Operational opportunities and challenges for addressing air transport's non-CO_2 environmental impacts

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Introduction

Air transport's total environmental impact results from both its CO_2 and non-CO_2 emissions (e.g., NO_X, PM, SO_X, water vapor and subsequent formation of contrail-cirrus clouds). Most of the non-CO_2 climate warming effects are due to contrails and NO_x emissions and are short-lived compared to CO_2 emissions which accumulates in the atmosphere for hundreds of years (Figure 1). According to the Intergovernmental Panel on Climate Change Sixth Assessment Report[1], the effective radiative forcing from historic non-CO_2 emissions up to 2018 is estimated to account for more than half of the aviation net warming effect. However, the level of uncertainty from the non-CO_2 effects is eight times higher than that of CO_2, in part due to the lack of estimates from Earth System Models (ESMs)[2]. Nevertheless, the climate warming footprint of aviation is larger than its carbon footprint alone, highlighting that non-CO_2 effects are non-negligible and may be a potential mitigation lever to reduce aviation's total short-term environmental impact.

The air transport industry's priority has been and should remain on reducing CO_2 emissions because of their long-term cumulative warming effect. Leveraging non-CO_2 climate drivers (e.g., contrails) may potentially offer a means for the air transportation sector to further advance in decoupling growth from emissions and reduce its total environmental short-term impact as other decarbonization levers have sufficient time to scale up and develop into fully sustainable solutions.

Potential non-CO_2 mitigation solutions include flight trajectory optimization, fuel optimization, and new engine technologies. Here we provide a high-level overview of the main scientific, technological and operational challenges associated with flight optimization and how the air transport industry is working together with researchers and other stakeholders to find solutions.

1 IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, doi:10.1017/9781009157896.

2 Lee, D.S. (2020). "The Contribution of Global Aviation to Anthropogenic Climate Forcing for 2000 to 2018." *Atmospheric Environment*, 244, p.117834, https://doi.org/10.1016/j.atmosenv.2020.117834.

