Investigation of mid-latitude contrail formation regions in EMAC in comparison to in-situ observations from aircrafts

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Motivation and Scope

- Aviation is seeking for ways to **reduce its climate impact** caused by CO_2 emissions and non-CO_2 effects. While the effects of CO_2 on climate are independent of location and situation during release, non-CO_2 effects such as contrail formation vary depending on meteorological background.
- The ClimOP Project aims to estimates the mitigation potential of climate optimized aircraft trajectories, building on concepts established in previous studies that investigated the influence of different weather situations on aviation's contribution to climate change, identified climate sensitive regions and generated data products which enable air traffic management (ATM) to plan for climate optimized trajectories [3,4].
- In research presented here, a Lagrangian approach is further developed to determine the sensitivity of the atmosphere to aviation emissions with respect to climate effects in order to identify **climate optimized aircraft trajectories**.

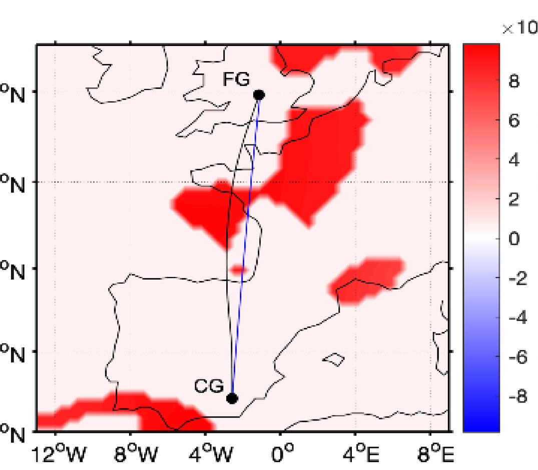


Figure: Optimized trajectories for the route between London and Spain [5].

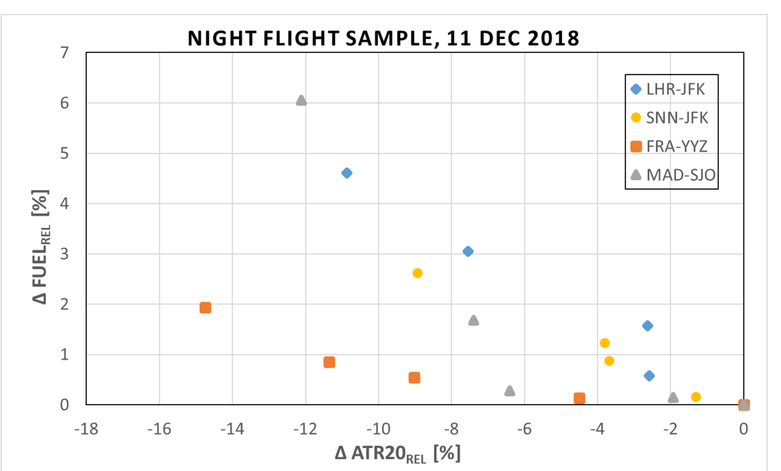


Figure: Reduction in climate effects (ATR20) vs. increase in fuel burn (pareto optimal) [6].

Contrail climate effect

- **Non-CO_2 effects** are important, determining most of the climate effect of aviation (approx. 2/3).
- Contrail-cirrus (57%) are one of the largest contributors to the **effective radiative forcing** of global aviation.
- Large uncertainties exist in magnitude in part due to incomplete representation of key processes [3].
- Very different time scales between CO_2 and non-CO_2 effects are accounted for by using climate metrics (e.g., ATR20).

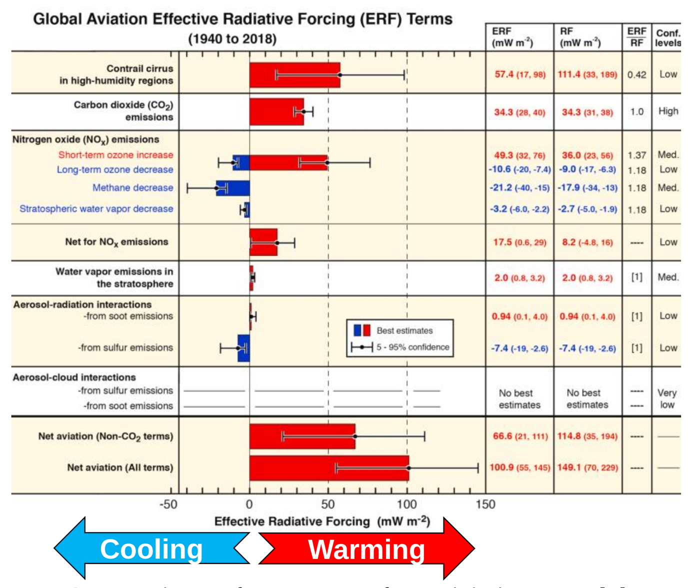


Figure: Climate forcing terms from global aviation [3].

