Operational Opportunities to Reduce Climate Effects of Contrails

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Introduction

According to current scientific understanding, the impact of persistent contrails and aircraft-induced cloudiness on the climate is significant as they affect the Earth's radiative balance. These contrails, which form in the immediate wake of an aircraft at cruise altitudes, along with the associated contrail cirrus clouds, are estimated to have a notable radiative forcing (RF) effect and, on balance, contribute to global warming.

However, uncertainty on the magnitude of the contribution is considerable, especially on a smaller scale / locally and for individual flights. The related upper air chemistry and physical processes are complex and not well understood (such as the impact of background aerosols and interaction with existing cirrus). Additionally, missing data on the humidity field in the upper atmosphere and on particulate matter emissions from engines limits understanding of contrail formation and in particular, persistence.

As research on the scientific basis of contrail formation, and the related radiative forcing and climate impacts continues to evolve, it is essential to assess the operational opportunities as well to reduce these impacts. How can we effectively avoid formation of warming aircraft-induced cloudiness in practice, in a safe and efficient way?

This article relates to the findings in the ICAO Committee on Aviation Environmental Protection (CAEP) report on "Operational Opportunities to Reduce Climate Effects of Contrails and other non-CO_2 Emissions" [1], written by operational experts and contrail scientists under leadership of the two authors. The report identifies potential operational measures, which are embedded in various concepts of operations, along with the associated challenges and interdependencies with other aspects of flight, such as flight time and fuel consumption. To address these challenges, future opportunities and enablers have been identified to support the effective and efficient mitigation of contrails.

Trajectory adjustment

Three pathways are available for reduction of warming contrails: 1) through operational measures, 2) through adaptation of engine and aircraft design, and 3) through modification of fuel type and composition.

Note. Experimental evidence is available that low-aromatic sustainable aviation fuels (SAF) may reduce the soot and ice number concentrations, reducing contrails and more importantly the warming potential of contrails, but this needs more research and validation.

The ICAO CAEP report focuses on operational measures, and in particular, trajectory adjustments of flight: horizontally, vertically, or in time, either planned before the flight or applied during flight. The different pathways are not mutually exclusive and could complement and/or impact each other.

1 ICAO CAEP Report on Operational Opportunities to Reduce Climate Effects of Contrails and Other Non-CO_2 Emissions, to be published.

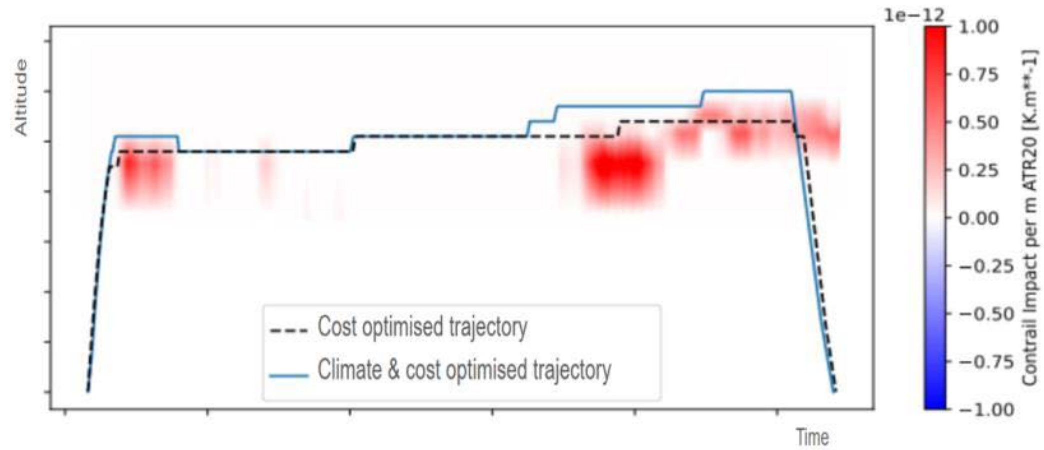

FIGURE 1: Example of vertical trajectory adjustment to reduce climate impact of contrails.

Challenges

Multiple challenges are identified for effective and safe implementation of trajectory adjustment for contrail mitigation. These challenges relate to:

- the availability of relevant meteorological data (especially relative humidity to ice),
- the modeling of persistent contrail formation and calculation of subsequent climate impact,
- the verification of the effectiveness of interventions,
- the flight planning capabilities of the operator
- and the required flexibility of air traffic management (ATM).

