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ENVIRONMENT

Report on

Operational Opportunities to Reduce Climate Effects of Contrails and Other Non-CO2 Emissions

Deliverable of ICAO Committee on Aviation Environmental Protection (CAEP)

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Notes

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Disclaimer

EXECUTIVE SUMMARY

This report explores operational measures to avoid non-CO_2 climate effects from aviation and as a first step a synthesis of existing literature and research is presented.

The focus is on contrail mitigation through horizontal and vertical trajectory adjustments of the flight path, both in-flight and in the flight planning phase. Limited information has been found in this literature review on operational measures to avoid the climate impact of nitrogen oxides (NO_x). The net-NO_x effect of the operational measures on the climate is difficult to comprehend due to the strong dependence on the background atmosphere and the non-linear atmospheric chemistry, and this may change in time. For other non-CO_2 emissions, no information has been found on operational measures to reduce the related climate effects.

Multiple challenges are identified for effective and safe implementation of trajectory adjustment for contrail mitigation. These challenges are related to the accurate prediction of the location of ice-supersaturated regions (ISSR), the calculation/modeling of the climate impact of the persistent contrails, the verification of the effectiveness of the interventions, the flight planning capabilities of the operator and the required flexibility of air traffic management (ATM). 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.

Several potential concepts of operations are explored in this report, depending on the main initiator (airline or the air navigation service provider - ANSP), the choice of climate impact and the associated metrics, and the timing of intervention, together with associated challenges and interdependencies. The impact on safety, fuel consumption, CO_2 emissions, airspace capacity and workload are all addressed in the report.

The concepts are neither tested nor implemented in practice but could serve as basis for further assessment and research. Technological and operational enablers will be necessary for effective and safe implementation in future operations.

While there is scientific consensus that persistent contrails, on balance, contribute to global warming, uncertainty on the magnitude of the contribution is considerable, especially on a smaller scale / locally and for individual flights. Because of the uncertainties and the interdependencies especially with respect to fuel and CO_2 emissions and airspace capacity, a cautious approach is recommended on definitive courses of action or policies for contrail management since they may be of limited effect or have unintended consequences on climate.

Contrails are not expected to disappear with new fuel composition or new engine technology and operational measures for contrail management will remain meaningful.

This document is not guidance material but serves as a reference for any stakeholder wishing to explore mitigation of the climate impacts from contrail cirrus and other non-CO_2 emissions through operational measures and it complements the Committee on Aviation Environmental Protection (CAEP) Impacts and Science Group (ISG) Contrail Science Workshop Report, which addresses the scientific knowns and unknowns of contrail formation, persistence and climate impact.

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ACRONYMS AND ABBREVIATIONS

ACCF	Algorithmic climate change function
ADS-B	Automatic Dependent Surveillance-Broadcast
AIC	Aircraft-induced cloudiness
ANCEN	Aviation Non-CO_2 Expert Network
ANSP	Air navigation service provider
AOC	Airline operations centre
APCEMM	Aircraft plume chemistry, emissions, and microphysics model
ATC	Air traffic control
ATCO	Air traffic controller
ATFCM	Air traffic flow and capacity management
ATM	Air traffic management
ATM4E	(SESAR) Air Traffic Management for Environment
ATR	Average temperature response
BADA – APM	(EUROCONTROL) Base of Aircraft Data – Airline Performance Model
CAEP	(ICAO) Committee on Aviation Environmental Protection
CCF	Climate change functions
CCI	Cumulative climate impact
CDM	Collaborative Decision Making (initiative)
CoCiP	Contrail Cirrus Prediction Tool
CONOPS	Concept of operations
COOP	Contrail Observation Program
CO_2	Carbon dioxide
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
EF	Energy forcing
EFB	Electronic Flight Bag
ERF	Effective radiative forcing
FF-ICE	Flight & Flow Information for a Collaborative Environment
FL	Flight level
FMS	Flight management system
GEO	Geostationary Earth orbit
GTP	Global temperature change potential
GWP	Global warming potential
H_2	Hydrogen (gas)
IAGOS	In-service Aircraft for a Global Observing System
ICAO	International Civil Aviation Organization
ISSR	Ice-supersaturated region

ISG	(CAEP) Impacts and Science Group
LEO	Low Earth orbit
LIDAR	Light detection and ranging
LTO	Landing and take-off
MUAC	Maastricht Upper Area Control Centre
NATS	North Atlantic Track System
NGO	Non-governmental organization
NO_x	Oxides of nitrogen
NvPM	Non-volatile particulate matter (soot)
NWP	Numerical weather prediction
OCC	Operational control centre
OTS	Organized track system
REACT4C	Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate
RF	Radiative forcing
RH_i	Relative humidity with respect to ice
S-A	Schmidt-Appleman (criterion)
SAF	Sustainable aviation fuels (SAF) are defined as renewable or waste-derived aviation fuels that meets sustainability criteria and can be used in blends with or in place of traditional jet fuels.
SO_x	Sulphur oxide
	Sea surface temperature
TAS	True airspeed
TBO	Trajectory-based operations
TT	Thermal tropopause
UHC	Unburned hydrocarbons
WG2	(CAEP) Airports and Operations Working Group
WG3	(CAEP) Emissions Working Group

CHAPTER 1 – BACKGROUND

1.1 Introduction

According to current scientific understanding the impact of aviation on the climate stems from CO_2 emissions and non-CO_2 emissions, including persistent condensation trails (or contrails) and aircraft-induced cloudiness. These contrails, which may form in the immediate wake of an aircraft at cruise altitudes, and related contrail cirrus, collectively referred to as aircraft induced cloudiness (AIC), are estimated to have a significant radiative forcing (RF) effect, contributing to global warming.[1]

Contrail cirrus radiative forcing is expected to increase over time largely due to the projected increases in air traffic and the expected upward shift in flight altitudes.[2] The increase in contrail cirrus radiative forcing due to the projected increase in air traffic volume is not expected to be compensated by reduced soot emissions resulting from new fuels or changes in engine technology[3] and thus operational measures for mitigation will remain of interest.

Three pathways are being explored for reduction of warming contrails:

- operational measures,
- adaptation of engine and aircraft design,
- modification of fuel type and composition.

This document focuses on operational measures for reducing non-CO_2 impacts in the current aircraft equipage and ATM environment and identifies potential future technological and operational opportunities in anticipation of new engine and aircraft technology and fuel composition.

These three pathways cannot be seen separately, as the result of each pathway depends on or may be impacted by the deployment of the other pathways. In general, operational improvements will complement the improvements from new fuel composition and engine technology.

Non-CO_2 emissions from aviation, such as nitrogen oxides (NO_x), sulfur oxides (SO_x), soot – also referred to as non-volatile particulate matter (nvPM) –, water vapour, and unburned hydrocarbons (UHC) have a direct or indirect warming and/or cooling effect as well, but are less pronounced in terms of global radiative forcing mean estimate and as with contrail cirrus, the magnitude remains highly uncertain. See Figure 1-1.

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[1] Lee et al., "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018," *Atmospheric Environment vol. 244* (2021) https://doi.org/10.1016/j.atmosenv.2020.117834

[2] Gryspeerdt et al., "Operational differences lead to longer lifetimes of satellite detectable contrails from more fuel efficient aircraft," Environ. Res. Lett. vol. 19-8 (2024) https://doi.org/10.1088/1748-9326/ad5b78

[3] Bock, L. and Burkhardt, U., "Contrail cirrus radiative forcing for future air traffic," *Atmos. Chem. Phys. vol. 19-12* (2019) https://doi.org/10.5194/acp-19-8163-2019

Figure 1--1 (Effective) Radiative forcing from CO_2 and non-CO_2 emissions.

In general, flight routes are optimized for fuel, costs and flight time within the operational constraints. Operational measures to reduce fuel use and CO_2 emissions are already well documented, for instance in International Civil Aviation Organization (ICAO) Doc 10013 Operational Opportunities to Reduce Fuel Burn and Emissions and practiced in aviation. Guidance for operational measures to avoid non-CO_2 climate effects is not yet available.

For data collection, a literature review of available and on-going research and operational trials was conducted in collaboration with the ICAO Committee on Aviation Environmental Protection (CAEP) Impacts and Science Group (ISG). The assessments in this report are made for a contemporary aircraft equipage and ATM environment and for near future opportunities.

Contents of the report

This report presents as a first step a synthesis of existing literature on possible operational measures to reduce contrail formation, aircraft induced cloudiness (AIC) and possibly other non-

CO_2 effects. It also identifies potential future technological and operational enablers and opportunities to reduce these non-CO_2 effects with minimal impact on other aspects of flight.[4]

Background information on contrail formation, radiative forcing, climate impact and metrics is included in Chapter 1 to serve as initial reference. However, more extensive information on the science behind contrail formation and the climate impact can be found in the CAEP/13 ISG Contrail Science Workshop Report and several syntheses in literature.[5]

Operational mitigation of contrails could entail actively rerouting aircraft either horizontally or vertically to avoid airspace in which contrails are likely to form and persist under favourable atmospheric conditions. Deviation is possible in both planes, but as discussed later in Chapter 2, vertical rerouting may be, in general, more feasible than horizontal rerouting.[6] These navigational avoidance opportunities and considerations are more thoroughly discussed in Chapter 2.

Effective use of operational avoidance measures requires an accurate forecast of where contrails may occur and persist in time and space, together with an accurate prediction of the climate impact of the contrails that are produced. Currently, numerical weather prediction (NWP) and climate models suffer from large uncertainties in their representation of relative humidity, ice-supersaturation and the associated climate impact of contrail cirrus.

Operational measures for contrail avoidance may impact other (environmental) parameters and operational aspects, such as fuel consumption, flight time and airspace capacity. These interdependencies can play an important role in the successful implementation of operational measures and may require further study and/or technological development to avoid significant trade-offs. These interdependencies are addressed in Chapter 2.5.

Operational procedures for NO_x emission reductions are documented but only for take-off and climb operations, where reduced-thrust take-off (when feasible and safe to do so) could considerably reduce NO_x emissions during these flight segments due to the lower engine operating temperature.[7] Operational procedures for NO_x reductions during cruise are only briefly touched upon in existing literature and require more scientific understanding on the impact. Operational measures to mitigate other non-CO_2 emissions are not available. These findings are discussed in Chapter 3.

Technological and operational opportunities are identified for the near-future and are addressed in Chapter 4. These opportunities potentially help to reduce the climate impact of these non-CO_2 emissions and contrails while minimizing impacts on other aspects of the flight.