Contrail formation during a flight

- Persistent contrail formation requires **ice-supersaturated conditions** along a flight track.
- Water vapor is emitted into a cold environment, localized increase in water vapor can **raise the relative humidity** of the air past saturation point.
- Vapor condenses into tiny water droplets which **freeze** if the temperature is low enough, forming the contrail.

Figure: Contrail formation regions [7].

Developing Contrail CCFs: A Lagrangian Approach

Lagrangian concept to study development and radiative effect of contrails in the global climate model EMAC/ATTILA:

- **Pulse emission** at specific location and specific time (32 time-region-grid-points).
- Following the **air parcel moving** along 50 trajectories (Lagrange).
- Input variables from EMAC grid box (e.g. Temperature and Humidity).
- Microphysics are computed on these trajectory.

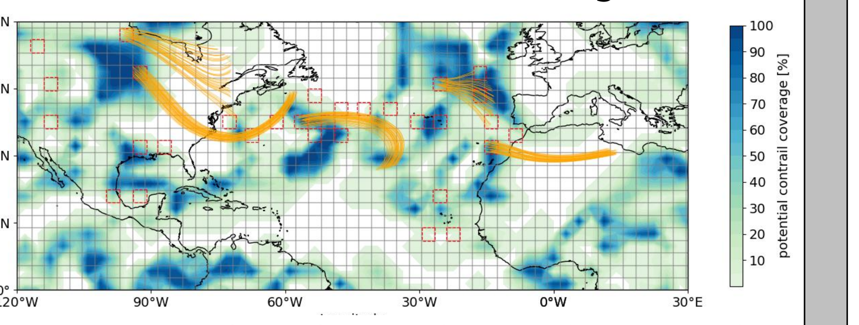
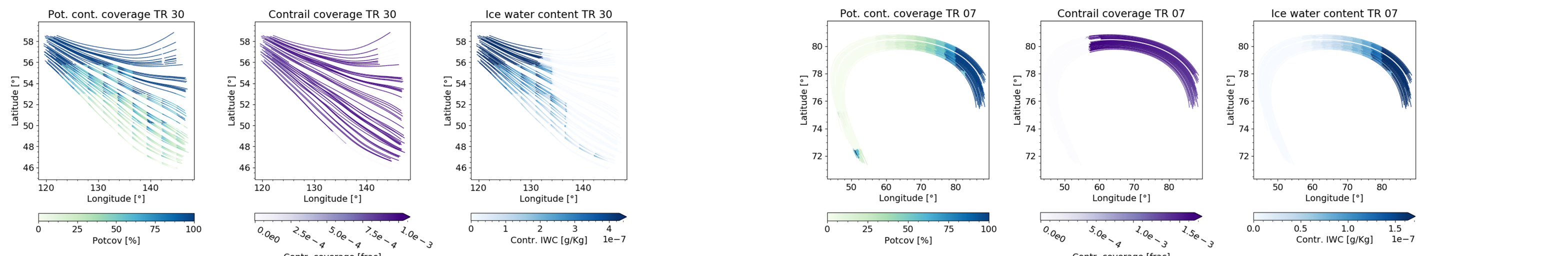


Figure: Potential contrail coverage for 26 March 2014 at 250 hPa (blue), location of time-region grid points (red) and Lagrangian trajectories (orange) from five time-regions [1].



- 4-Dimensional climate change functions (CCFs) are then calculated by investigating the effects of these contrails on the radiative forcing.

