Eco-efficient Flight Trajectory Exploration by Using the Chemistry-climate Model EMAC

Hiroshi Yamashita and Bastian Kern
Institute of Atmospheric Physics, German Aerospace Center (DLR)
DLR at a glance

- Research institution
- Space Administration
- Project Management Agency
Locations and employees

More than 9000 employees work in 54 institutes and facilities at 30 sites across Germany.

International offices in Brussels, Paris, Tokyo and Washington D.C.
National and international networking

**Clients and partners:** Governments and ministries, agencies and organisations, industry and business, science and research

### Worldwide

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<tr>
<th>Country</th>
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<tr>
<td>Germany</td>
<td>DLR</td>
<td>Deutsches Zentrum für Luft- und Raumfahrt</td>
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<tr>
<td>Europe</td>
<td>EADS</td>
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### Germany

- Helmholtz Gemeinschaft
- Bundesministerium für Bildung und Forschung
- Bundesministerium für Wirtschaft und Energie
- Bundesministerium der Verteidigung
- Siemens
- Diehl
- OHB
- Airbus
- LIEBHERR
Areas of research:

- Aeronautics
- Space research and technology
- Transport
- Energy
- Security (cross-sectoral area)
- Digitalisation (cross-sectoral area)
DLR Oberpfaffenhofen

Employees: 1,959
Area: 249,508 m²
Research institutes and facilities:
• Microwaves and Radar Institute
• Institute of Communications and Navigation
• Remote Sensing Technology Institute
• Institute of Atmospheric Physics
• Institute of Robotics and Mechatronics
• Institute of System Dynamics and Control
• German Remote Sensing Data Center
• Flight Experiments Facility
• Complex Plasmas Research Group
• Space Operations and Astronaut Training
• Galileo Control Centre
The DLR Institute of Atmospheric Physics

Physics and chemistry of the global atmosphere: 0-120 km altitude

Socially relevant issues related to the atmosphere in aviation, space travel, transport and energy

Climate protection, mobility of the future, digitalization & artificial intelligence, energy system transformation

Both basic and application-oriented questions

Broad spectrum of methods

Internationally competitive and in some areas internationally leading

Competent contact for DLR, society, industry and politics
The institute at a glance

Founded 1.7.1962 (1924)
End of 2019 150 employees (51f, 99m)
thereof ~ 37 PhD students
18 Lectureships/professorships at 9 universities/colleges

Overall budget 2019: 18,8 M€ (~ 2256 M¥)
Basic funding : 13,2 M€
(48% Aerospace, 39% Aviation, 11% Traffic, 2% Energy)
Third-party funds : 5,6 M€ (ESA, EU/ERC, BMBF, BMWi, DFG, HGF, Airbus,...)
**Organization**

**Earth System Modelling**
- Prof. Robert Sausen
  - YIG MACClim
    - J.-Prof. Hella Garny

**ESM – Evaluation and Analysis**
- Prof. Veronika Eyring

**Atmospheric Trace Species**
- Dr. Anke Roiger

**Cloud Physics**
- Prof. Christiane Voigt
  - Passive Cloud-Remote Sensing
    - Dr. Luca Bugliaro

**Transport Meteorology**
- Dr. Thomas Gerz

**Lidar**
- Dr. Andreas Fix
  - Lidar/Radar-Synergy
    - Dr. Silke Groß

**Logistics**
- Sonja Koch
- Stefanie Zähnle
- Controlling

**Institute of Atmospheric Physics**
- Prof. Markus Rapp
  - Director

**Quality Management**
- Dr. Arthur Schady

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a) New appointment as of 01.07.2021; W2 appointment procedure with LMU ongoing

close cooperation with

[LMU Logo]
(Numerical) Modelling in a nutshell

- There is no second Earth (to experiment with)

NOAA/NASA

Wikimedia, user Hellerick
https://commons.wikimedia.org/wiki/
File:Division_of_the_Earth_into_Gauss-Krueger_zones_-_Globe.svg
(Numerical) Modelling in a nutshell

