Seasonal Variability of Aircraft Trajectories reducing NO_x-climate Impacts under a Multitude of Weather Patterns

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Introduction

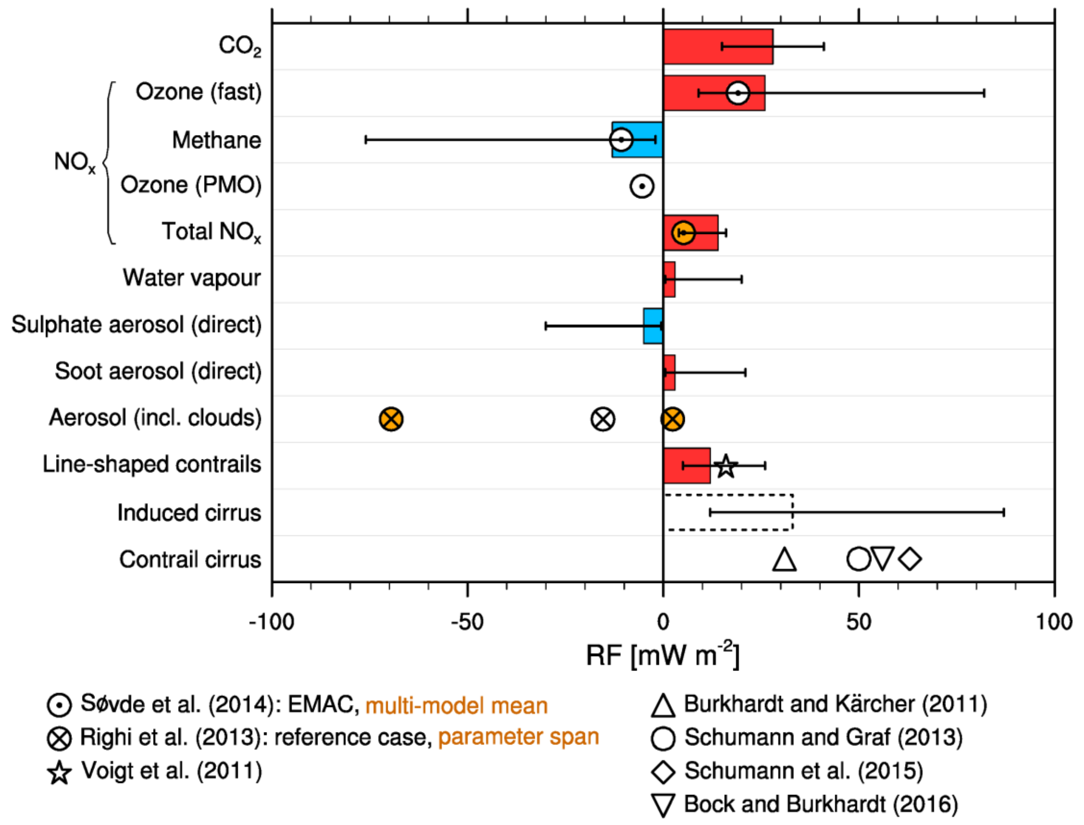


Figure: Aviation-induced Radiative Forcing terms from different components (*from Grewe et al., 2017, updating Lee et al., 2010).*

- Aviation climate impact is due to **CO_2 and non-CO_2 effects,** including:
  - →NO_x emissions (ozone and methane perturbations)
  - →Water vapour
  - →Formation of contrails

- Non-CO_2 effects of aviation are highly dependent on **time and location of emission**
  - → potential of mitigating the climate impact of aviation by optimizing the aircraft trajectories.

Motivation

Previous projects results:

- **REACT4C**: 25% reduction in the climate impact with 0.5% increase in the operational costs (**one winter day**, westbound trans-Atlantic flights)[1].

- **ATM4E**: 75% - 85% of the overall climate impact mitigation potential can already be achieved modifying 25% of the routes (**one winter day**, European air traffic)[2].