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[4] ICAO CAEP/13 Work Programme (2021)

[5] Kärcher, B., "Formation and radiative forcing of contrail cirrus," *Nat Commun vol. 9-1824* (2018) https://doi.org/10.1038/s41467-018-04068-0;
Singh, D. K., Sanyal, S., and Wuebbles, D. J., "Understanding the Role of Contrails and Contrail Cirrus in Climate Change: A Global Perspective," *EGUsphere [preprint]* (2024) https://doi.org/10.5194/egusphere-2024-127

[6] Schumann, U. and Heymsfield, A., "On the lifecycle of individual contrails and contrail cirrus," *Meteorological Monographs vol. 58-1* (2017) https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0005.1;
Kärcher, B., "Formation and radiative forcing," (2018)

[7] "Effects of PANS-OPS Noise Abatement Departure Procedures on Noise and Gaseous Emissions (Cir 317)," *ICAO* (2008) https://store.icao.int/en/effects-of-pans-ops-noise-abatement-departure-procedures-on-noise-and-gaseous-emissions-cir-317

Amongst other (meteorological) factors, contrail formation and contrail characteristics are also dependent on fuel composition and on engine technology, but currently to an uncertain extent. These uncertainties will be a factor when considering operational measures for contrail mitigation. The effects of fuel composition and engine on contrails will be addressed in Chapter 5.

> *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.*[8] *Aircraft with modern engines, with higher overall efficiency and lower exhaust temperatures, may produce contrails at lower altitudes and over a larger range of cruise altitudes.*[9] *At the same time, modern engine combustion technology (e.g. lean burn) can help to reduce incomplete combustion and reduce the number of soot particles and reduce contrail formation.*[10]

This document is not guidance material but serves as a report to CAEP on the exploration of mitigation of the climate impacts from contrail cirrus and other non-CO_2 emissions through operational measures. It does not preclude the development of future guidance material on operational mitigation strategies when research evolves, enabling reliable operational guidance for every actor in the airspace (ATM, airports, airlines, pilots, private, cargo and corporate operators, national regulators, etc.).

1.2 Contrail Formation and Contrail Impact

Formation of Contrails

Condensation trails (contrails) are line-shaped ice clouds generated by jet aircraft cruising in the upper troposphere at 8–13 km altitude, FL260 to FL420. When water vapour is exhausted from an aircraft engine into sufficiently cold and humid air, it condenses and freezes, creating tiny ice crystals. The water vapour comes as a byproduct of combustion but also from the surrounding atmosphere which condenses and contributes to the ice crystal growth. The water vapour condenses onto the solid carbon particles at the exhaust of jet engines as well as onto the atmospheric (background) aerosol particles.[11]

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[8] Voigt, C., Kleine, J., Sauer, D. et al., "Cleaner burning aviation fuels can reduce contrail cloudiness," *Commun Earth Environ vol. 2-114* (2021). https://doi.org/10.1038/s43247-021-00174-y

[9] Schumann, U., "Influence of propulsion efficiency on contrail formation," *Aerospace Science and Technology, vol. 4-6* (2000) https://doi.org/10.1016/S1270-9638(00)01062-2

[10] Schumann, U., "On conditions for contrail formation from aircraft exhausts," *Meteorologische Zeitschrift, vol. 5-1* (1996) https://doi.org/10.1127/metz/5/1996/4;

"Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)," *EASA* (2020) https://www.easa.europa.eu/en/document-library/research-reports/report-commission-european-parliament-and-council;;

Teoh et al., "Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption," *Environ. Sci. Technol. vol. 54-5 (*2020) https://doi.org/10.1021/acs.est.9b05608https://doi.org/10.1021/acs.est.9b05608

[11] Kärcher, B., "Formation and radiative forcing," (2018)

Note. There is an overall framework by which contrail formation is understood for present fuels and aircraft, where contrail formation is predicted by thermodynamics alone (the Schmidt-Appleman criterion). However, contrail ice crystals are formed as the result of microphysical processes such as supersaturation and nucleation from the interaction of particles and water vapour, which might not be captured by the Schmidt-Appleman criterion.[12] *Homogeneous nucleation can result in contrail formation under clean air conditions, but more commonly it is the condensation of water vapor on soot particles in traditional rich burn combustion architectures (through heterogeneous nucleation) which is responsible for contrail formation.*[13]

Most of these contrails disappear within a few minutes, but if the aircraft flies through an area with very cold and humid air — the so-called ice-supersaturated regions (ISSRs) —the ice crystals in the contrails can persist, spread over time due to propagation by prevailing upper-level winds, and create stratiform layers of cirrus clouds that may be of great horizontal extent.

Whether a contrail can develop and persist, can be estimated with the Schmidt–Appleman (S-A) criterion on the basis of simple thermodynamic principles when the exhaust air mixed with ambient air is adiabatically cooled. The S-A criterion defines a critical temperature T_{crit}, above which contrails cannot form, and a critical relative humidity RH_{crit}, above which value contrails form.[14] See Fig 1-2. The critical temperature depends on the ambient air pressure, engine–aircraft specific parameters, and fuel properties.

Note. In general, larger aircraft produce optically thicker contrails. Near ice saturation (and above) conditions, contrail width and optical depth increases with the fuel flow rate.[15]

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[12] Jensen et al., "Spreading and growth of contrails in a sheared environment," *Atmospheres vol. 103-D24* (1998) https://doi.org/10.1029/98JD02594;
Kärcher B. and Voigt C., "Susceptibility of contrail ice crystal numbers to aircraft soot particle emissions," *Geophysical Research Letters vol. 44-15* (2017) https://doi.org/10.1002/2017GL074949
[13] Kärcher et al., "The microphysical pathway to contrail formation," Atmospheres vol. 120-15 (2015) https://doi.org/10.1002/2015JD023491
[14] Wolf K., Bellouin N., Boucher O., "Long-term upper-troposphere climatology of potential contrail occurrence over the Paris area derived from radiosonde observations," *Atmos. Chem. Phys. vol. 23-1* (2023) https://doi.org/10.5194/acp-23-287-2023
[15] Jeßberger et al., "Aircraft type influence on contrail properties," *Atmos. Chem. Phys. vol. 13-23* (2013) https://doi.org/10.5194/acp-13-11965-2013

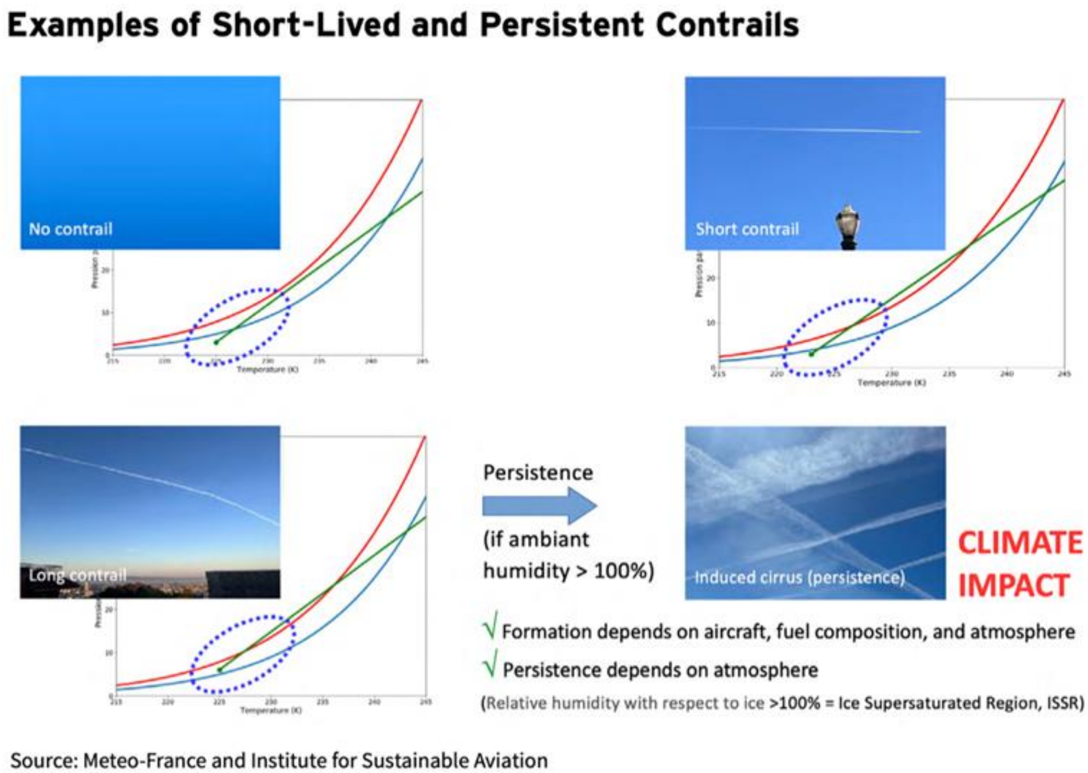

Figure 1--1 The S-A criterion indicating the formation of contrails during adiabatic cooling, based on the saturation level with respect to liquid water (upper/red curve) and to ice (lower/blue curve).[16]

Depending on surrounding atmospheric conditions, contrails can be short- or long-lived (also referred to as persistent contrails). Generally, contrails that last beyond a few minutes are referred to as 'persistent contrails', although there is not a precise definition, and definitions of 'persistence' vary in the literature. The World Meteorological Organization (WMO) defines long-lived or persistent contrails, "Cirrus Homogenitus", as those that remain for at least 10 min.[17] Only the persistent contrails that spread to form contrail-cirrus (potentially to hundreds of km²) may have a significant radiative effect (see below).

Persistent contrails may persist up to 8 to 10 hours and sometimes more, and for 3 hours on average. Aircraft condensation trails may undergo a fairly rapid state of change and may display a variety of transient shapes. Persistent contrails that disperse and do not retain their linear shape are referred to as contrail cirrus, and together with persistent contrails are collectively referred to as aircraft-induced clouds or cloudiness (AIC).[18]

The contrail lifetime may be reduced in regions with turbulence and windshear. On the other hand, vertical up-winds (which typically occur in cumulus clouds or thunderclouds) may extend

[16] Cathcart et al., "Understanding Contrail Management: Opportunities, Challenges, and Insights," *RMI* (2024) https://rmi.org/insight/understanding-contrail-management-opportunities-challenges-and-insights/
[17] "International Cloud Atlas," *WMO* (2017) https://cloudatlas.wmo.int/aircraft-condensation-trails.html
[18] Kärcher, B., "Formation and radiative forcing," (2018)

the contrail lifetime, because these up-winds may lift the contrail in cold and ice-supersaturated regions.[19]

AIC	Short-lived	Long-lived	
Ice cloud type	Contrail	Persistent contrail	Contrail cirrus
Morphology	Line shaped	Line shaped	Irregularly shaped
Meteorological condition	Ice subsaturated	Ice supersaturated	
Duration	0.1–10 min	10 min–10 h	
Depth	100 m	100–1000 m	
Width	10–100 m	0.1–10 km	<100 km
Length	0.1–10 km	0.1–10 km	<100 km
RF potential	Negligible	Small	Large

Table 1 Characteristics of Contrails and Contrail Cirrus (Bernd Kärcher, DLR, 2018)

The ISSRs have their own internal variability. The ice-supersaturation conditions inside an ISSR are in general heterogeneous on a small-scale and can be inconsistent in both vertical and horizontal extent.[20] Based on persistent contrail observations in some world areas, the average spatial scale of ISSRs is estimated to be 150 km to several hundred kilometers wide (in the horizontal) and a few hundred to a few thousand feet in the vertical with a very wide horizontal variability.[21] [22]

The ISSRs are relatively rare depending on the latitude and weather: typically, 10-15% of the time over the UK as example.[23] In high density air traffic regions such as Europe and the US East coast the annual mean contrail cirrus cover can be up to 10% of the sky area, and on average 0.09% of the global sky area.[24] [25] The North Atlantic is interesting to note as contrail prone due to the traffic density at cruising altitude and the regular presence of ISSRs (refer to regional differences in fig 2.2).