The climate impact from contrails is in general quantified with low confidence, compared to that of CO_2. Uncertainties exist for both the spatial and temporal characteristics of individual contrails, as well as the climate impact of individual contrails, multiple contrails and the combined global impact.

A key element is the availability of relevant meteorological data, especially relative humidity with respect to ice (RH_i) at flight altitudes with sufficient accuracy and at sufficient temporal and spatial scales. Other relevant scientific gaps relate to the (unknown) impact of background emissions and the cloud aerosol interaction and the impact of changing fuel composition.[2]

Potential concept of operations

Guidance for operational measures to avoid non-CO_2 climate effects is not yet available. Several operational concepts for trajectory adjustment can be identified. These concepts involve all operational stakeholders (the flight planner, the airline operational control center, the flight crew and the ANSPs). The choice of concept may depend on the mitigation objective, the region of applicability, the timeframe for decision-making, the availability of observations, forecasts, and modeling tools, and on the decision initiator (Figure 2).

The decision and intervention for navigational adjustment can be made pre-flight (during flight planning), strategically in-flight (in anticipation), or tactically in-flight through ATC intervention. Pre-flight interventions may be preferential from a workload and flight planning perspective. On the other hand, tactical interventions may be preferential to reduce the forecasting window. Tactical intervention may reduce the actual regions of the airspace to be avoided and enable verification with real-time observational data.

Flight operations are by essence a multiple stakeholder cooperative effort and given the potential interdependencies between contrails avoidance at scale and for specific flights, the initiative for pre-flight or in-flight trajectory adaptation might be handled by the airline operator, the ANSP or a collaboration between both. The ANSP has the bigger picture and oversees the complete flow of operations in their control area, ensuring that the global flow of

2 ICAO CAEP Impacts and Science Group (ISG), "Contrail Science Workshop Report," [to be published]

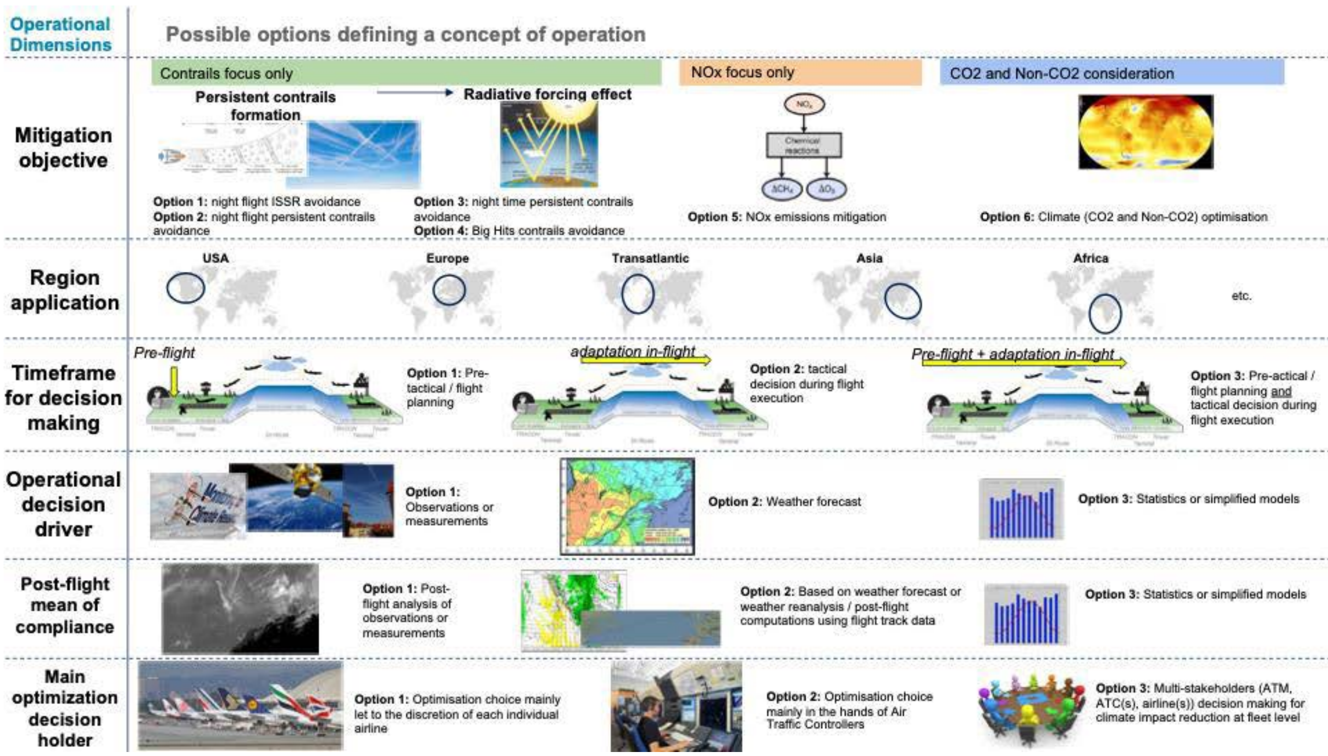

FIGURE 2: Possible options defining a concept of operations (from the EU project Ciconia).