- There is no second Earth (to experiment with)
- A mathematical model
  - based on physical equations
  - coupled system of (non-linear) partial differential equations
  - solved numerically on a “supercomputer”

https://www.dkrz.de/about/media/galerie/Media-DKRZ/hle-3
(Numerical) Modelling in a nutshell

- There is no second Earth (to experiment with)
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- Climate projection (vs. weather forecast)
  - no forecasts, but climate projections → statistical analyses
  - boundary value problem (vs. initial value problem)
  - model produces realistic weather systems from internal variability
Modular Earth Submodel System (MESSy)

EMAC = ECHAM/MESSy Atmospheric Chemistry

https://www.messy-interface.org/

> 20 partner institutes

Framework to couple scientific codes to numerical weather prediction and climate models
Climate projections with EMAC

- Model simulations with 2 PByte output
- Contribution to Chemistry Climate Initiative (CCMI)
- Data for WMO Ozone Assessment and Intergovernmental Panel on Climate Change (IPCC)

Total ozone column (DU), Antarctic, October

Dohmse et al., ACP, 2018
“communication” between individual components through mutual access of distributed objects via standard interfaces

expandability without intervention in other components

- scalable development
- coexistence of alternatives
→ “community”-ansatz
2nd part

Application study
Contents

- Aviation and climate impact
- Climate-optimized routing
- Research objectives and methodologies
- EMAC/AirTraf model components
- 1-day air traffic simulations over the North Atlantic with different aircraft routing options
- Multi-objective optimization in EMAC/AirTraf
- Summary – research topics for further collaborations
Growth of air transport

• Strong growth in air traffic: +5 %/yr (1945 - 2019)
• World passenger traffic collapsed due to COVID-19 Pandemic, but it is recovering
Aviation emissions and climate change

Aircraft emissions and climate change

Fuel: $C_nH_m + S$

Engine fuel combustion

Direct emissions

- $CO_2$
- $NO_x$
- $H_2O$
- $SO_x$
- $HC$
- Soot

Atmospheric processes
- Ocean uptake
- Chemical reactions

Changes in radiative forcing components

- $\Delta CO_2$
- $\Delta CH_4$
- $\Delta O_3$
- $\Delta H_2O$
- $\Delta Aerosol$

Climate change

Changes in temperatures, sea level, ice/snow cover, precipitation, etc.

Impacts

Agriculture and forestry, ecosystems, energy production and consumption, human health, social effects, etc.

Damages

Social welfare and costs

Complete combustion products:
$CO_2 + H_2O + N_2 + O_2 + SO_2$

Actual combustion products:
$CO_2 + H_2O + N_2 + O_2 + NO_x + CO + HC + soot + SO_x$

Lee et al. 2009
Aviation and radiative forcing for 2005

Grewe et al. 2017
Impact of aviation on global surface temperatures

- Air traffic contributes around 5% to anthropogenic warming

Main contributions from:
- CO₂
- Contrails
- NOₓ (O₃ and CH₄)

-0.03 K von 0.7 K
≈ 5%

PMO="Primary mode ozone"
Results from less CH₄ ⇒ less HO₂ ⇒ less O₃ production

Grewe et al. 2016
Climate-optimized routing

• “Climate cost function (CCF) identifies climate sensitive regions for emissions (CO$_2$, H$_2$O, ozone, Methane, contrails) and estimates climate impacts

• Climate-optimal route was calculated by air traffic simulator SAAM by Eurocontrol:
  - 19 % less climate impact
  - 1 % longer flight time
  - 14 % more fuel
  - 22 % more NO$_x$
  - 10 % more costs

Frömming, et al. 2013
Matthes, et al. 2012, 2017
Research objectives

- To investigate an eco-efficient aircraft routing strategy that reduces the climate impact of global air traffic over the next few decades
- To estimate its mitigation gain for different aircraft routing strategies