[19] Rosenow, J. and Fricke H., “Individual Condensation Trails in Aircraft Trajectory Optimization,” *Sustainability vol. 11-21* (2019) https://doi.org/10.3390/su11216082
[20] Tan, X. et al., “An assessment of the radiative effects of ice supersaturation based on in situ observations,” *Geophysical Research Letter vol. 43-11* (2016) http://doi.org/10.1002/2016GL071144
[21] Gierens, Spichtinger, ”On the size distribution of ice- supersaturated regions in the upper troposphere and lowermost stratosphere”, Ann. Geophys., 18, 499–504, 2000.
[22] Schumann, U. and Heymsfield, A., “On the lifecycle of individual contrails and contrail cirrus,” *Meteorological Monographs vol. 58-1* (2017) https://doi.org/10.1175/AMSMONOGRAPHS-D-16-0005.1;
[23] Lee et al., “Uncertainties in mitigating aviation non-CO2 emissions for climate and air quality using hydrocarbon fuels,” *Env. Sciences: Atmospheres vol. 23-12* (2023) https://doi.org/10.1039/D3EA00091E
[24] Burkhardt, U. and Kärcher B., “Global radiative forcing from contrail cirrus,” *Nature Clim Change 1* (2011) https://doi.org/10.1038/nclimate1068
[25] Sausen, Gierens,”A Diagnostic Study of the Global Distribution of Contrails Part I: Present Day Climate”, (1998)

As based on recent modelling, 40.2 million flights collectively flew 60.9 ×109 km in 2019, of which 24% of flights and 5% of the annual distance flown formed persistent contrails. [26] These persistent contrail segments have a mean lifetime of 2.4h.

In order to assess the climate impact of individual aircraft flights, e.g. as input for route optimization or for prediction of contrail cover in an area with intense air traffic day by day, one needs a model which is able to compute contrail properties for individual flights as well as for a large fleet of aircraft regionally and globally with short computation times.

Various contrail prediction models have been and continue to be developed. These models utilize atmospheric inputs from NWP tools along with aircraft and air traffic information to predict the formation and evolution of contrails. Some models also utilize satellite observations (where the satellite imagery is of sufficient coverage, spatial resolution and temporal frequency) to enhance contrail identification. These models may also generate an estimate of the radiative cloud forcing from the assumed contrail properties (see paragraph on Climate Impact Models).

Tropopause

A correlation exists between contrail formation layers and the thermal tropopause (TT) and the jet stream maximum.[27] By definition, the TT is associated with the lowest temperature in the atmosphere and with a lack of vertical mixing and humidity exchange with the stratosphere. Therefore, advected humid air from lower altitudes (driven by convection or other atmospheric processes) is likely to aggregate just below the TT. The combination of low temperatures, adiabatic cooling, and enhanced relative humidity is favourable for ice cloud formation.

In general, non-persistent contrails form at the tropopause level and around 1.5 km above the jet stream, and persistent contrails are located approximately 1.5 km below the thermal tropopause and at the altitude of the jet stream.[28] The correlation between contrail formation layers and the thermal tropopause and jet stream maximum allows to use these quantities as proxies to identify potential contrail formation in numerical weather prediction models.[29]

Net Radiative Forcing Effect

With their persistence, contrail cirrus can affect the Earth's net radiative equilibrium. Although they reflect incoming sunlight (shortwave radiation) back to space during the day (having a cooling effect), they cause a "blanket" effect as well, keeping warmth trapped in the lower atmosphere through the "trapping" of outgoing longwave radiation from the Earth's surface.[30] The second impact prevails on a 24-hour basis and throughout the year, studies show. The

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[26] Teoh R. et al., "Global aviation contrail climate effects from 2019 to 2021," *Atmos. Chem. Phys. vol 24-10* (2024) https://doi.org/10.5194/acp-24-6071-2024

[27] Wolf K., Bellouin N., Boucher O., "Upper-troposphere climatology," (2023)

[28] Wolf K., Bellouin N., Boucher O., "Upper-troposphere climatology," (2023)

[29] Curat V. and Péchaud L., "Prediction of contrails formation & observation process" *(Conference lecture, CANSO/EUROCONTROL Sustainable Skies: Contrails in Focus)*, Brussels, BE, Nov 07, 2023 https://www.eurocontrol.int/sites/default/files/2023-11/2023-11-07-contrails-conference-session-004-curat-pechaut-prediction-contrail-formation-observation-process.pdf

[30] Cathcart et al., "Understanding Contrail Management," (2024)

resulting overall impact of contrails is a net positive (warming) climate forcing effect. In general, flights during the night will have a higher net warming effect than during the day.[31]

The net radiative effect on climate from contrails depends on their microphysical and optical properties, persistence and spread, as well as on the time of day, season, local surface albedo and the vertical distribution of temperature, humidity and cloudiness in the atmosphere.[32]

While there is scientific consensus that persistent contrails, on balance, result in warming, uncertainty on the magnitude of the contribution is considerable and hard to quantify, especially on smaller scale or for individual flights.[33]

Natural and anthropogenic cloud interaction play a role.[34] In most cases, overlap between a contrail and a second cloud layer (or an existing contrail) reduces both the cooling and warming effects of the specific contrail.

> *Note. This effect is sensitive to the optical depth of each cloud layer and the solar zenith angle. Contrails forming above low-level clouds are more likely to be strongly warming because the incoming solar radiation would have been reflected by the low-level cloud regardless of the presence of contrails, thereby reducing the cooling effect of contrails. In contrast, strongly cooling contrails (in daytime) are more common over regions with little low-level clouds, especially through a strong albedo contrast with a dark (ocean) surface.*

For example, contrails over the North Atlantic corridor (where warming contrails are likely to form) have in daytime, on average, a small cooling effect under clear-sky conditions, but may switch to a warming effect in cloudy conditions.

The seasonal cycle or time-of-year influences both contrail formation and for the net warming effect of contrails. This is due to the course of meteorological (ISSR) conditions, the average background cloudiness and the incoming solar radiative energy.

In summary, in the Northern Hemisphere, for the mid-latitudes, strongly warming contrails are generally formed in wintertime between 15:00 and 04:00 UTC, and above low-level clouds.[35] The most cooling contrails occur in the spring, in the upper troposphere, between 06:00 and 15:00 UTC, and without lower-level clouds. Furthermore, non-summer months show a large daily variability in contrail coverage, more than summer months.

Uncertainties

[31] Teoh et al., "Aviation contrail climate effects in the North Atlantic from 2016 to 2021," (2022) https://doi.org/10.5194/acp-22-10919-2022

[32] Meerkötter et al., "Radiative forcing by contrails," Ann. Geophys. vol. 17-8 (1999) https://doi.org/10.1007/s00585-999-1080-7

[33] Lee et al., "Uncertainties in mitigating" (2023);
Impacts and Science Group (ISG), "[CAEP/13] ISG Contrail Science Workshop Report," *ICAO CAEP* (2025) [to be published]

[34] Sanz-Morère et al., "Impacts of multi-layer overlap on contrail radiative forcing," *Atmos. Chem. Phys. vol. 21-3* (2021) https://doi.org/10.5194/acp-21-1649-2021;

[35] Teoh et al., "North Atlantic," (2022)

Non-CO_2 radiative effects from aviation on climate are in general quantified with low confidence, compared to that of CO_2.[36] Contrail science is highly complex, and uncertainties exist for both the exact time and location where a contrail might form and persist, as well as the radiative impact of that contrail.

For climate and weather, these predictions may be acceptable - however, a recent study indicates that even with the extensive ongoing research, the relative importance of the climate effects of contrails compared to other aviation effects on climate still has major uncertainties requiring further research.[37]

The ICAO CAEP Impact and Science Group (ISG) Contrail Science Workshop report[38] presents an overview of the state of knowledge of AIC radiative forcing and contrail prediction and accuracy and the numerous related uncertainties, originating from a lack of actual relative humidity data around the tropopause altitudes (which is at the moment estimated from NWP models), and the unknowns in the microphysical processes, the impact of fuel composition and background atmosphere.

The result is that accurate prediction of contrail formation and evolution in time and space and the quantification of the impact of contrails and aviation induced cirrus on climate are still challenging. Although the phenomenon of contrails and contrail cirrus is clearly observable, the size of the radiative effect is still under discussion.[39]

Other complicating factors are how the aircraft fleet is changing in time, the increase in air traffic, and the changing background atmosphere and climate, which will all have an effect on the non-CO_2 climate impact.

For operational procedures, the unknowns in predicting ISSRs and the energy forcing (EF) of an individual flight are critical.[40] It is found that the uncertainties of non-CO_2 effects can be two orders of magnitude larger for individual flights than the fleet-average values.[41]

Because of the uncertainties and trade-offs involved, it may be inappropriate to recommend definitive courses of action, policies or regulations on aviation non-CO_2 emissions at present since they may be of limited effect or have unintended consequences. However, the potential climate benefits warrant a continued increase in research to close scientific knowledge gaps to address and increase the effectiveness of operational (or technological) measures and concepts. Many current projects aiming at contrail observation and recognition, have resulted and will result in better understanding of contrails and improve contrail modeling.[42]

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[36] Lee et al., “Uncertainties in mitigating” (2023)
[37] Singh, D. K., Sanyal, S., and Wuebbles, D. J., “Role of Contrails” (2024)
[38] Impacts and Science Group (ISG), “Contrail Science Workshop Report,” (2025) [to be published]
[39] Lee et al., “Uncertainties in mitigating” (2023)
[40] Impacts and Science Group (ISG), “Contrail Science Workshop Report,” (2025) [to be published]
[41] Teoh et al., “Small-Scale Diversions,” (2020)
[42] “EUROCONTROL launches ContrailNet - the new network to create a common repository of contrail observation data,” *EUROCONTROL* (2023) https://www.eurocontrol.int/news/eurocontrol-launches-contrailnet-new-network-create-common-repository-contrail-observation

Contrail Climate Sensitive Areas

The contrail (climate) sensitive area can be described as an area where aviation induced cirrus may appear and persist (ISSR) and have a significant net positive (warming) radiative effect on the atmosphere. Any mitigation strategy starts by identification of such areas.

Three elements are important to identify the relevant contrail climate sensitive area (in time and position) with sufficient accuracy and reliability:

- Prediction of contrail formation,
- Prediction of contrail persistence (ISSR) and,
- Prediction of the individual contrail radiative forcing.