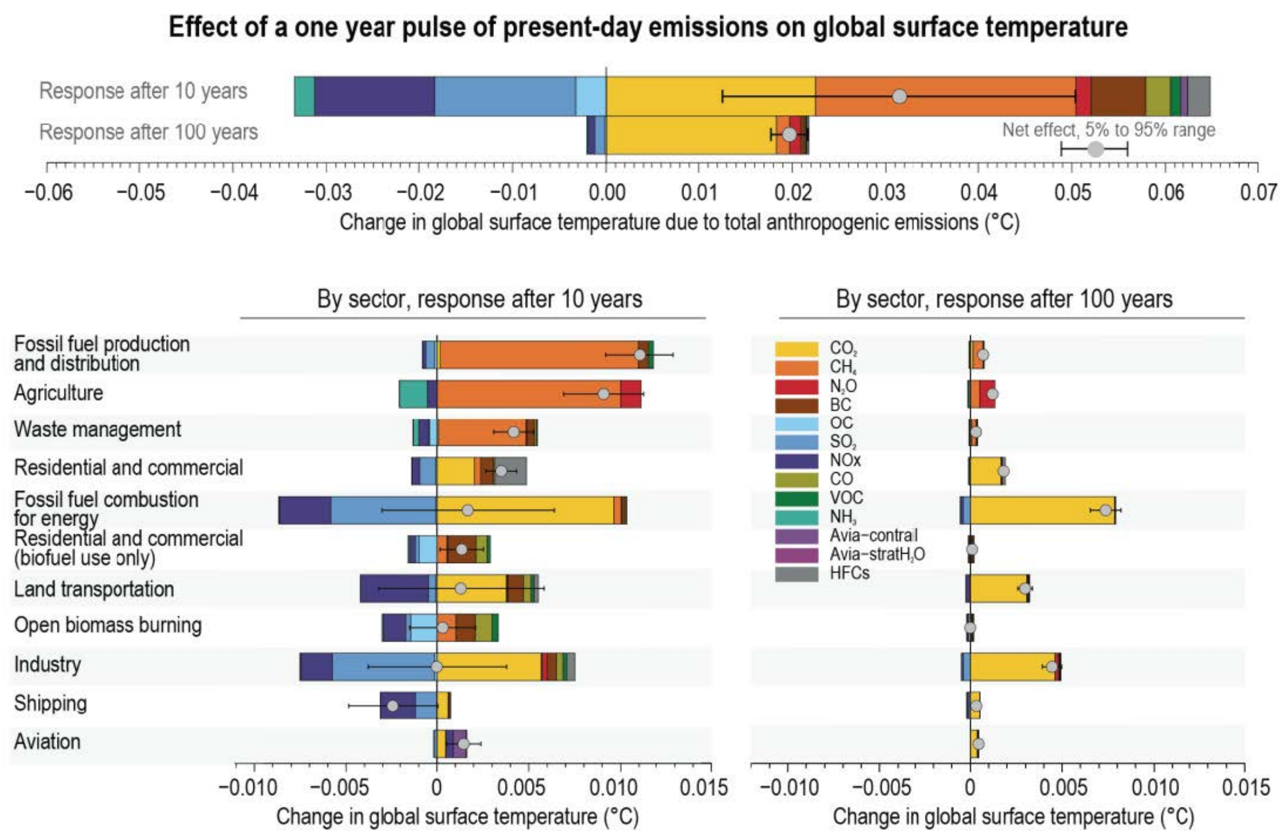

FIGURE 1: Global surface temperature change 10 and 100 years after a one-year pulse of present-day emissions. Non-CO_2 emissions account for more than half of air transportion's short-term climate impact, although the uncertainties are much higher than for CO_2.[1]

Flight trajectory climate-optimization

Operational flight trajectory climate-optimization strategies involve rerouting aircraft either vertically or horizontally to avoid climate-sensitive airspace, for example, where persistent warming contrails are likely to form under favourable atmospheric conditions. Contrails form and persist in cold, humid air where the relative humidity is saturated with respect to ice in so-called Ice Supersaturated Regions (ISSRs). Studies have shown these regions are horizontally quite large (~100 – 250 km), but vertically thin (~1000 – 4000 ft on average), thus, in some cases, deviating flights above or below these regions could be more efficient given the implied CO_2 trade-off (Figure 2). Additionally, studies indicate that only a small fraction of flights contribute to the majority of contrail warming, therefore not all flights would need to be rerouted. However, the challenge lies in the fact that this small percentage of flights may be in the same airspace, rendering operational and safety obstacles.

On the surface, it seems that flight climate-optimization could be implemented easily and cost-effectively, however, there are still significant scientific, technological, and operational issues and challenges that need further investigation, including the crucial question of which flights should be diverted, given the great uncertainty in predicting climate-sensitive regions and estimating the associated climate impacts.

Airlines (e.g., Lufthansa, Delta, American Airlines, Etihad, SWISS, and AirFrance-KLM) are working together with scientists and other stakeholders through various cross-collaborative projects such as the German project D-KULT (led by DLR and funded by the German Federal Aviation Research Programme - LuFo) and the SESAR EU-funded