Methodologies

- Chemistry-climate model EMAC (ECHAM5/MESSy 2.54)  
  - Submodel AirTraf 2.0  
    - 9 routing strategies (called options)
    - Trajectory optimization (3D)
    - Geographic location, altitude, time of released non-CO₂ emissions/contrails are considered
    - Simplifications:
      - Only cruise flight phase
      - No potential conflicts of flight trajectories
      - No operational constraints from ATC

Aircraft routing options

- 0 - Great circle
- 1 - Flight time
- 2 - Fuel use
- 3 - NOₓ emission
- 4 - H₂O emission
- 5 - Contrail formations
- 6 - Simple operating cost
- 7 - Cash operating cost
- 8 - Climate impact

Roeckner et al., 2006  
Jöckel 2010, 2016
EMAC/AirTraf model components

**Base model**
ECHAM5/MESSy 2.54 (EMAC)
Roeckner et al., 2006, Jöckel 2010, 2016

**Submodel AirTraf 2.0**

**Aviation data**
- ICAO engine performance data
- Aircraft data (BADA 3.9)
- Flight plan, fuel price, etc.

**Fuel/emissions calc.**
- Total energy model
- DLR fuel flow correlation method
  Deidewig 1996, Schaefer 2012

**Optimizer**
- Genetic algorithms (ARMOGA1.2.0)
  Sasaki, 2009

**Coupled submodels**
- CONTRAIL 1.0
- ACCF 1.0
  Van Manen, 2017, 2019; Yin, 2018, 2020

- Optimized flight trajectories
- Flight performance measures:
  - Flight distance, flight time, fuel use, NO\textsubscript{x} emission, H\textsubscript{2}O emission, contrail distance, operation cost, climate impacts (ATR20s)
- Radiative forcing (surface temperature change)
Flight trajectory optimization

- A trajectory (candidate) is created by B-spline curve with 11 design variables: 6 (geographical location), 5 (altitude)
- Waypoints are automatically generated
- GA evaluates single objective function and finds out one optimal trajectory to minimize objective function value

\[
\begin{align*}
\text{Minimize} & \quad f \\
\text{Subject to} & \quad x_j^l \leq x_j \leq x_j^u, \quad j = 1, 2, \ldots, n_{dv}
\end{align*}
\]

Yamashita et al. 2016
Formulations of objective functions

• Cost option
  - Min. Cash Operating Cost (international flights [USD])  Liebeck, 1995

  \[ f = \text{COC} = C_{\text{flightcrew}} + C_{\text{cabincrew}} + C_{\text{landing}} + C_{\text{navigation}} + C_{\text{fuel}} + C_{\text{airframe}} + C_{\text{engine}} \]

• Climate option
  - Submodel ACCF 1.0
  - Min. climate impact over 20 yrs [K] estimated by algorithmic Climate Change Functions aCCFs  Van Manen, 2017,2019; Yin, 2018,2020

\[
\begin{align*}
\text{ATR20}_{O_3,i} &= \text{aCCF}_{O_3,i} \times \text{NO}_x,i \times 10^{-3}, \\
\text{ATR20}_{CH_4,i} &= \text{aCCF}_{CH_4,i} \times \text{NO}_x,i \times 10^{-3}, \\
\text{ATR20}_{H_2O,i} &= \text{aCCF}_{H_2O,i} \times \text{FUEL}_i, \\
\text{ATR20}_{CO_2,i} &= \text{aCCF}_{CO_2} \times \text{FUEL}_i, \\
\text{ATR20}_{contrail,i} &= \text{aCCF}_{contrail,i} \times \text{PCC}_\text{dist,i}.
\end{align*}
\]

\[
\text{ATR20}_{\text{total},i} = \text{ATR20}_{O_3,i} + \text{ATR20}_{CH_4,i} + \text{ATR20}_{H_2O,i} + \text{ATR20}_{CO_2,i} + \text{ATR20}_{contrail,i},
\]

\[
f = \sum_{i=1}^{n_{wp}-1} \text{ATR20}_{\text{total},i},
\]
# 1-day air traffic simulations over the North Atlantic