The Schmidt-Appleman (S-A) criterion rules whether contrails are formed and will be persistent based on thermo-dynamic principles when the exhaust air mixed with ambient air is adiabatically cooled. Two key parameters in the S-A criterion for contrail formation are the ambient temperature and the relative humidity (see Fig 1-2).[43]

> *Note. The Schmidt/Appleman criterion depends on the thermal efficiency of the engine, the lower heating value (LHV) of the fuel and (most importantly) the relative humidity of the surrounding air.*

Metrics for Climate Impact of Contrails

Mitigating the climate impacts of aviation requires creation of a decision rule for whether to avoid creating contrails and a choice of how to measure climate impacts.[44]

Radiative forcing (RF) measures the energy imbalance between preindustrial times and a given year. RF at a target year is directly captured in the instantaneous climate impact metric. The scientific community has adopted the derived 'Effective Radiative Forcing' (ERF) as a suitable metric for short-lived climate forcers such as contrails, that accounts for short-term feedback processes in the atmosphere (such as changes in natural clouds). The ERF shows proportionality to changes in global mean surface temperature response including for short-lived climate forcing agents such as AIC but may not necessarily provide an accurate measure of long-term temperature response.[45]

The climate indicators Global Warming Potential (GWP) and Cumulative Climate Impact (CCI) go one step further by integrating the ERF over the time horizon. Global Temperature Change

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[43] Schumann, "Conditions for Contrail Formation," (1996)
[44] Cathcart et al., "Understanding Contrail Management," (2024)
[45] Impacts and Science Group (ISG), "Contrail Science Workshop Report," (2025) [to be published];
"Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30(4)," *EASA* (2020) https://www.easa.europa.eu/en/document-library/research-reports/report-commission-european-parliament-and-council;
Bickel et al., "Estimating the effective radiative forcing of contrail cirrus," *Journal of Climate vol 33-5* (2020) https://doi.org/10.1175/JCLI-D-19-0467.1

Potential (GTP) and Average Temperature Response (ATR) measure the temperature impacts of emissions, instead of the total forcing, since temperature is the main driver of climatic impact and also mentioned in international treaties.

The metric that is currently widely used, including within the EU ETS, is the Global Warming Potential or the Global Temperature Change Potential for a time-horizon of 100 years (GWP100/GTP100).[46]

When comparing the climate impact stemming from aviation CO_2 emissions to non-CO_2 emissions on a common scale, an equivalent emission metrics is often used: CO_2-equivalent (CO_2e). However, this implies a specific weighting of the temperature/climate response at different times. When CO_2 e metrics are used, the choice of time horizon and metrics will play in important role. The following figure demonstrates the outcome of the different choices with an illustrative example from a study of the relative impacts of CO_2 and non-CO_2 impacts for 2018. The impacts are expressed in CO_2 -equivalent according to different metrics (GWP and GTP associated to 20-, 50- and 100-year time horizons).

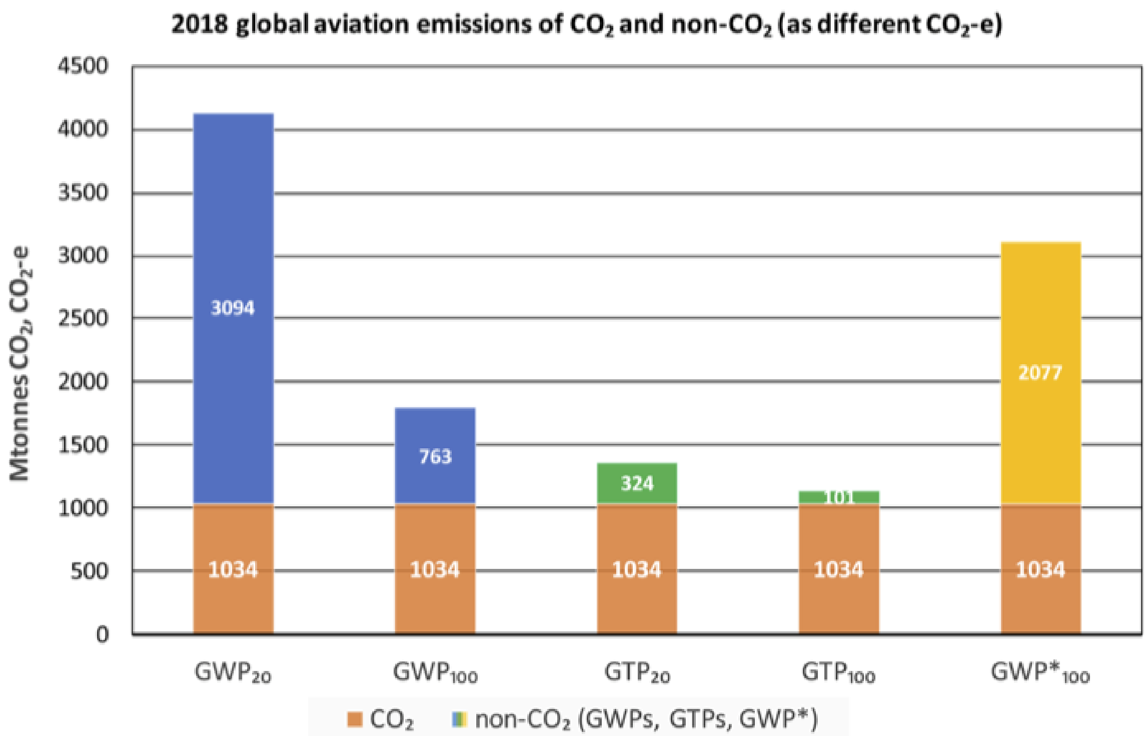

Figure -1-3 Emissions from global aviation in 2018, expressed as Mtonnes of CO_2 and apparent emissions of non-CO_2, expressed as various metrics and time horizons. The CO_2 emissions (orange) for 2018 are evidently invariant,

[46] Megill, L., Deck, K. & Grewe, V., "Alternative climate metrics to the Global Warming Potential are more suitable for assessing aviation non-CO2 effects." *Commun Earth Environ 5-249* (2024) https://doi.org/10.1038/s43247-024-01423-6

whereas the non- CO_2 -e emission magnitude varies with metric (blue, GWP; green GTP, yellow GWP) and time horizon.*[47]

The inclusion of short-lived climate forcers such as AIC presents scientific and policy challenges where the choice of time-horizon may have a large impact. Contrail management at the cost of extra fuel and CO_2 emission can help to achieve short-term climate change targets in the next decades. Nevertheless, the long lifetime of CO_2 may require a conservative approach to ensure net benefits for a wide range of timescales.

Climate Impact Models

Modelling contrails for operational avoidance requires a different approach than determining the net effect of aircraft induced cirrus at a global level.

Global modelling of contrail ERF has made significant progress in the last 10-15 years and these global climate model (GCM) type models are now widely used. They can indicate urgency to mitigate the contrail effects but require extensive computational efforts. In contrast, predicting the (climate) impact of a single contrail in a reliable and verifiable way is more complicated and according to the ICAO CAEP ISG "currently not possible".

For the representation of the radiative forcing impact of a single contrail during its lifespan, an assessment on a smaller scale is required to predict the formation, persistence and properties of a contrail plus the associated radiative forcing. It requires accurate data from meteorological models as inputs to so-called "plume" models – see the ICAO CAEP/13 ISG Contrail Workshop report for more explanation. These functions or models can then be used for flight planning purposes and for climate impact assessment per flight but have limitations as these are based on simplifications and weather predictions.

Models include Global Climate (GCM) type models that have a representation of contrails as 'extra clouds' by using many assumptions and simplifications but have closed water vapor budgets.[48] These can be run to determine Effective Radiative Forcing. Other models such as the Contrail Cirrus Prediction Tool (CoCiP)[49] or other plume models like Aircraft Plume Chemistry, Emissions, and Microphysics Model (APCEMM)[50] attempt to better represent formation, starting at the emissions of species in the engine exhaust, and instantaneous forcing along the lifetime of individual contrails, but the forcing model has no adjustments with the water vapour budget (unless implemented inside a GCM framework) and therefore cannot calculate radiative forcing.

CoCiP is computationally efficient, but the nature of this model (evaluation of contrails formation and simulation of its evolution) makes it incompatible as such with flight planning

[47] Lee et al, "Contribution of global aviation," (2021)
[48] Bock L. and Burkhardt U., "Reassessing properties and radiative forcing of contrail cirrus using a climate model," *Atmospheres* (2016) https://doi.org/10.1002/2016JD025112
[49] Schumann U., "A contrail cirrus prediction model," *Geosci. Model Dev. vol 5-3* (2012) https://doi.org/10.5194/gmd-5-543-2012
[50] Fritz et al., "The role of plume-scale processes in long-term impacts of aircraft emissions," *Atmos. Chem. Phys. vol. 20-9* (2020) https://doi.org/10.5194/acp-20-5697-2020

system application which requires instantaneous reactivity to be compatible with trajectory optimization methodologies. Nevertheless, estimates of climate effects along a trajectory may be interpolated from the gridded (per flight segment) estimates of climate effects.

For this reason, algorithmic climate change functions (aCCFs)[51] were developed, relying on statistical methods to correlate non-CO_2 climate effects as calculated by the CCFs with the local meteorological conditions at the time and location of emissions (including for NO_x, contrails, stratospheric H_2O). These aCCFs are thus computationally efficient and may offer a viable pathway to predicting total non-CO_2 climate effects of aviation.

However, these models only assume meteorological conditions from a specific region, for instance, the North Atlantic flight corridor during summer and winter conditions. Off-use design (e.g., in the tropics, during spring or autumn) is not recommended, and can lead to inaccuracies in the determined climate effect.[52] A concept towards robust aCCFs is under development, which will further integrate information on uncertainties arising from the lack of understanding that currently exist in aspects of climate science.

Other models predicting the formation and evolution of contrails, like the Aircraft Plume Chemistry, Emissions, and Microphysics Model (APCEMM), and global non-CO_2 climate impact models exist but do not provide a sufficient computation time performance to be integrated into operational solutions like flight planning systems.

Continued focus and further work is needed to develop better models that will provide operational flight planning integration capabilities.

1.3 Reduction of Warming Contrails

Three pathways are available for reduction of warming contrails:

- Operational measures,
- adaptation of engine and aircraft design,
- modification of fuel type and composition.

This document focuses on operational measures for reducing non-CO_2 impacts in the current aircraft equipage ATM environment and identifies potential future technological and operational opportunities in anticipation of new engine and aircraft technology and fuel composition.

Trajectory Adjustment

The only operational measure at present being explored, according to an assessment of existing research data and literature, is mitigation of contrail formation through trajectory adjustment.