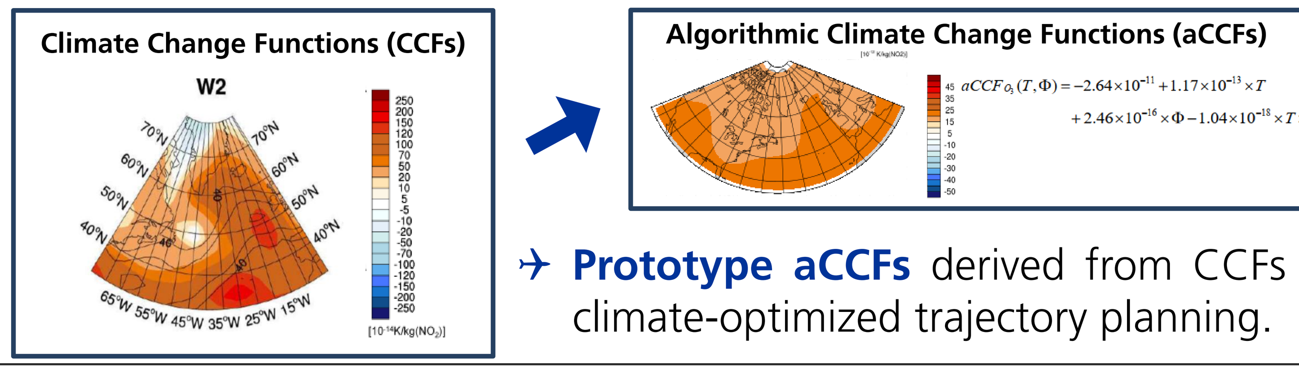


Figure: Climate Change Functions (left) [2] and algorithmic climate change functions (right) [8].

- **Prototype aCCFs** derived from CCFs can be used for climate-optimized trajectory planning.

Contrail formation parameter in EMAC vs airborne observations

- Comparing temperature and humidity based on airborne observations (HALO measurement campaign) and different EMAC model setups.

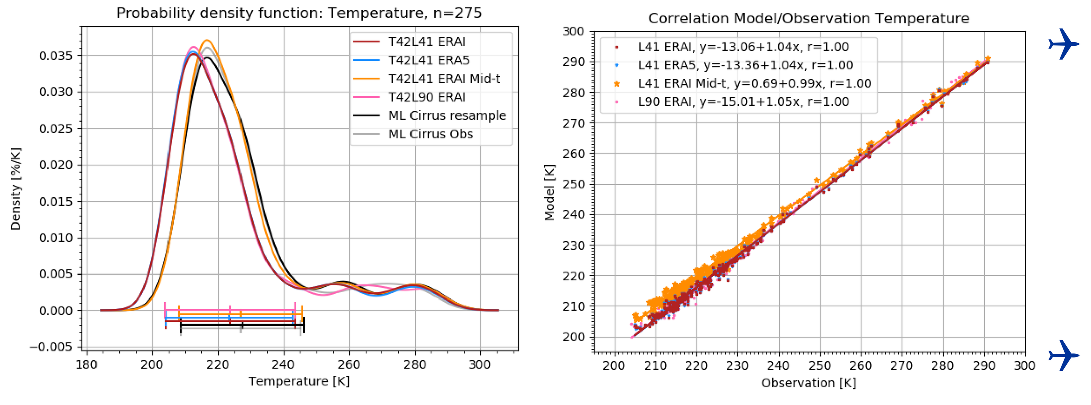


Figure: Probability density function of model and observational temperature data for the ML-Cirrus time period (left). Correlation between observational data and model data (right) [6].

- **Temperature difference** between observations and simulation (**model cold bias** up to **5 K**) for non mean temp. nudged simulation between 200 K and 240 K.
- **Strong correlation** between model and observational data.
- Mixing ratio analysis shows a **model dry bias**, with a higher concentration of low humid values (< 200 ppmV) for L41 model data. compared to observations.
- Increased correlation for L90 simulation due to reduced output interval (15->12m).