<table>
<thead>
<tr>
<th>Routing options</th>
<th>Great circle</th>
<th>Cost/Climate/Others options</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECHAM5 Resolution</td>
<td>T42/L31 ECMWF (2.8° × 2.8°)</td>
<td></td>
</tr>
<tr>
<td>Duration / Time step</td>
<td>Dec.01.2015 - Dec.02.2015 / 12 min</td>
<td></td>
</tr>
<tr>
<td>Waypoints</td>
<td>101</td>
<td></td>
</tr>
<tr>
<td>Flight altitude change</td>
<td>Fixed FL350</td>
<td>FL290 - FL410</td>
</tr>
<tr>
<td>Flight plan</td>
<td>103 Transatlantic flights by REACT4C Project (Eastbound 52/Westbound 51)</td>
<td></td>
</tr>
<tr>
<td>Aircraft / Engine type</td>
<td>A330-301 / CF6-80-E1-A2 (2GE051)</td>
<td></td>
</tr>
<tr>
<td>EIH₂O [g(H₂O)/kg(fuel)]</td>
<td>1,230 (IPCC 1999)</td>
<td></td>
</tr>
<tr>
<td>Load factor</td>
<td>0.62 (ICAO 2009)</td>
<td></td>
</tr>
<tr>
<td>Unit time cost [USD/h]</td>
<td>2710.0 (Boeing 2015)</td>
<td></td>
</tr>
<tr>
<td>Mach number</td>
<td>0.82 (A330-301, Eurocontrol 2011)</td>
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</tr>
<tr>
<td>Optimization</td>
<td>–</td>
<td>Min. $f$ (single-objective optimization)</td>
</tr>
<tr>
<td>Design variable</td>
<td>–</td>
<td>11 (Location 6/Altitude 5)</td>
</tr>
<tr>
<td>Generation number</td>
<td>–</td>
<td>100</td>
</tr>
<tr>
<td>Population size</td>
<td>–</td>
<td>100</td>
</tr>
</tbody>
</table>
Optimized flight trajectories
Dec. 1 2015, 103 North Atlantic flights (A330-301)

Yamashita, Kern et al. 2020
Distribution maps
Dec. 1 2015, 103 North Atlantic flights (A330-301)

Yamashita, Kern et al. 2020
Flight characteristics
Dec. 1 2015, 103 North Atlantic flights (A330-301)

• Trade-off exists between operational cost and climate impact
• Climate-optimized routing can reduce expected climate impact (ATR20), compared to cost-optimized routing
  - Climate option: $-67.9\%$ ATR20, $+9.8\%$ COC $\rightarrow$ $0.13$ [US Mil$/10^{-7}K$]
Multi-objective flight trajectory optimization in AirTraf

AirTraf initialization

Multi-objective optimization problem
e.g. Min. $f_1 = $ Operating cost
     Min. $f_2 = $ Climate impact
Subject to constraints

Multi-objective optimizer
ARMOGA of AirTraf submodel

Multiple-trade-off solutions found

Air Traffic simulations for eco-efficient routing strategy

Choose one solution (decision-making)

Higher-level information

Step 1

Step 2

Deb 2001
Benchmark test

Min. $f_1 = $ Flight time [s]
Min. $f_2 = $ Fuel use [kg(fuel)]
Min. $f_3 = $ Climate impact (ATR20) [K]

Flight route: from JFK (New York) to CDG (Paris), flight alt. at FL290 (fixed)
Target day: 01 June 2015
Departure time (local time): from 07:00 to 17:00 (every 2h)
Non-dominated solutions
Summary – research topics for further collaborations

1. To detect some unique points of the nondominated solutions and visualize the structure of nondominated fronts

2. To examine how much nondominated fronts vary under different weather conditions

3. To develop a decision-making method in EMAC/AirTraf