[51] Matthes et al., "Updated algorithmic climate change functions (aCCF) V1.0A: Evaluation with the climate-response model AirClim V2.0," *Geosci. Model Dev. [preprint]* (2023) https://doi.org/10.5194/gmd-2023-92
[52] Dietmüller et al., "A Python library for computing individual and merged non-CO2 algorithmic climate change functions: CLIMaCCF V1.0," *Geosci. Model Dev. vol 16-15* (2023) https://doi.org/10.5194/gmd-16-4405-2023

Two options are available: to avoid formation of any persistent contrail through avoiding ISSRs or by avoiding contrail climate sensitive areas (see Chapter 1.2), where persistent contrails will have a positive radiative forcing and a significant warming impact.

The avoidance strategy may be planned before the flight or implemented during the flight (in the tactical phase). Trajectory adjustment will be discussed in more detail in Chapter 2.

The availability of meteorological data and prediction capabilities on contrail formation and persistence and on the climate impact, the flight planning capabilities of operators, and the required flexibility of air traffic management (ATM) will play an important role for a successful implementation as well as the potential impact on the flight, airspace capacity and fuel use.

New Technology and Fuel Composition

New engine technology, new fuel standards and the use of SAF may alter the exhaust temperature, the water content and the number of particles which are emitted from engines. This may change the S-A criterion and impact contrail formation and /or properties. The newest generation of jet engines emit fewer soot particles thanks to a lower fuel consumption, as well as improved combustor technology and/or design. Reduction of soot emissions can help reduce the amount of ice crystals and potentially the lifetime of persistent contrails.

The formation of soot appears to be largely associated with the aromatic content in jet fuel. The aromatic content may vary widely per fuel batch and fuel origin from a minimum of 8% currently (for operational reasons) to a maximum limit of 25%, according to international jet aviation standards. SAF and hydro-treated fuels have lower concentrations of aromatic compounds resulting in reduced soot emissions, ice crystal numbers and reduced contrail formation. This effect has been demonstrated, but precise quantification of effects still needs to be further validated due to currently limited numbers of ground and in-flight measurements. See Chapter 5 and the CAEP/13 ISG report for further details.

Should there be consensus that high SAF blends with zero or minimal aromatics impact contrail formation and the climate forcing of contrails, then these blends could be used on specific flights or combined with operational measures as documented in this report to enhance the climate benefits of SAF.

(Supersonic) Flights through the lower stratosphere are less likely to form contrails on most of the routes due to the lower humidity of the stratosphere but require new aircraft technology and will have implications on upper air chemistry, ozone content, and other non-CO_2 impacts, taking into account the longer residence times at higher altitudes. Water vapour emissions into the stratosphere have consistently been identified as being either the largest or second largest component of supersonic transport (SST) climate impacts.[53]

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[53] Impacts and Science Group (ISG), "White Paper Update on Understanding of Potential Impacts of Supersonic Aircraft," *ICAO CAEP* (2025) [to be published]

1.4 Potential Other Non-CO_2 Impacts

Next to CO_2 and contrails, climate impacts of aviation also stem from other emissions and related effects: nitrogen oxides (NO_x), sulfur compounds, water vapour, soot particles, other aerosol-cloud interactions, the formation of ozone and reduction of methane lifetime in the atmosphere.

Of all these other non-CO_2 emissions, NO_x is considered to have the largest impact in terms of radiative forcing.[54] However, the impact (which is indirect through chemical reactions with ambient gases), is uncertain and dependent on ambient conditions which may change in time. See Chapter 3.

Aerosol-cloud interactions (of sulfur on low-level clouds and soot on high-level ice clouds) could also be potentially large, but there is still significant uncertainty associated with the magnitude of these impacts and even the sign (warming/cooling) of soot effects on ice clouds.[55]

Limited information has been found in this literature review on operational measures to avoid the climate impact of NO_x. For other non-CO_2 emissions, no information has been found. The available measures for reduction of the NO_x effects during cruise (flight altitude modification) are documented in Chapter 3.

1.5 Collection and Review of Research

A literature review has been undertaken to collect existing documentation. Twenty-eight studies and research publications have been identified to date that specifically focus on operational measures to avoid or mitigate contrails and two publications on other non-CO_2 emissions. The publications are listed in Appendix A. Multiple other publications are consulted as background information and referenced throughout the report.

Collectively, the identified studies represent the current status of research across the world. However, this is a rapidly evolving field with much active work ongoing. During compilation of these data, many other research programs have started, and where available some preliminary results have been included during the drafting period.

The geographic spread of the focus of the available studies mirrors the areas where contrails prevail, through atmospheric conditions and traffic intensity: in the Northern Hemisphere covering Europe, the US, the North Atlantic airspace and Japanese airspace.

Review Process

The review of the documented research projects was conducted by members of the ICAO CAEP Airports and Operations Working Group (WG2) through a review questionnaire, attached in Appendix B. Relevant information on operational measures, timeline, feasibility,

[54] Skowron et al., "Greater fuel efficiency is potentially preferable to reducing NOx emissions for aviation's climate impacts," *Nat Commun 12-564* (2021) https://doi.org/10.1038/s41467-020-20771-3
[55] "Updated analysis," EASA (2020)

interdependencies, and future opportunities is assembled and this information is subsequently used as the basis for this document.

The background information on contrail science has been reviewed by the ICAO CAEP Impact and Science Group (ISG) and ICAO CAEP Emissions Working Group (WG3).

CHAPTER 2 – TRAJECTORY ADJUSTMENT FOR CONTRAIL MITIGATION

2.1 Introduction

In this chapter, operational opportunities to mitigate warming climate impacts of persistent contrails are examined for contemporary practice, i.e. for current aircraft equipment and ATM system and currently available tools for weather prediction and contrail modeling. Future opportunities forthcoming from implementation of new weather and contrail forecasting, airspace management and flight planning capabilities are presented in Chapter 4.

The only operational measure at present being explored for contrail mitigation in literature and practice is to adapt the flight trajectory of the aircraft (also known as navigational avoidance or deviation) to avoid a predicted or observed contrail climate sensitive area either in a preflight (planned) or tactical (in-flight) phase. See paragraph 1.2 for the definition of the contrail climate sensitive area.

Multiple theoretical and simulated assessments of the feasibility of navigational avoidance have been conducted, but actual flight trials and tests for implementation are lacking. These navigational avoidance strategies should still be validated on a larger scale for effectiveness and feasibility. Trajectory adjustment for one single flight in a controlled environment, e.g., during a trial, is not equivalent to adapting the trajectories of one flight in a congested airspace. The complexity is even higher for multiple aircraft in a congested airspace. Tactical interventions in congested airspace might not be possible at all due to safety considerations. While numerous simulated studies have been done, to date only two actual flight trials have been documented, both in low-density traffic situations[56], and a few other experiments have been conducted without documented results.[57]

The effectiveness of the (operational) interventions is strongly dependent on the actual radiative forcing of the contrails that would have been formed without action. The radiative forcing from persistent contrails is strongly dependent on the seasonal changes in meteorological aspects and solar radiation, time-of-day, on the cloud-contrail overlap, and on the Earth's albedo. Any effective intervention strategy should therefore consider all these variables. As an example, in the North Atlantic oceanic region, strongly warming contrails are generally formed in wintertime and less so in the summer months, putting emphasis on intervention during the winter months. See to Chapter 1 Introduction - Net Radiative Forcing.

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[56] Sausen et al., "Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world?" *Meteorologische Zeitschrift, vol. 33-1* (2024) https://doi.org/10.1127/metz/2023/1157;
Elkin C. and Sanekommu D., "How AI is helping airlines mitigate the climate impact of contrails," (2023) https://blog.google/technology/ai/ai-airlines-contrails-climate-change/

[57] "Sustainability developments from around the world," *EUROCONTROL* (2022) https://www.eurocontrol.int/article/sustainability-developments-around-world

According to a limited number of studies, only a (small) subset of flights is on average responsible for most of the warming effect of contrails. On average, 5% of the annual distance flown formed persistent contrails with a strong regional variation (see below).[58]

Studies and trials have shown that only 2%–16% of flight plans need to be adjusted to avoid 54%–80% of contrail-induced warming, depending on location, season and meteorological conditions.[59] A global assessment based on contrail prediction and actual Automatic Dependent Surveillance-Broadcast (ADS-B) data, indicates that only ~ 2.7% of all flights (or 11% of contrail-forming flights) accounted for 80% of the global annual contrail warming (EF).[60] Another study refers to ~12% of flights, concentrated on ~45% of the days which account for 80% of the annual warming effect in the North Atlantic between 2016 and 2021.[61] See Figure 2-1. A recent study (based on actual North Atlantic flights in 2023 and 2024) indicates a similar number: ~2.8% of flights accounting for 80% of the total contrail energy forcing.[62]

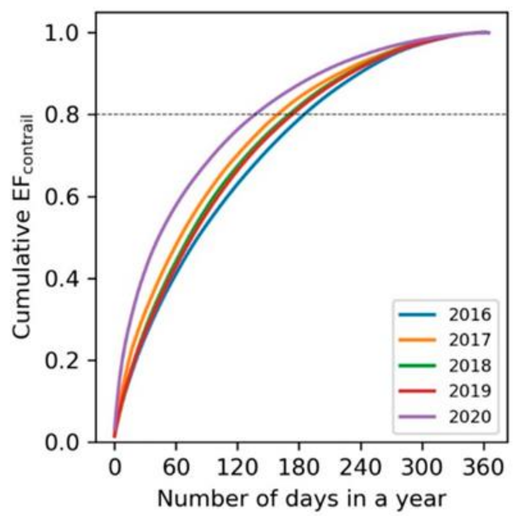

Figure 2-1 Cumulative warming effect versus the number the number of days in a year that accounts for the proportion of $EF_{contrail}$ over the North Atlantic (Shanwick and Gander FIRs) between 2016 and 2020.

Although the assessment indicates a small subset of flights overall, these flights are not spread out evenly across days or time. Although there would be plenty of days with no contrail mitigation action needed per sector, we would still see a high proportion of flights to be acted upon on a small subset of days in a similar geographical area.

Challenges

Four elements will play an important role for an effective implementation of trajectory adjustment for contrail management:

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58 Teoh R. et al., "Global aviation", (2024)
59 Cathcart et al., "Understanding Contrail Management," (2024)
60 Teoh R. et al., "Global aviation," (2024)
61 Teoh et al., "North Atlantic", (2022)
62 Frias et al., "Feasibility of contrail avoidance in a commercial flight planning system: an operational analysis," *Environ. Res: Infrastruct. Sustain. vol 4-1* (2024) https://doi.org/10.1088/2634-4505/ad310c

- the availability of relevant meteorological data (especially relative humidity to ice),
- the modeling for reliable predictions of contrail formation and subsequent climate impact,
- the flight planning capabilities of operators, and
- the required flexibility of ATM.

These elements will also determine the potential impact on the flight, the fuel use, and airspace capacity.