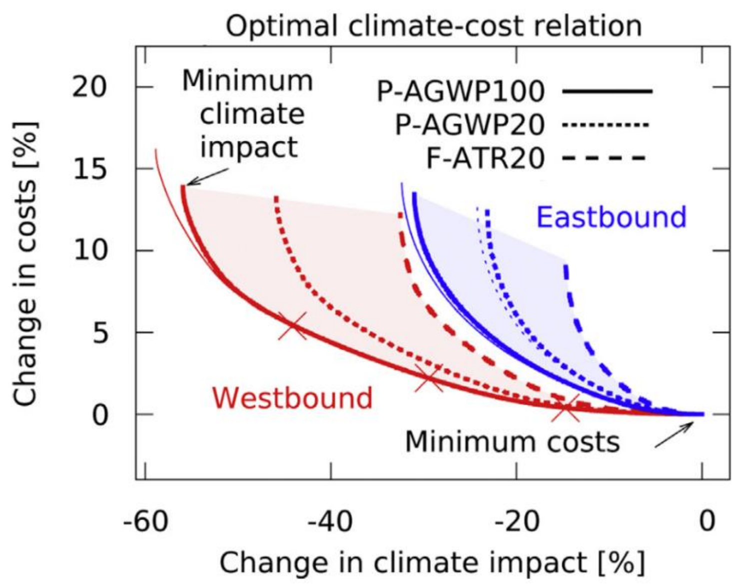


Figure: Optimal climate-cost relations obtained optimizing the trans-Atlantic air traffic, under the weather conditions of a representative winter day[1].

[1]*Grewe, V. et al. (2014)*, [2]*Lührs, B. et al. (2021)*

Objective

- Objective of this study:

  Enhance the understanding of the relation between **NO_x-climate impacts** and **routing strategies** considering a **multitude of weather patterns**.

- In particular, here we focus on:

  1. the **effects** of optimizing aircraft trajectories w.r.t. the impact of their NO_x emissions on climate.
  2. the **seasonal variability** of these optimised trajectories, caused by the **natural atmospheric variability**.

- Initial step towards objective of FlyATM4E project:

  Identify trajectories leading to a **significant reduction** of aviation **climate impact**, while leaving the **economic costs nearly unchanged**.

Methods – EMAC and ACCFs

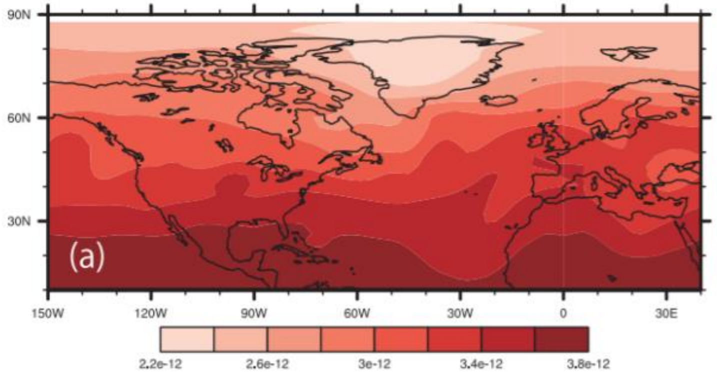
- **Base model:** ECHAM5/MESSy2 Atmospheric Chemistry Model (**EMAC**).
- A set of **prototype algorithmic Climate Change Functions (aCCFs)** estimate the flight climate impact in terms of **Average Temperature Response over a time horizon of 20 years (ATR20):**
- Example: NO_x- climate impact on ozone*:

$$aCCF_{O_3} = -5.20 \cdot 10^{-11} + 2.30 \cdot 10^{-13} T + 4.85 \cdot 10^{-16} \Phi - 2.04 \cdot 10^{-18} T\Phi,$$
if $aCCF_{O_3} > 0$ (= 0 otherwise)

where T is atm. temp., and Φ is the geopotential.