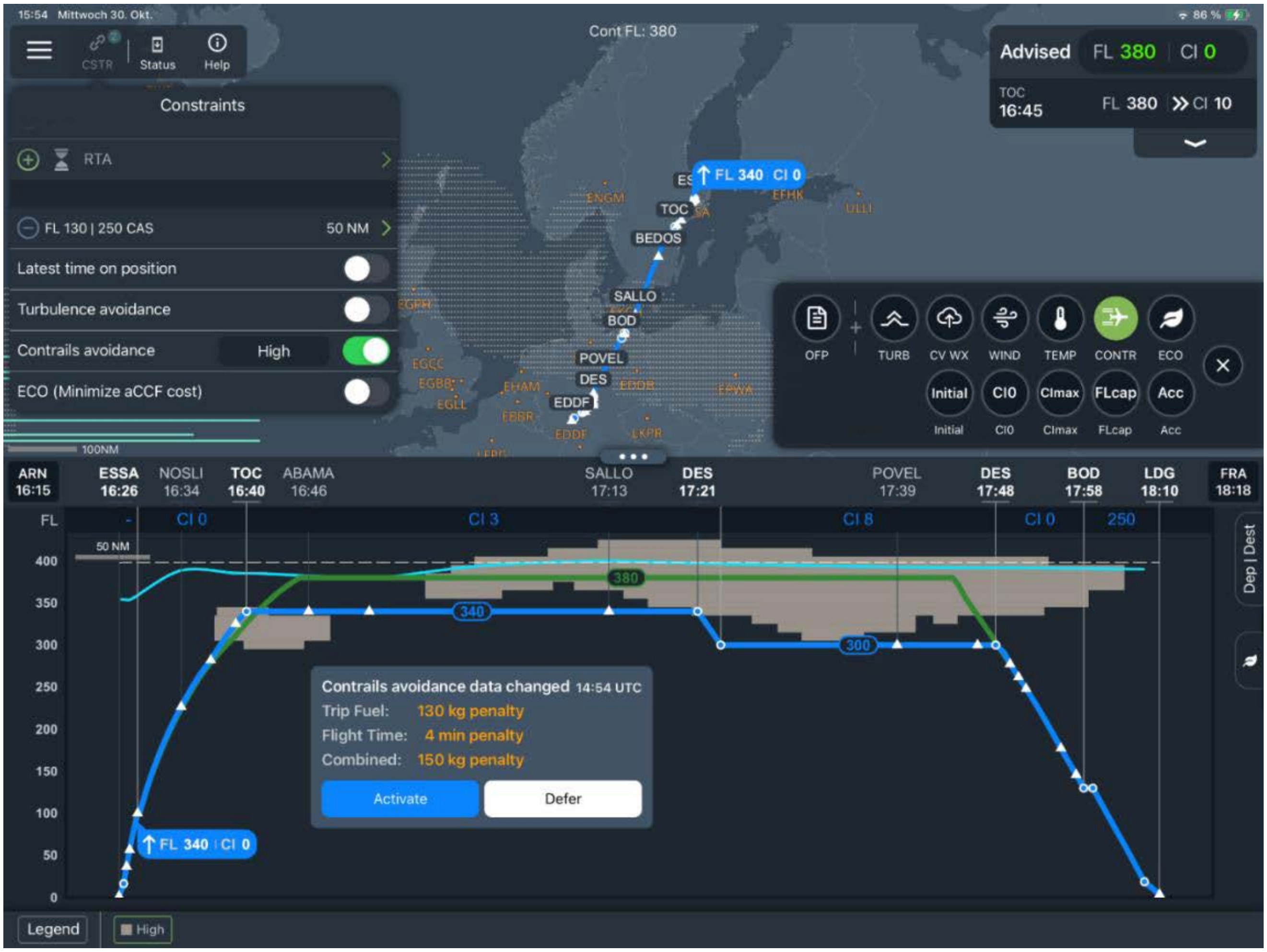

FIGURE 2: A sample flight from Stockholm to Frankfurt was optimized using PACE's FPO-Cloud prototype (see below), resulting in a lower flight profile including a flight level change (step descent) to avoid climate-sensitive regions.

projects (e.g., CICONIA) to investigate the feasibility of navigational avoidance strategies and their impact on flight operations and on the airspace as a whole.

Science and technology

A fundamental requirement of an effective and verifiable navigational avoidance strategies is reliable forecasts of meteorological conditions and accurate predictions of the potential non-CO_2 climate impacts at the strategic (pre-flight) and tactical (in-flight) levels. Today, both are associated with large uncertainties. Contrail-cirrus and climate response models used to estimate non-CO_2 effects are driven by inherent large uncertainties (e.g., meteorological variables, emissions estimates) and are based on highly simplified parameterizations of complex, nonlinear processes. For contrail avoidance, being able to accurately predict when and where contrails will form and persist, as well as how they will evolve over their entire lifetime, is crucial in assessing the CO_2 trade-off due to the extra fuel burn and deciding whether flights should be rerouted.

Because accurate meteorological data and climate response models are essential elements for navigational avoidance decisions, significant improvements have been made in weather forecasting models which have enhanced the forecasting skill of key variables needed to predict potential persistent contrails at cruise altitudes. National weather service providers such as Deutscher Wetterdienst (DWD) and Météo-France have made major upgrades in their forecasting capabilities of ISSRs (i.e., 2-moment ice-scheme), a critical parameter for contrail avoidance.

The work to improve ISSR forecasts is ongoing by developing and integrating new observational data including in-situ measurements and satellite imagery. Towards this end, the DWD has partnered with Lufthansa as part of the MEFKON project (LuFo-funded) to test data assimilation techniques of near real-time humidity measurements taken on-board commercial aircraft to improve ISSR and contrail forecasting and robust verification capabilities.

Using commercial aircraft to collect meteorological and atmospheric composition data in the upper atmosphere is not a new concept. Airlines have been utilizing their aircraft to help collect data for research and operational purposes in this sparse region for decades[3]. The global Aircraft Meteorological Data Relay (AMDAR) program was initiated by the World Meteorological Organization (WMO) with the objective to relay meteorological data in real time from commercial aircraft platforms in support of improved weather forecasts and applications for aviation and the wider community. Since 1994, European scientific institutions, weather services and several commercial air transportation companies have been collaborating through the MOZAIC/IAGOS programs to collect essential data on atmospheric composition and air quality. Since 2015 the IAGOS fleet are also providing near-real time data of ozone and carbon monoxide, and of water vapour (since 2019), for operational users. Boeing, Airbus and government-funded projects (e.g., NASA, US DOE ARPA-E) are working towards developing and commercializing low-cost, higher-accuracy water vapor sensors that can be installed on more commercial aircraft to support contrail avoidance systems and verification.