Considering all uncertainties in modelling and weather measurements, several challenges have been identified. Firstly, the ISSRs are difficult to detect and predict. The ISSR itself is non-stationary and constantly changing in shape and extent; the boundaries of the ISSR evolve with changes in meteorological conditions. Accuracy, timeliness and high reliability are needed to enable operational avoidance strategies for individual flights. In the worst case, flights could be diverted from an area outside the contrail climate sensitive area with fuel penalties into an area where they will form warming contrails.

The net radiative effect is dependent on local conditions which may change in time as well (see section 1.2). On a small scale, at the individual trajectory level (per flight), the measurement of the effectiveness of intervention is complicated and the result may be significantly less certain.[63] On a global scale, or on a regional scale, a more reliable annual mean radiative forcing attributable to contrail cirrus can be derived in hindsight from weather data, actual flight trajectories and climate modeling.[64]

Together with the feasibility and efficacy of measures, the assessment of interdependencies and their related trade-offs will be an important factor for successful implementation. The potential interdependencies will be discussed in section 2.4. Because no operational evidence is available and assessments are only based on modelling studies, an option could initially be to divert flights only if there is minimal or no trade-offs such as a system-wide fuel penalty, additional CO_2 emissions or airspace capacity.

The effect of operational measures should be reviewed in the context of changing circumstances such as new fuel composition with less aromatic compounds, engine technology improvements, ATM architecture improvements, increased traffic, and changed atmospheric circumstance due to climate change.[65] The (selective) use of SAF is not considered as an operational measure in this report; it is addressed in Chapter 5 together with the impact of fuel composition.

Regional Variation

Recent studies underline that the climate impact of contrails is highly dependent on the geographic location and that regional avoidance mechanisms may be appropriate.[66] The contrails climate impact depends on the existing atmospheric conditions for persistent contrail formation, the warming effect of these contrails and the air traffic density. All of these three variables are

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[63] Teoh et al., "Small-scale diversions," (2020)
[64] Teoh R. et al., "Global aviation," (2024)
[65] Irvine, E. A. and Shine, K. P., "Ice supersaturation and the potential for contrail formation in a changing climate," *Earth Syst. Dynam., vol 6-2* (2015) https://doi.org/10.5194/esd-6-555-2015
[66] Teoh R. et al., "Global aviation," (2024);
Cathcart et al., "Understanding Contrail Management," (2024)

dependent on the geographic location. The regional variation of these three elements can be identified in fig 2-2, showing the air traffic density around the globe, the persistent contrail coverage and the associated radiative effect per unit of persistent contrail length.

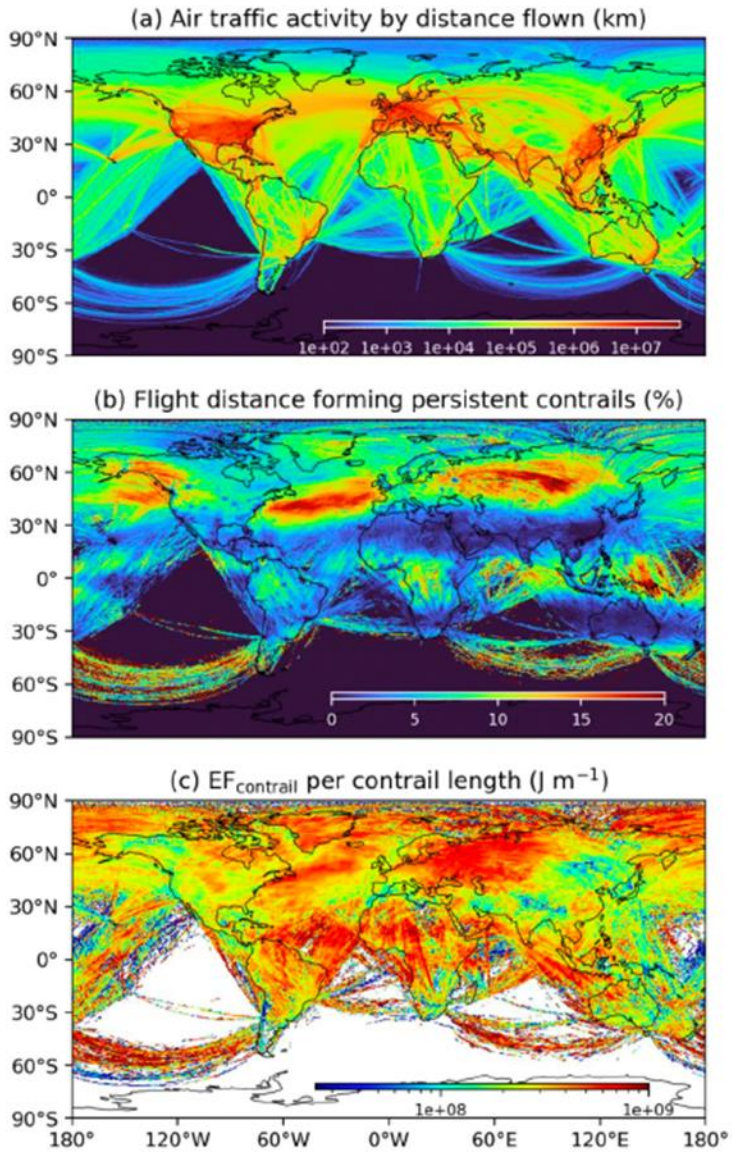

Figure 2-2-- The 2019 global annual flight distance flown, percentage of flight distance forming persistent contrails, and the EF contrail per unit length of persistent contrail (from global aviation contrail climate effects 2019-2021, Teoh)

As shown in figure 2-3, Europe (876 mW/m2), the US (414 mW/m^2), and the North Atlantic (300 mW/m^2) have the largest contrail net RF, while East Asia (64 mW/m^2) and China (62 mW/m^2), where aviation has seen rapid growth, is close to the global mean (62 mW/m^2). In East Asia and China, less contrails are formed due to lower flight cruising altitudes on average, and limited existence of ice-supersaturated regions (ISSRs) in the subtropics because of higher atmospheric temperatures at cruising altitude.

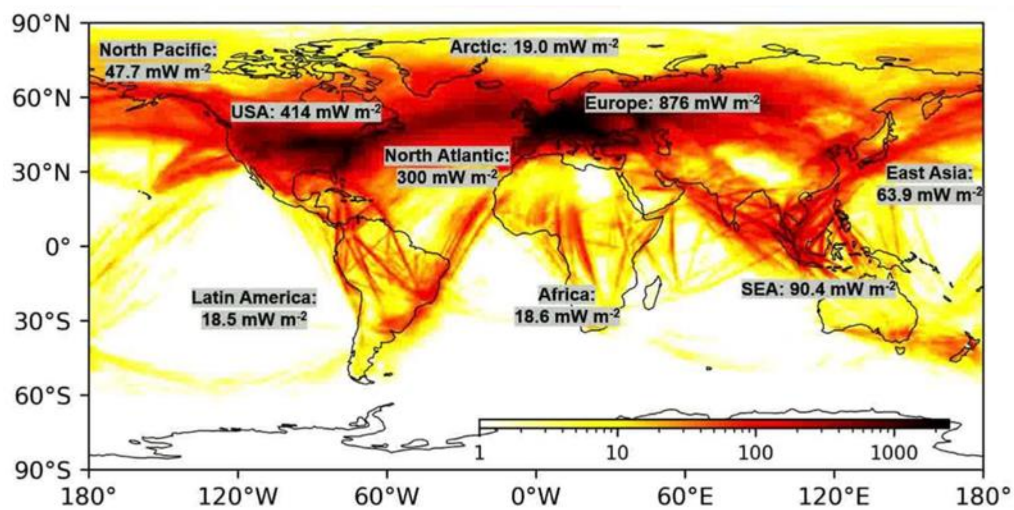

*Figure 2-**Error! Use the Home tab to apply 0 to the text that you want to appear here.**-3 Estimated 2019 annual mean contrail cirrus net radiative forcing.*

Furthermore, the impact of the potential trajectory adjustments on traffic flow, capacity and costs also varies per region. Potential concepts of operations for contrail reduction are explored in section 2.4 and preferred concepts may be different depending on the region of application.[67]

Collaboration both cross border and between regions will be required when adopting a potential concept of operations, for consistency and efficiency of measures throughout the flight. As a note, it must be stated that any concept will have to be proven in practice on feasibility and efficiency. No research data is yet available to determine the proof of concept or readiness level.

Seasonal Differences

Contrail formation, persistence and spread is strongly dependent on meteorological conditions, as stated in Chapter 1 and these vary per season. On the North Atlantic routes, the temperature is high and the relative humidity at flight altitudes is low in the summer, which is not favorable for contrail formation. A simulation study[68] indicated that in June, July, and August, less than 3% of total flight distance may form persistent contrails on the North Atlantic routes, whereas in wintertime, the contrail distance increases substantially, up to more than 10% of the total flight distance (with a large daily variability). From winter to summer, the contrail distance decreases successively.

[67] Cathcart et al., "Understanding Contrail Management," (2024)
[68] Yin et al., "Impact on flight trajectory characteristics when avoiding the formation of persistent contrails for transatlantic flights," *Transportation Research Part D: Transport and Environment vol. 65* (2018) https://doi.org/10.1016/j.trd.2018.09.017

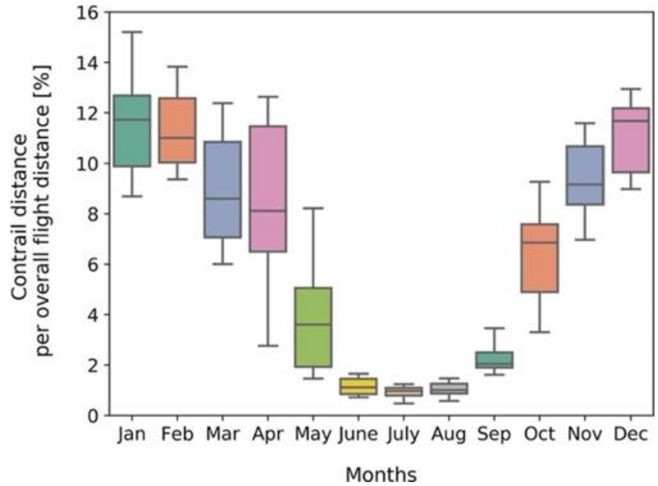

Figure 2-4 The seasonal variability of contrail distance based on a daily flight schedule of 103 transatlantic flights (and a contrail prediction model).

Not only contrail formation and persistence is affected by seasonal changes, also other circumstances such as meteorology, background cloud fields and the solar position play a role in the contrail RF and the overall climate impact.

The summer patterns show a larger variability and a larger potential to reduce the climate impact from aviation by climate-optimized routing.

2.2 Trajectory Adjustment or Navigational Deviation

Trajectory adjustment or navigational deviation means physically changing the flight trajectory for the purpose of avoiding the contrail climate sensitive areas, as defined in section 1.2. Navigational deviation is possible in three dimensions:

- vertical (spatially),
- horizontal (spatially),
- in time (temporal).