$$\Rightarrow \; ATR20_{O_3} = aCCF_{O_3} \times emitted\ NO_x$$

aCCFs of NO_x- O_3 →



aCCFs of NO_x- CH_4 →

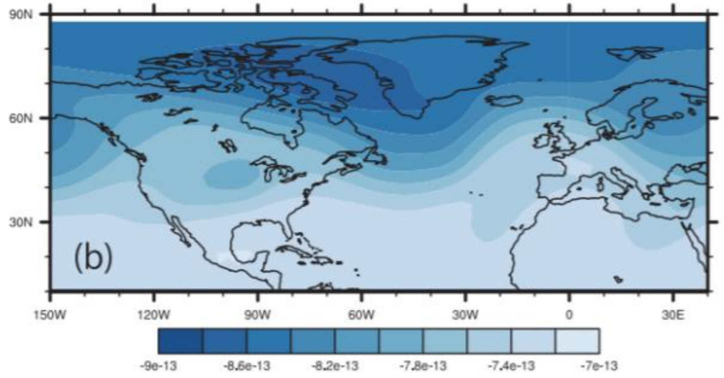


Figure: Values computed with EMAC at FL350 (~10.7 km) on 1 Dec. 2015 at 12:00:00 UTC (supplement of *).

*Yamashita et al., 2020.

Methods - AirTraf 2.0

- **AirTraf:** air traffic simulator coupled with EMAC.
- Optimizer: Genetic algorithm (**ARMOGA**)
- **Design variables**:
  - 6 coordinates (x_1, …, x_6)
  - 5 altitudes (x_7, …, x_{11})

8 control points define the B-spline curve representing the trajectory.

- Available strategies minimise e.g. flight time, fuel use, simple operating cost, climate impact (using aCCFs)*.