To complement in-situ measurements, ground-based cameras, satellite imagery and artificial intelligence (AI) are being utilized as additional sources of data for navigational avoidance system validation. In addition, satellite imagery and artificial intelligence technologies are being exploited to improve weather forecasting models through data assimilation.

Operations

From an operational perspective, climate-optimized rerouting has significant implications and can pose numerous challenges for both aircraft operators (AO) and air navigation service providers (ANSPs). Rerouting of flights for climate benefits implies extra fuel burn and can lead to flight schedule modifications, increased workload for pilots, dispatchers and air traffic controllers, potential safety issues and other concerns. To provide actual data and to help identify potential problems, airlines and other industry stakeholders are participating in live contrail avoidance trials.

Coordination, communication, and collaboration among all stakeholders will be essential for navigational avoidance strategies to be implemented. Live trials involving multiple stakeholders are designed to test and evaluate different options for operational management: Airline operator-led and/or ATC-led. Exercises conducted by DFS (Deutsche Flugsicherung) showed that in high traffic areas such as Central Europe, there was a significant reduction in airspace capacity and handling of air traffic. From an airline and an ANSP point of view, navigation avoidance strategies to minimize the impact of warming contrails will involve trade-offs. Concepts such as Flight and Flow Information for a Collaborative Environment (FF-ICE) and Trajectory Based Operators (TBO) provide opportunities to enable airlines and ANSPs to share information and make decisions regarding such trade-offs.

For the selected complex use cases such as when climate-sensitive areas were close to main flight paths, the workload of air traffic controllers increased while at the same time airspace capacity is reduced. In addition, it is important to understand how adverse secondary effects can be avoided and checked (e.g., additional congestion in airspace ending up in slots, high-speed flying, detours around even more congested airspaces). Knock-on effects for neighboring airspaces should also be considered.

Ongoing projects are also investigating the feasibility of integrating available information on weather and climate impacts into existing flight planning and air traffic management (ATM) processes to avoid climate-sensitive

3 https://www.iata.org/contentassets/726b8a2559ad48fe9decb6f2534549a6/aviation-contrails-climate-impact-report.pdf

regions. Lufthansa Systems and PACE have each added a module to their software for flight planning (Lido Flight 4D), pre- and in-flight optimization (FPO cloud) to avoid climate-sensitive regions. The integration of climate-relevant data into operational tools and processes raises the question of the quality of the overall process for calculating climate-optimized flight routes, and requires concepts on further developments, e.g. masking of data. This also includes verifying whether and how often, for example, contrails can be successfully avoided.

To better understand this, large-scale live trials such as that conducted by five German Airlines as part of the “100-Flights Trial”, provide the opportunity to test newly developed prototype tools and meteorological service data for climate-optimized flight planning and execution. Assessing whether a rerouting was successful is a complex task that currently cannot be addressed by any of the existing methods alone. Rather, analysis concepts must be developed, particularly for contrail avoidance, that utilize various climate response model calculations as well as satellite observations for verification. These observations play a crucial role in the analysis of individual diverted flights, as they enable independent verification of contrail formation. The results of the climate models must also be further analyzed to ensure that follow-up measures have a positive impact on the climate. In addition to the ongoing evaluation, concepts for risk analysis and the determination of confidence intervals for the parameters that play a decisive role in the forecast quality are currently being developed to adequately consider the uncertainties in models and input data.

Conclusions

Operational mitigation strategies such as climate-optimized flight rerouting could be a potential lever for the air transport industry to reduce their short-term climate impact if proven viable and reliable verification possible. To assess operational feasibility, trade-offs and interdependencies associated with navigational avoidance such as extra fuel consumption, safety issues especially in crowded airspaces, additional workload for operational staff, flight schedule modifications and passenger experience, etc. must be carefully evaluated and understood before mitigation processes are implemented. Effective exchange of reliable and accurate data and collaborative decision-making among multiple stakeholders will be crucial. Ongoing collaborative efforts between researchers and industry stakeholders are working together to address these issues. To ensure effective outcomes, it’s essential that we learn from the ongoing trials before moving forward with any final conclusions or policies.