Horizontal, vertical, or temporal deviation may be selected individually or in combination to optimize contrail avoidance and minimize impacts to flight time, fuel consumption, and airspace capacity. The interdependencies and trade-offs will be further explored in section 2.5.

Navigational avoidance strategies can be selectively applied to a subset of flights, as in general only a (small) portion of flights at specific flight levels contribute the most to the warming impact of contrail.[69] However, the relevant traffic will not be distributed evenly in time or place; locally, a higher proportion of traffic may be affected.

Small-scale adaptation strategies, targeting only those flights with significant contrail climate warming impacts, can be implemented more quickly with probably less impact on the ATM system and the air traffic. See section 2.4 Potential Interdependencies.

[69] Teoh et al., “Small-scale diversions,” (2020)

As cited previously, challenges exist for trajectory adjustment to be feasible, effective, and efficient.

Vertical Trajectory Adjustment (Deviation)

Vertical adjustment of a flight trajectory utilizes a change in flight level from the optimum or operator preferred flight altitude to avoid the contrail climate sensitive areas. These climate sensitive regions typically have large horizontal (150 ± 250 km) but shallow vertical extensions (on the order of 1000 to 2000 feet on average but may extend up to 6000 feet or more) as indicated in Chapter 1.2 Contrail Formation and Contrail Impact. Therefore, a small change in cruising altitude (± 2000 feet) could minimize the flight distance within regions of high humidity, thereby reducing the contrail lifetime and ERF.[70]

The optimum flight altitude (from a fuel consumption perspective) is based on several complex variables, but the primary ones are aircraft weight and aircraft speed as well as ambient conditions (i.e., wind and temperature). In general, the speed is chosen by the operator/flight crew according to a cost index which weighs fuel costs versus time costs.

As highlighted in paragraph 1.2, a correlation exists between persistent contrail formation layers and the thermal tropopause and jet stream maximum. Due to seasonal variations of the tropopause height (lower in wintertime), the required vertical adjustments will also change per season. In the Northern Hemisphere, warming contrails are more efficiently reduced when the aircraft is diverted to a lower cruising altitude during the summer months, and vice versa in winter, taking into account the operational limitations.[71]

Rules of thumb can be given for fuel penalties when flying off-optimum altitude: 1- 2% for 2000 ft off-optimum altitude and 5-6% for 4000ft off-optimum altitude.[72] These percentages are valid for standard atmospheric conditions without vertical wind changes and may be used as a proxy for most speeds. For example, a wide-body aircraft (with a fuel flow of 7000 kg/hr) burns 140 kg extra fuel per hour if it flies 2 000 ft below or above the optimum altitude and about 450 kg extra fuel per hour if flying at 4 000 ft below optimum level. Fig 2-5 gives a graphic presentation for several weights for a 4-engine aircraft. Accurate data on excess fuel burn data for most aircraft types can be found in the EUROCONTROL Base of Aircraft Data – Airline Performance Model (BADA – APM).

[70] Teoh R., Schumann U., and Stettler M., "Beyond contrail avoidance: efficacy of flight altitude changes to minimise contrail climate forcing," *Aerospace vol. 7-9* (2020) https://doi.org/10.3390/aerospace7090121
[71] Teoh et al., "Small-scale diversions," (2020)
[72] "Operational Opportunities to Reduce Fuel Burn and Emissions (Doc 10013)," *ICAO* (2014) https://store.icao.int/en/operational-opportunities-to-reduce-fuel-burn-and-emissions-doc-10013

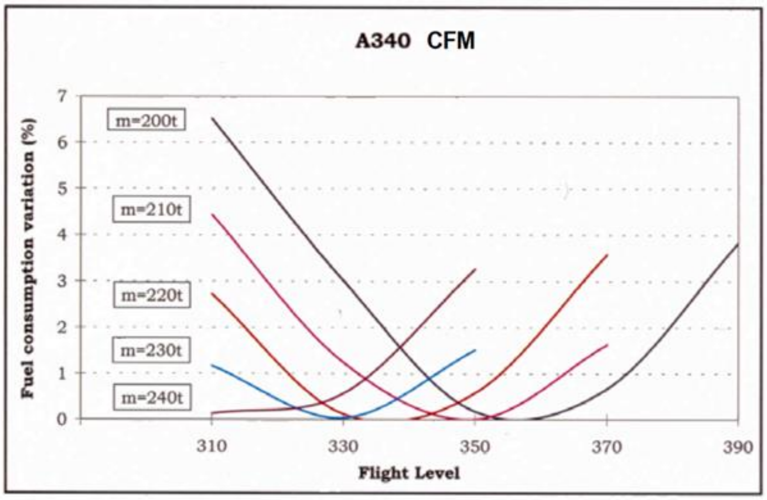

Figure 2-5 Fuel consumption increment for an Airbus A340 CFM at M .0.8 (from Airbus Getting to Grips with fuel economy)

Operational circumstances may limit vertical deviations: aircraft performance may limit any climb option as aircraft tend to operate near the actual aircraft performance or certification ceiling. Actual fuel on board may inhibit in-flight deviation from fuel-optimized flight altitudes, taking into account minimum fuel reserves. Traffic, ATM restrictions or weather (thunderstorms, areas with turbulence, icing conditions) may also limit vertical deviations upwards or downwards.

Examples from calculated simulations based on actual flight data indicate that depending on the season, the effective radiative forcing from contrails may be reduced significantly by adapting trajectories by a maximum 2000 feet vertically and for only a small percentage of flights.[73] The related study of Japanese airspace estimates that a deviation of 0.5 to 4.1% of the flights can lead to a contrail EF reduction of 50% up to 93%, depending on the daily variation of the atmospheric circumstances (see Fig 2-6).[74] A recent study for the North Atlantic indicates that on average 12% of all flights in this region cause 80% of the annual contrail energy forcing.[75] The study concluded that this subset of flights (with a large potential warming impact, based on up-to-date meteorological forecasts) could be supported by pre-flight changes to the airline flight plan and tactical (vertical) adjustments.

[73] Teoh et al., "Small-Scale Diversions," (2020)
[74] Teoh R., Schumann U., and Stettler M., "Beyond contrail avoidance," (2020)
[75] Teoh et al., "North Atlantic", (2022)

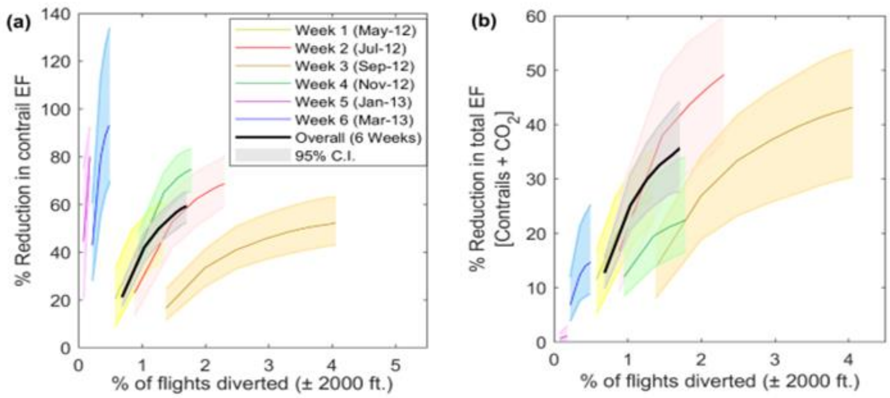

Figure 2-6 Example of a study on reduction of contrail Effective Forcing vs percentage of flights diverted in a simulation by +/- 2000 ft.

Horizontal Trajectory Adjustment (Deviation)

A horizontal change of flight trajectory may also help to avoid contrail sensitive areas. Current studies indicate that ISSR's typically have large horizontal (150 - 250 km) extensions. Deviation from the fuel-optimized flight trajectory will imply a higher fuel consumption and more flight time, especially when strong jet streams are present, and a large horizontal wind gradient exists. For this reason, most studies have assessed vertical deviation strategies, while only a few included horizontal or latitudinal deviations. With enough anticipation time, horizontal deviations might not be as detrimental for long-haul flights as they would for short-haul flights.

A simulation study[76] indicated a potential reduction of contrail distance ranging from 20 to 80% depending on the daily meteorological conditions on transatlantic flights through horizontal deviation, for a set maximum increase in flight time of 2%. A large variability of associated flight distance and fuel trade-offs was found. It was confirmed that the contrails RF vary by season; and shifting flight trajectories northward or southward depending on season may reduce the formation and impact of contrails. For the North Atlantic region, the southward (and upward) shifts of the trajectories are favorable in non-summer seasons for avoiding contrail formation. In summer, the northward (and upward) shifts are preferred.

Another simulation uses a set of model flights flying at fuel- and time-optimized speeds from Europe to North America and assessed lateral mitigation and combined vertical and lateral mitigation. Through ground track alterations nearly half of all contrails can be mitigated against 2-3% additional fuel and flight time.[77]

A third study evaluated multiple alternative routings (17 horizontal and 5 vertical) for each of the roughly 400 selected flights crossing the North Atlantic in either direction during several

[76] Yin et al., "Impact on flight trajectory," (2018)
[77] Barten, K.P.A.M., "Contrail Mitigation through Flight Planning," *TU Delft* (2017) https://resolver.tudelft.nl/uuid:54fef264-4585-49b4-9ffc-0280d49f9ff5

representative winter and summer days.[78] This simulation study aimed at reducing the climate impact, with minimal extra fuel and crew costs, while taking into account the actual winds and separation standards on the flight trajectories. The study concluded that the implications for ATM are yet to be identified. Although safety issues are found not to be limiting for the North Atlantic, these may limit the applicability in areas of higher air traffic densities. The summer patterns show a larger variability and a larger potential to reduce the climate impact from aviation by climate-optimized routing. The eastbound traffic takes advantage of tailwinds within the jet stream. Leaving the jet stream implies large penalties on fuel demand, emissions and climate impact; hence, eastbound winter flights show less potential to reduce climate impact.

Due to the average horizontal and vertical size of the contrail climate sensitive area and limitations with respect to airspace and route structure, a vertical deviation seems to be the preferred option over a horizontal deviation for most interventions.[79]

Temporal Adjustment of Trajectories

Temporal adjustment implies delaying or advancing flight departure times or changing aircraft speeds to avoid flying through predicted contrail climate sensitive areas. Adjustment of departure times may be effective to maintain optimal flight routes while reducing the climate impact of contrails, considering the shift over time of ISSR and the temporal warming effect of contrails during the day-and-night cycle.

However, temporal adjustment will have major impacts on flight scheduling, fleet usage, airport capacity, local noise regulations, operational predictability, airline operating costs and fleet connectivity. There is only very rudimentary research available assessing temporal adjustment as an effective strategy for contrail avoidance.