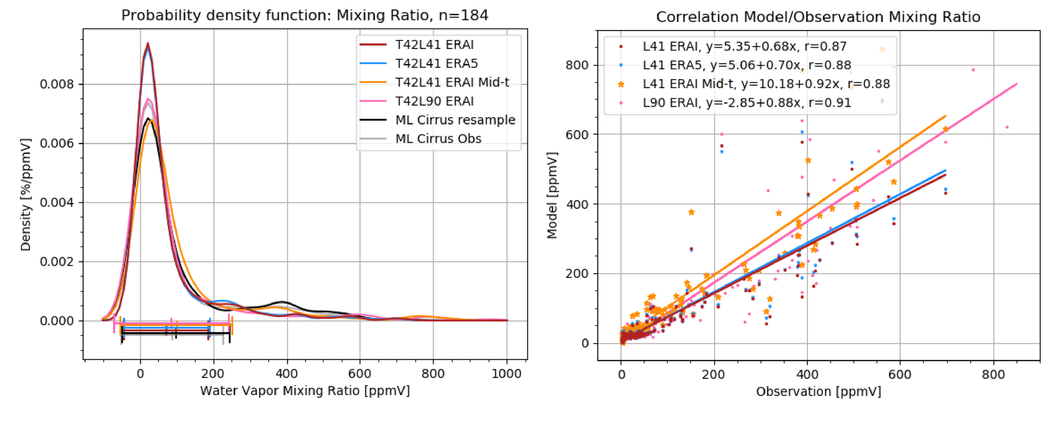


Figure: Probability density function of model and observational humidity data for the ML-Cirrus time period (left). Correlation between observational data and model data (right) [6].

Case Study: 26 March 2014

- **Key atmospheric parameters** (temperature and humidity) for contrail formation from the 26 March 2014 HALO ML-Cirrus campaign are compared to different EMAC model setup data along the aircraft trajectory.

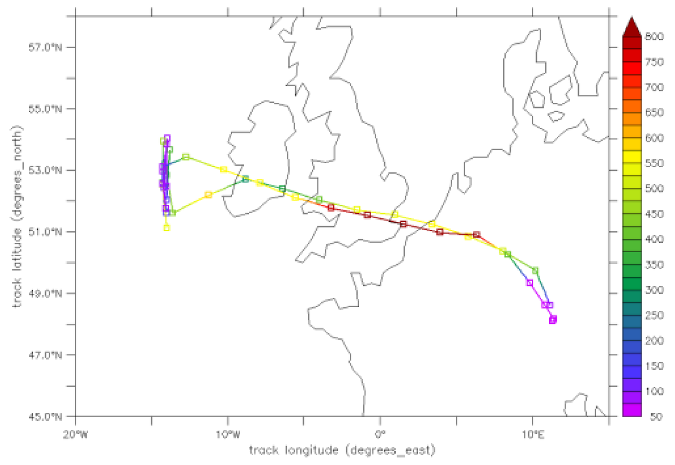


Figure 15: Flight Path HALO for 26 March 2014 (ML Cirrus)

Sampling (s4d) along trajectories, EMAC vs. ML-Cirrus

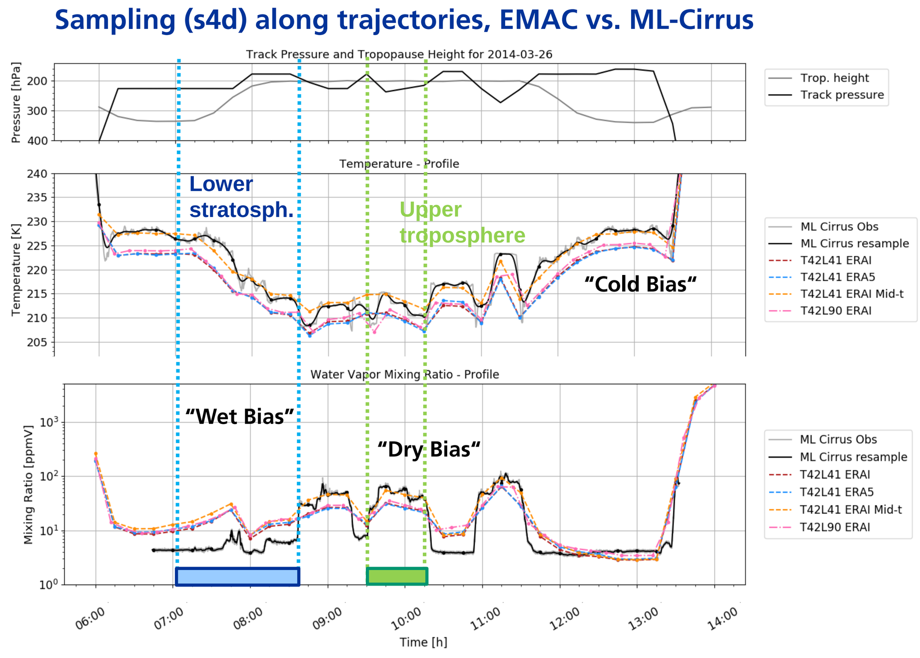


Figure: Comparison of temperature and humidity data for 26 March 2014 along flight trajectory. Model grid T42 (about 2.8°), L90/L41 vertical, ML-Cirrus data from FISH and BAHAMAS instrument [1].