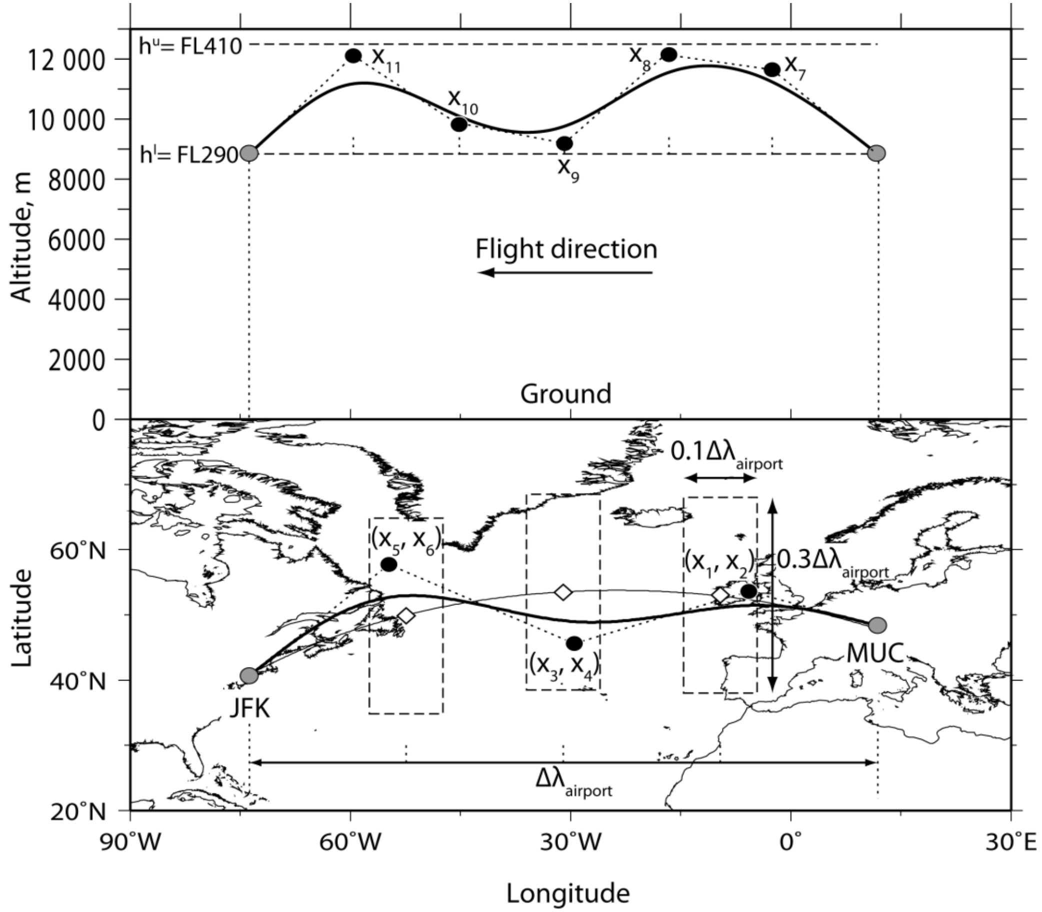


Figure: Geometry definition of flight trajectory. From H. Yamashita et al. (2016).

*Yamashita et al., 2020.

Methods - Simulations set-up

	ECHAM5
Horizontal resolution	T42 (2.81° × 2.81°)
Vertical resolution	L31ECMWF (31 vertical pressure levels up to 10 hPa ∼ 30 km)
Time step	20 min
Duration	1 year (from 1 Dec. 2015 to 1 Dec. 2016)
	AirTraf
Flight-plan	85 flights in the European airspace (ATM4E flight plan on 2015-12-18 with all A33x aircraft models)
Waypoints	101

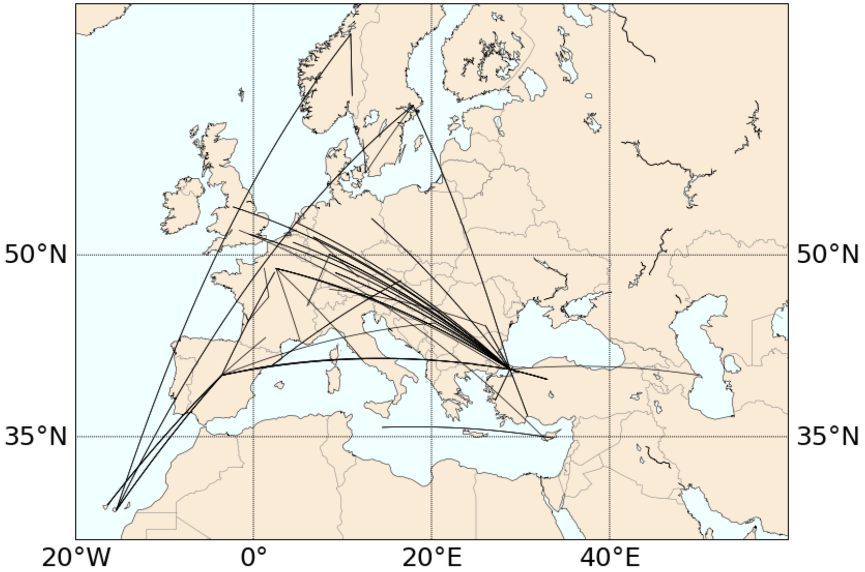


Figure: Location of the origin-destination pairs.

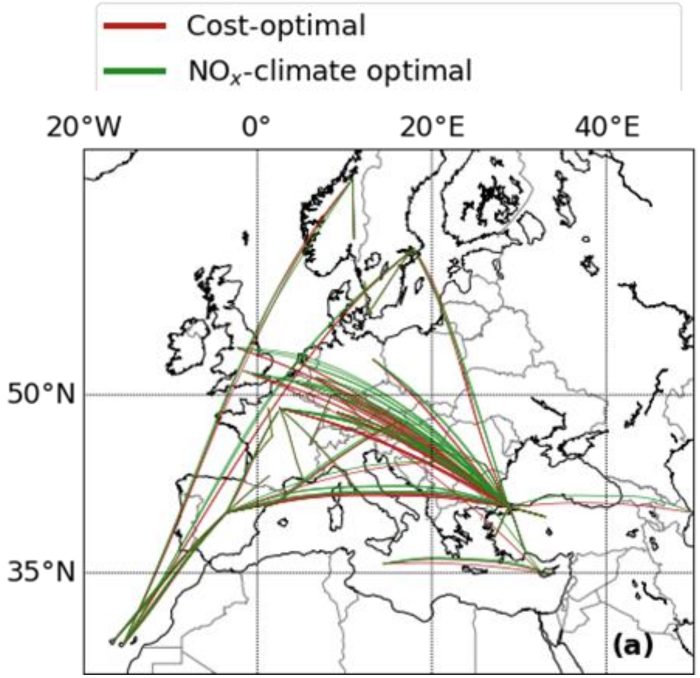
- Trajectory optimization strategies:

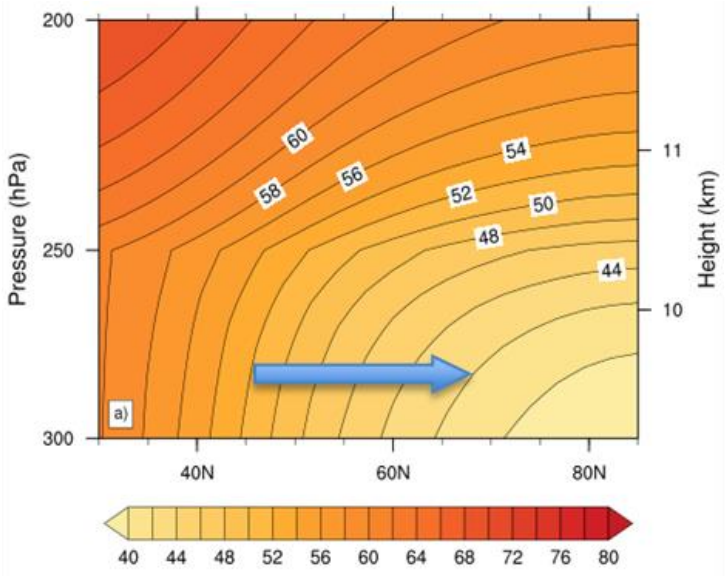
➢ *NO_x-climate optimal traj.* → minimize: $ATR20_{NO_x} = ATR20_{O_3} + ATR20_{CH_4}$

➢ *Cost-optimal trajectories* → minimize: $SOC = c_t \sum_{i=1}^{n_{wp}-1} TIME_i + c_f \sum_{i=1}^{n_{wp}-1} FUEL_i$

  - c_t = 0.75 [$/s] is the unit time cost and c_f = 0.51 [$/kg] is the unit fuel cost (Burris, 2015)
  - n_{wp}= 101 is the number of waypoints
  - $TIME_i$ and $FUEL_i$ are flight time and fuel used at the i^{th} flight segment.