operations matches all the criteria for safe operations. However, the ANSP stakeholders do not necessarily have the knowledge of airlines' strategies in terms of mission or cost management and have less accurate models in terms of aircraft performance or status which may lead to sub-optimal trajectory optimization.

To date, none of these concepts are tested or implemented in practice on a large-scale; however, they may serve as basis for further assessment and research. Large-scale trials and verification action will be required to assess the effectiveness and feasibility of these interventions. Technological and operational enablers will be essential for effective and safe implementation in flight operations and will be discussed further below.

Interdependencies

Current flight paths are mainly designed to minimize flight time or fuel consumption (cost), within the existing airspace and route structure, both which may be impacted with changes in the optimization strategy to include navigational contrail avoidance efforts. Airspace capacity and potential flight efficiency of other airspace users may be affected as well, especially in areas of congested airspace.

Consequently, navigational avoidance may result in increased climate forcing due to increased greenhouse gas emissions (primarily CO_2) associated with the specific flight and potentially other impacted flights. Efforts to balance the net climate impact from various CO_2 and non-CO_2 effects must be considered when implementing operational strategies to reduce contrails.

Crucially, safety must not be negatively impacted. Depending on the capacity of the airspace, the airspace structure and traffic density, ATM may lack flexibility to allocate climate-compatible flights quickly and safely without reducing airspace capacity. Areas prone to contrails formation such as Europe and the northeastern US could be more challenging to address due to high traffic density and congestion.

Targeting only the flights with significant contrail climate forcing might prove to be (partially) effective and less operationally impactful as only a portion of flights are responsible for most of the warming contrail formation.

However, as contrail formation and persistence are dependent on atmospheric conditions, this percentage may vary, and these flights are likely to be co-located in space and time. An initial option could initially be to divert flights only if there is minimal or no fuel penalty, avoiding additional CO_2 emissions.

The multiple trade-offs and interdependencies should be evaluated with respect to airspace, airport, other flights, and network operations. The following aspects should be considered when selecting a strategy for intervention:

- Impact on safety
- Impact on flight time
- Impact on fuel consumption and CO_2 emissions
- Impact on airspace capacity and predictability
- Impact on workload for operational staff
- Impact on schedules and passenger experience
- Overall net climate impact

Enablers

Without an improved scientific understanding of all physical, chemical, and meteorological processes involved and improvements in forecast accuracy, contrail mitigation may prove to be impractical. Uncertainties exist for both the spatial and temporal characteristics of individual contrails, as well as the climate impact of individual contrails, multiple contrails, and the combined global impact.

Enablers have been identified to address these uncertainties:

- *Weather data measurement and weather forecasting*
- *Forecasting of contrails and persistence*
- *Contrail observation*
- *Climate impact modeling*
- *Flight plannings*
- *Airspace Capacity and ATM flexibility*
- *Flight Execution*
- *Verification*
- *Collaboration and continuous improvement efforts*

These enablers, ranging from installation on-board humidity sensors and improved contrail modeling to contrail observation and flight planning tools, will contribute to progress towards feasible and effective operational contrail impact mitigation. See the ICAO CAEP report[3] for more detailed information.

The importance of quantifying the climate impact of persistent contrails, relative to CO_2, cannot be understated. Because of the uncertainties and trade-offs involved, it may be inappropriate to recommend definitive actions on aviation non-CO_2 emissions since they may be of limited effect or have unintended consequences on the global climate. However, the potential climate benefits justify efforts to address scientific gaps and continue studying and testing potential operational concepts.

Looking Ahead

The findings of the ICAO CAEP report establish a basis of understanding of operational opportunities to mitigate non-CO_2 effects. While the scientific understanding of contrail formation, persistence and climate impact and the impact of new fuel composition continues to evolve it is essential to also continue progressing the understanding of operational considerations for the mitigation of adverse climate impacts from contrails.

3 ICAO CAEP Report on Operational Opportunities to Reduce Climate Effects of Contrails and Other Non-CO_2 Emissions, to be published.