 \cdot 10^{-11} + 2.3 \cdot 10^{-13} \cdot T + 4.85 \cdot 10^{-16} \cdot geopot - 2.04 \cdot 10^{-18} \cdot T \cdot geopot \)

- T is temperature in Kelvin

- Geopot is geopotential in \( m^2/s^2 \)

NOx-Methane algorithmic climate change functions

\[
\begin{cases}
    aCCF_{NOx-CH4}(F, \text{geopot}) = ATR20_{NOx-CH4} \\
    0
\end{cases}
\]

\[
\begin{cases}
    aCCF_{NOx-CH4}(F, \text{geopot}) < 0 \\
    \text{else}
\end{cases}
\]

Where:

- \( ATR20_{NOx-CH4} = -9.83 \cdot 10^{-13} + 1.99 \cdot 10^{-18} \cdot \text{geopot} - 6.32 \cdot 10^{-16} \cdot F + 6.12 \cdot 10^{-21} \cdot F \cdot \text{geopot} \)

- \( F \) is the incoming solar radiation at the top of the atmosphere as a maximum value over all longitudes in \( W/m^2 \)
- \( F = S \cos(\theta) \), with
- \( S \) is the total solar irradiance of 1360 Wm-2, \( \theta \) is the solar zenith angle.

Implementation of aCCFs in Earth System Model (EMAC)

- The aCCFs are implemented in the Earth-system Model (EMAC) as a sub model (ACCF)

- The aCCFs can be easily implemented as advanced MET service
Verification of the algorithmic climate change functions

To verify the climatology of the ozone aCCFs

To verify the effectiveness of the ozone aCCFs to reduce the climate impact caused by NOx-O\textsubscript{3} from a subset of European flights on the daily basis

An Earth-System Model which includes climate impact information, routings and optimisation options is basis for the verification

EMAC/AirTraf
EMAC/ACCF
### NO$_x$-O$_3$ aCCFs climatology verification

<table>
<thead>
<tr>
<th>Options</th>
<th>Set up</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMAC Resolution</td>
<td>T42/L31ECMWF (2.8° longitude × 2.8° latitude)</td>
</tr>
<tr>
<td></td>
<td>Altitude up to 10 hPa (about 30km)</td>
</tr>
<tr>
<td></td>
<td>Time step (12 mins)</td>
</tr>
<tr>
<td>Simulation period</td>
<td>1 year simulation</td>
</tr>
<tr>
<td>Models</td>
<td>ACCF sub model coupled with EMAC</td>
</tr>
</tbody>
</table>
The NOx-O₃ effects increase towards the lower latitude. The NOx-O₃ effects increase towards the higher altitude. The variation pattern of the ozone aCCFs shows agreement with the literature within the northern hemisphere: vertical range 9 km to 12 km; latitude between 30° N and 90° N.
Closure experiments on NO$_x$-O$_3$ effects from ozone aCCFMs
Overall structure of Air Traffic Simulator (AirTraf)

Yamashita et al., ATM seminar, 2015.
AirTraf trajectory optimization

- 11 design variables: 6 lateral, 5 vertical
- Genetic algorithm

Yamashita et al, GMD, 2017
Tagging chemistry in EMAC

- Ten chemical species and families are tagged: O₃, CO, NOy, OH, etc.
- Ten emission sources: natural emissions (e.g., lightening) and anthropogenic emissions (e.g. road, ship, industry, air traffic, ....below example for NOx concentration by Road and Ship NOx emissions)
- Online emission calculation: AirTraf
- Model details: Grewe, et al. GMD, 2017
Radiative forcing calculation

- Calculate the amount of long- and short- wave radiation travelling through the atmosphere
- Taking into account the changes induced by clouds, aerosols, albedo, and greenhouse gases (both natural and anthropogenic emissions)
- Analyse the difference in radiation when the ozone produced by the AirTraf emissions is subtracted.

Models details provided in Dietmüller et al., GMD, 2016
# Trajectory optimization setup

<table>
<thead>
<tr>
<th>AirTraf Options</th>
<th>Cost optimal</th>
<th>Clime optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMAC Resolution</td>
<td>T42/L31ECMWF (2.8° longitude × 2.8° latitude)</td>
<td>Altitude up to 10 hPa (about 30km)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Time step (12 mins)</td>
</tr>
<tr>
<td>Waypoints</td>
<td></td>
<td>101</td>
</tr>
<tr>
<td>Flight plan</td>
<td></td>
<td>85 European flights</td>
</tr>
<tr>
<td>Simulation period</td>
<td></td>
<td>3 months</td>
</tr>
<tr>
<td>Aircraft/Engine type</td>
<td></td>
<td>One type aircraft/engine model</td>
</tr>
<tr>
<td>EI H2O [g/kg(fuel)]</td>
<td></td>
<td>1230 (IPCC 1999)</td>
</tr>
<tr>
<td>EI NOx [g/kg(fuel)]</td>
<td>DLR fuel method + BADA 3.9</td>
<td></td>
</tr>
<tr>
<td>Mach number</td>
<td>0.82</td>
<td></td>
</tr>
<tr>
<td>Flight altitude</td>
<td>[FL290, FL410]</td>
<td></td>
</tr>
<tr>
<td>Optimization objective</td>
<td>Cost (time and fuel related)</td>
<td>Ozone ATR20</td>
</tr>
<tr>
<td>Optimization approach</td>
<td>Genetic algorithm</td>
<td></td>
</tr>
</tbody>
</table>
Cost and NOx-O₃ optimized traffic flow over Europe
Performance of the cost-optimal and climate optimal flights

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Cost optimal</th>
<th>NOx-O₃ optimal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel consumption [Tons]</td>
<td>728</td>
<td>810</td>
</tr>
<tr>
<td>NOₓ emissions [Tons]</td>
<td>7.26</td>
<td>8.33</td>
</tr>
<tr>
<td>Flight time [hrs]</td>
<td>157</td>
<td>156</td>
</tr>
<tr>
<td>Flight distance [km]</td>
<td>134000</td>
<td>134346</td>
</tr>
<tr>
<td>Cost [k€]</td>
<td>636.56</td>
<td>667.76</td>
</tr>
</tbody>
</table>
Closure experiments on $NO_x-O_3$ effects from ozone aCCFs

- AirTraf NOx emission induced NOy concentrations changes compared for climate-optimal versus cost-optimal trajectory optimization.

- Climate optimal flights emit NOx emission at lower altitude than the cost optimal flights.

- The increase in NOy at lower altitude is less than the reduction at higher altitude due to faster wash out.
Closure experiments on $NO_x$-$O_3$ effects from ozone aCCFs

- AirTraf NOx emission induced O$_3$ concentrations changes compared for climate-optimal versus cost-optimal trajectory optimization
- Largely reduced ozone concentrations at higher altitude
- The radiative forcing calculation shows 2.2% reduced climate impact
• The aCCFs can be implemented easily in different weather/climate model system as an advanced-MET service.

• The variations pattern of the ozone aCCFs shows the agreement with the literature within the northern hemisphere flight corridor: i.e., the vertical range of about 9km to 12 km and the latitude between 30° N and 90° N.

• The NOx-O3 effects from aCCFs are verified by using sophisticated chemistry. The trajectories optimized using ozone aCCFs reduce the ozone climate impact
Thank you!