Results - seasonal mean horizontal paths



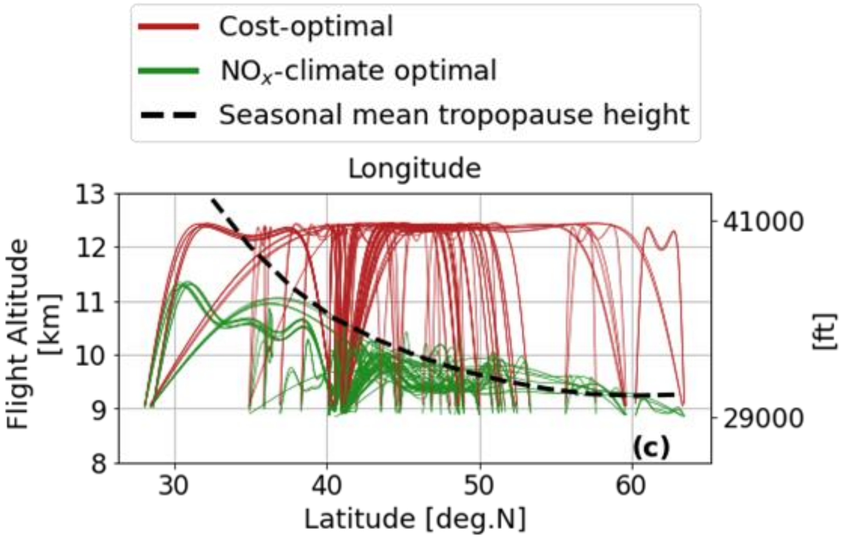


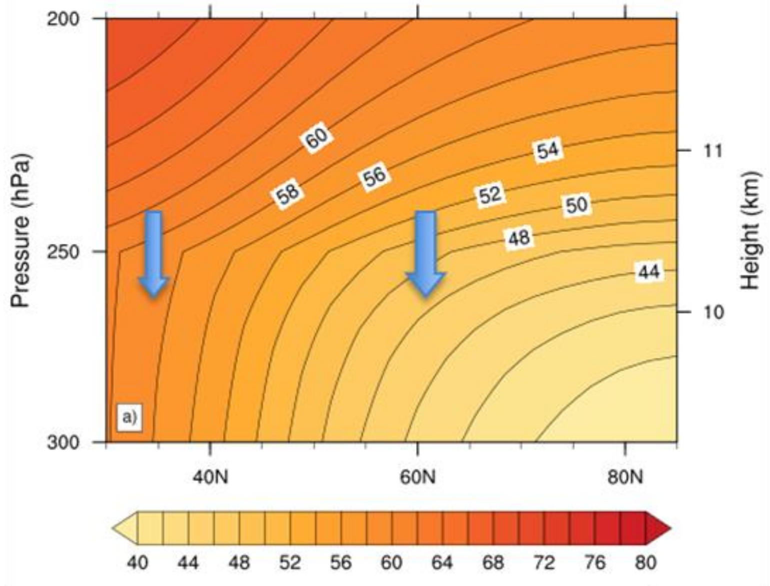
Annual zonal mean aCCFs of NO_x-O_3 (10^{-12} K/kg(NO_2)) *

- Left figure: Comparison of winter (DJF) seasonal mean horizontal paths.
- In general, northward shift of aircraft location.
- Warming effects from ozone are reduced moving to higher latitudes.
- Other seasons: similar behavior, effects have lower magnitude.

*Yin et al., 2021, *in preparation*.