- **Model cold bias** up to **5 K** at all layers, highly reduced by mean temperature nudging (MTN).
- **Dry bias of 10%** for all non nudged EMAC simulations in the **troposphere**.
- **~20% wet bias** in the "lower" **stratosphere** near the tropopause for all EMAC model results compared to observational data.

CONCLUSIONS

- **Cold bias** can be **reduced** with mean temperature nudging. Systematic cold bias and dry/wet bias between EMAC and aircraft measurements differs with nudging concept.
- Water vapor mixing ratios increase with MTN. **Impact on relative humidity**, **ISSR** and **potential contrail coverage**, correction of the output might be necessary.
- The Lagrangian approach to contrail trajectories shows the possible spread of contrail characteristics (e.g., ice water content, radiation effects) during the multi-hour life cycle of the contrail and allows the derivation of **climate effects** of aviation emissions.
- Novel CCF data describing spatial and temporal variation of contrail climate effects combined with aCCFs [9] enables to identify **climate optimized flight trajectories**.

REFERENCES and ACKNOWLEDGEMENTS

[1] Peter, Patrick und Matthes, Sigrun und Grewe, Volker (2021) *ClimOP Project - Climate assessment of innovative mitigation strategies towards operational improvements in aviation.* 11th EASN Virtual International Conference on "Innovation in Aviation & Space to the Satisfaction of the European Citizens", 1-3 Sept. 2021, Online.

[2] Frömming, C., Grewe, V., Brinkop, S., Jöckel, P., Haslerud, A., Rosanka, S., . . . Matthes, S. (2021). Influence of weather situation on non-CO2 aviation climate effects: the REACT4C climate change functions. *Atmospheric Chemistry and Physics* (21), 9151-9172. doi:10.5194/acp-21-9151-2021

[3] Lee, D., Fahey, D., Skowron, A., Allen, M., . . . Wilcox, L. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. *Atmospheric Environment* (244), 1352-2310 doi: https://doi.org/10.1016/j.atmosenv.2020.117834

[4] Matthes, S., Schumann, U., Grewe, V., Frömming, C., …., Mannstein, H. (2012). Climate optimized air transport. In *Atmospheric Physics: Background – Methods – Trends* (p.877). Berlin/Heidelberg, Germany: Springer. doi:https://doi.org/10.1007/978-3-642-30183-4_44

[5] Matthes, S. Dahlmann, K. Dietmüller, Baumann, S., Soler, M, Simorgh, A., González Arribas, D., Linke, F., Lührs, b., Meuser, M.M., Castino, F., Yin, F. et al. 2023 (in prep.): How to integrate uncertainties when identifying robust climate-optimized aircraft trajectories in FlyATM4E; MetZet; FlyATM4E Deliverable D2.2 (www.flyatm4e.eu)

[6] Peter et al., "Characteristics of mid latitude contrail formation regions (in model and observations) and impacts on contrail predictions" 2023 (in prep)

[7] Meijer, V. R., L. Kulik, S. D. Eastham, F. Allroggen, R. L. Speth, S. Karaman, and S. Barrett (2022), Contrail coverage over the United States before and during the COVID-19 pandemic, *Environmental Research Letters*, doi:10.1088/1748-9326/ac26f0.

[8] Dietmüller, S., Matthes, S., Dahlmann, K., Yamashita, H., Simorgh, A., Soler, M., Linke, F., Lührs, B., Meuser, M. M., Weder, C., Grewe, V., Yin, F., and Castino, F.: A python library for computing individual and merged non-CO_2 algorithmic climate change functions: CLIMaCCF V1.0, Geosci. Model Dev. Discuss. [preprint], https://doi.org/10.5194/gmd-2022-203, in review, 2022.

[9] Matthes, Dietmüller, Dahlmann, K., Frömming, C., Peter, P. Yamashita, H., Grewe, V. Yin, F., Castino, F., 2023 (submitted): Updated algorithmic climate change functions (aCCF) V1.1: Evaluation with AirClim, GMDD.

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