Results - seasonal mean flight profiles



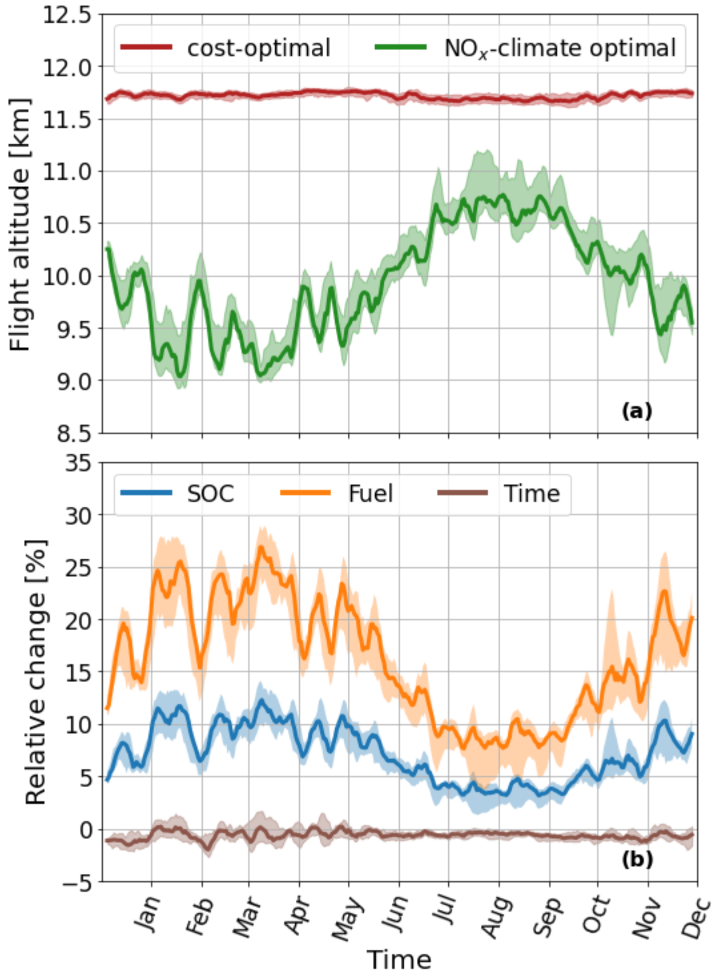


Annual zonal mean aCCFs of NO_x-O_3 (10^{-12} K/kg(NO_2))*

- Figure: Comparison of winter (DJF) seasonal mean flight altitude vs. latitude.
- NO_x-climate optimal trajectories flying at lower altitudes → relation with tropopause height.
- Warming effects of O_3 is lower at lower altitudes, with larger gradients at higher latitudes.

*Yin et al., 2021, *in preparation*.

Results - variability throughout 1 year



- Figure: The thick lines indicate the median values over the 85 flights. The shaded areas extend from the first to the third quartile.
- Reduction in the cruise altitude is smaller in summer.
  → Elevation of the average height of the tropopause during the summer season / lower mitigation potential.
- Fuel increase driven by the increase in aerodynamic drag caused by flying at lower altitudes.
- Larger variability in flight time during winter/spring.

Results - changes in NO_x-climate impact

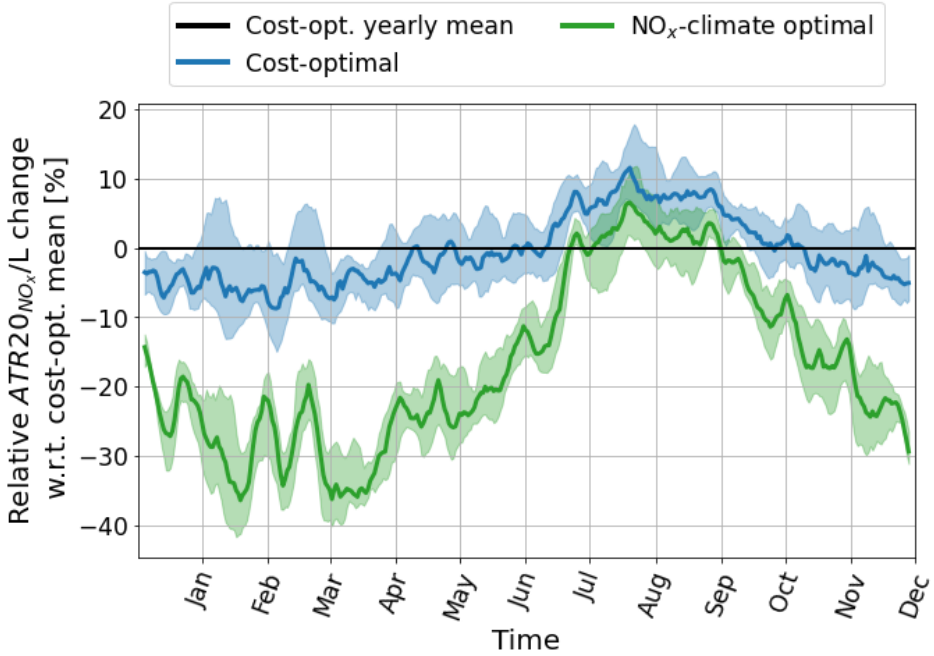


Figure:

- Relative change in NO_x-climate impact.
- Baseline: yearly mean NO_x-climate impact of cost-optimal trajectories.

- NO_x-climate optimal trajectories successfully reduce the aviation climate impact from NO_x emissions.
- Larger mitigation potential in winter and spring.
- Interpretation: in winter jet stream stronger and located further south, leading to larger vertical and latitudinal gradients in temperature and geopotential.

Results - changes in NO_x-climate impact

FlyATM4E

Cost-opt. yearly mean
Cost-optimal
NO_x-climate optimal

Figure: NO_x- ozone

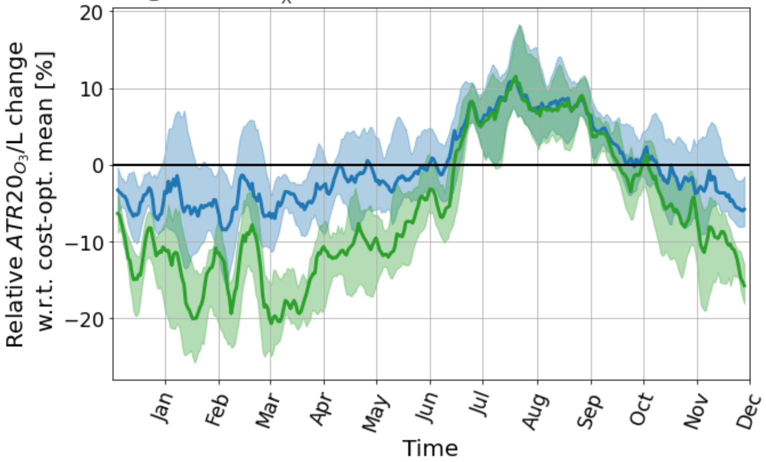
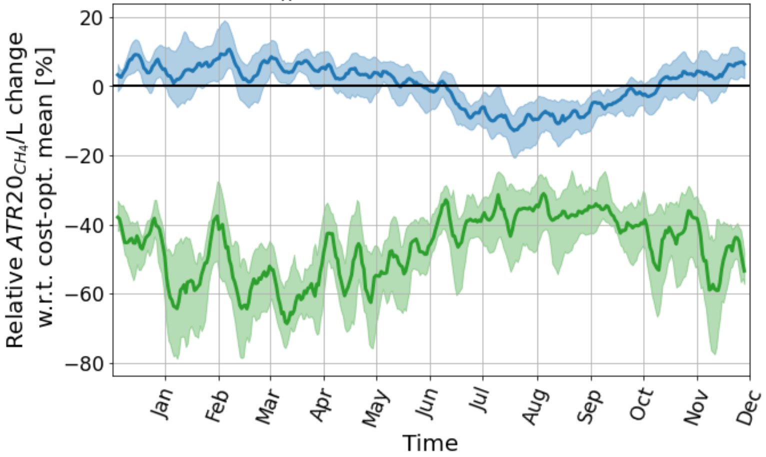


Figure: NO_x- methane



- NO_x-ozone climate impact reaches a maximum in summer due to a higher photochemical activity (both optimization strategies).
- Seasonality of NO_x-ozone climate impact drives total NO_x-climate impact seasonality → dominant over methane effects.
- Cooling effects from methane depletion are always enhanced.

Conclusion

- The air traffic simulator AirTraf coupled with the Atmospheric Chemistry Model EMAC allowed us to analyze different routing strategies under the atmospheric conditions computed during one year of simulation.

- NO_x-climate optimal trajectories are:
  - flying at lower altitudes

  and
  - affected by larger temporal and latitudinal dependencies

  than cost-optimal trajectories.

- The mitigation potential of NO_x-climate optimal trajectories is larger in winter/spring.

On-going research

- In this study, we employ prototype algorithmic Climate Change Functions.

- On-going research to extend the simulations in the following aspects:

  - Take into account all main components of aviation climate impact (CO_2 and non-CO_2 effects, i.e. NO_x, water vapour, and contrail cirrus)

  - Identify trajectories leading to a significant reduction of aviation climate impact, while leaving the economic costs nearly unchanged

  - Include uncertainty ranges.

References and links

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- LinkedIn https://www.linkedin.com/company/flyatm4e
- Project Homepage: www.flyatm4e.eu

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Thank you very much for your attention!

TU Delft

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