Some temporal adjustment may be considered in the form of network delay to avoid airspace capacity constraints caused by planning for contrail avoidance. This could be considered as a hybrid of temporal and spatial adjustment, such as in cases where navigational avoidance would otherwise not be efficient due to excessive deviations to avoid the climate sensitive areas and traffic hot spots. The flight would not necessarily wait for the ISSR to disappear, but instead take a small amount of ground delay until capacity is available for a suitable/efficient trajectory adjustment to be flown.

The aircraft speed may have an effect on contrail formation as well. An aircraft may avoid contrail formation for a limited time, at least near threshold conditions, by flying with reduced power (and speed) due to lower exhaust temperature.[80] This, however, may not be a viable mitigation technique to use in practice and is not suggested as such in any literature.

[78] Grewe et al., "Climate-optimized air traffic," (2017)
[79] "Updated analysis," *EASA* (2020)
[80] Schumann, U., "Propulsion efficiency," (2000)

2.3 Considerations for Operational Implementation

Before any horizontal, vertical or temporal trajectory adjustment for contrail mitigation can take place, two options for implementation can be distinguished:

- the timeframe for decision making and intervention: in the flight planning phase or during flight execution, and
- the initiator: the ANSP or the airline operator.

Timeframe for Decision Making and Intervention

The decision and intervention for navigational adjustment can be done at several moments in time:

- Pre-flight (in the flight planning phase)
- In-flight
    - In-flight strategic (in anticipation),
    - In-flight tactical (in real time),
- A combination of pre-flight and in-flight intervention.

In general, more advanced (with respect to time) planning is accompanied by increased uncertainty of contrail prediction and corresponding climate impact and may increase the contrail climate sensitive area for a fixed level of certainty. Due to the lack of effective models and weather data for advanced prediction of contrails, strategic implementation of navigational adjustments may not always be effective.

Pre-flight Intervention

Pre-flight avoidance refers to efforts made to avoid contrail formation during the flight planning stage. In some research documents,[81] the term 'pre-tactical' may be used to indicate short-term pre-flight interventions, reaching from a few days before the flight up to the flight departure time or up to the tactical phase.

Pre-flight avoidance strategies consider predictions of the location of ISSR where contrails are likely to form and have a warming effect, in order to generate a flight plan to avoid those regions.[82] These strategies require accurate weather prediction, accurate and reliable contrail formation forecasting and climate models and lead time to optimize routes, assess any impacts on flight time and fuel requirements, and submit flight plans in accordance with the amended flight trajectory.

During flight planning, the contrail sensitive areas can be taken into account, and the flight plan may be optimized including costs, fuel use, time and the non-CO_2 climate impact. Consequences for flight time and fuel requirements can be anticipated before the flight. This process of climate-

[81] "Mitigating the climate impact of non-CO_2 emissions," *EUROCONTROL* (2021) https://www.eurocontrol.int/press-release/mitigating-climate-impact-non-co2-emissions

[82] Barten, K.P.A.M., "Contrail Mitigation Flight Planning," (2017)

optimized track selection may be an elaborate, labor-intensive task in the preflight phase without proper integration in the normal flight planning system and without automation of tasks.

Requirements for separation standards, airspace availability, and airspace capacity may limit options for pre-tactical avoidance strategies, particularly for lateral track modification. This may result in refusal or renegotiation of the ATC flight plan (refer to paragraph 2.4).

For pre-flight intervention, the effect on the actual flight, on ATM procedures and on controller and flight crew workload during flight will likely be relatively small but this needs confirmation during further development.

To date, a limited number of examples are available of actual avoidance trials containing pre-flight trajectory adjustments on different routes and with different operators. One is based on short-term contrail forecasting and post-flight verification.[83] The other on contrail prediction models assisted with artificial intelligence supported contrail recognition.[84] Large-scale implementation and validation data are not yet available. Further trials are anticipated in SESAR e.g. using pre-tactical flight plan decisions to avoid contrail formation in the Shanwick Oceanic area[85] and in the German airspace.[86]

In-flight Intervention

In-flight avoidance describes efforts to adjust the flight trajectory while the aircraft is in the air flying to its destination. This could be pilot initiated, or air traffic controller (ATCO) initiated and is done in advance before entering the sector or region of concern or by means of tactical avoidance in real time (for instance, through supplemental flight instructions from air traffic control (ATC)).

In-flight strategic avoidance strategies include amendments to the flight plan to avoid regions where contrails are likely to form and have a warming effect, while the aircraft is in an earlier portion of the flight, but in advance of the sector/region where the deviation would be required - for instance, through requesting an updated oceanic profile for avoidance by submission of an amended clearance message before entering the oceanic airspace.

Tactical avoidance relies on accurate and consistent real-time information on weather, and traffic, combined with accurate prediction of contrail sensitive areas in the atmosphere. Validation of appearing contrails may be supported through live imagery from ground and satellite observations. Tactical avoidance may be considered in the absence of accurate weather information, model accuracy or time required for pre-tactical avoidance.

Tactical strategies in-flight may not be possible in a congested airspace if they have an impact on workload and airspace capacity. Unforeseen extra fuel use may exceed safe fuel reserves.

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[83] "Contrail forecasting case study," *SATAVIA* https://satavia.com/contrail-forecasting/
[84] Elkin C. and Sanekommu D., "AI helping airlines," (2023)
[85] "Contrail avoidance – Exploring techniques for minimising contrail formation," *NATS* (2024) https://www.nats.aero/about-us/research/n/contrail-avoidance/
[86] "A future without contrails – How targeted flight route planning can reduce the climate impact of aviation," DLR (2024) https://www.dlr.de/en/media/publications/magazines/all-digital-magazines/dlrmagazine-175

Additionally, trade-offs will be a factor, for example, assessing the impact of a change in flight level on overall flight performance and efficiency, including impact on fuel consumption.

The first-ever operational contrail avoidance trials were conducted in 2021 during the pandemic by the German Aerospace Center (DLR) and Maastricht Upper Air Centre (MUAC) using in-flight tactical avoidance.[87] During this trial, flights during the night period of 1600-2200 UTC, were asked to deviate from their requested flight level in real time. A simplified decision tree was used to assist the controllers of MUAC, to identify if contrails were observed, clear sky was present and air traffic could be deviated. The issues that were identified included cross-border coordination, imperfect ISSR forecasts, and lack of observational data for validation. The temporal lower air traffic density (due to the pandemic) made the additional work for controllers easier to handle.

Combination of In-flight and Pre-flight Intervention

Pre-flight implementation is less disruptive versus in-flight interventions, but it requires accurate and reliable prediction capacities. Tactical intervention is potentially more accurate (reducing the contrail sensitive area and avoiding action), because it allows for intervention to respond to short-term predictions or actual contrail observations, but it is also more potentially disruptive to air traffic management (ATM) and aircraft operations.

The air navigation services provider (ANSP), flight crew and aircraft operator may lack flexibility to effectively react in real time at fleet level, particularly in congested airspace. Aircraft in-flight fuel management must allow avoidance as flight adjustments are not planned in advance. A smart combination of both pre-flight and in-flight intervention might be a good option but should be evaluated properly in larger-scale simulations and actual trials.

Initiator: ANSP or Airline-led

Flight operations are by essence a multiple stakeholder cooperation and given the potential interdependencies between contrails avoidance at scale and airspace level safety implications (see Chapter 2.5) the initiative for pre-flight or in-flight trajectory adaptation might be handled by different stakeholders:

- The airline operator.
- The ANSP.
- Collaboration between airlines and ANSP.

Airline-led Concept

The airline operator encompasses both the strategic horizon function of flight and fuel planning led by the dispatcher in the Operational Control Centre (OCC) – also referred to as Airline Operations Centre (AOC) – and the tactical horizon functions of mission execution led by the flight crew assisted by the dispatcher as part of his ground flight follow-up mission.

[87] Sausen et al., “Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world?” (2024) https://doi.org/10.1127/metz/2023/1157

The dispatcher with the help of dedicated tools, performs full flight operations support to the flight crews so that the flight is conducted safely and efficiently according to the airline priorities. They are in charge of flight planning (including trajectory and fuel planning), and they also monitor the safe progress of each flight so that they may act as intermediary between the pilots and the ANSP stakeholders in case of unexpected event. Note that the importance given to the role of dispatcher may vary around the world and that this role may be completely automated for some specific (e.g. short-range) mission types.

The flight crew is responsible for the safe and efficient execution of the flight from departure gate to destination gate. They control and monitor the aircraft flight assisted by automation when relevant and manage navigation and monitor the fuel onboard according to the flight plan. In addition to monitoring weather conditions and aircraft systems, they also manage and prepare for potential unpredicted events such as failures, medical emergencies, ATC constraints, weather hazards, etc., in coordination with their operations control centre and the involved ATCO.

In an airline led concept, the dispatcher would be in charge of planning the aircraft trajectory, accounting for aircraft performance and weather forecast information as well as potentially newly introduced climate impact models to identify the most optimal route from a climate and economics perspective. The flight crew should target to fly as filed but in case of weather condition change affecting the climate impact during the flight execution (see paragraph 2.4), the pilot may have to adapt the aircraft trajectory to minimise the climate footprint of the flight when appropriate and safe to do so.

Such airline-led concept presents both pros and cons. The main pros are that the airline has the best knowledge of its aircraft performance and has a good understanding of its costs (linked to aircraft fuel consumption but also to mission / network specific configuration), both being key data for an appropriate climate versus cost balanced decision making. In addition, even though most flight planning systems do not integrate specific logics to tackle climate sensitive areas impact mitigation (which represents nowadays an obvious limitation), airlines do already have the personnel and processes in place to address flight planning optimization.

The main con of this concept lies in the potential interdependencies between optimization at aircraft mission level and the impact at the fleet/sector level. Indeed, optimizing all flight independently for a cost and climate footprint balance may not be compatible with safety related ATM constraints such as capacity and separation. This way to operate may limit performance of mitigation measures or have adverse effects at fleet level and such system-level consequences should be analysed in more detail as part of research projects and trials.

ANSP-led Concept

The work of ANSPs encompasses both the strategic horizon functions used in the air traffic Flow and capacity management (ATFCM) and the tactical horizon functions led by the air traffic control officer (ATCO).

- The objective of ATFCM is to provide sufficient airspace and aerodrome capacity to meet traffic demand and, when the latest capacity opportunities have been exhausted, make the demand meet the maximum available capacity.

- The ATCOs seek to facilitate the safe, orderly, and expeditious flow of air traffic within their area of responsibility, ensuring that flights can fly as filed to the greatest extent possible, whilst ensuring safe separation between other aircraft in the vicinity. ATCOs will endeavor to facilitate the requested cruise level for the flight and will respond to tactical requests for deviation as safety and workload permits.

In an ANSP-led concept, the flow of aircraft is optimized to achieve minimum climate impact at fleet level using the most up to data weather forecast information and starting with a set of initial flight plan proposals from the airlines. During execution any update of the aircraft trajectories needed to optimize the climate impact would be delegated to the ATCO who should consider the updated weather information as well as the current and planned position of aircrafts flying in its control area. Using climate models and/or actual detection of contrails, the ATCO would be in charge of optimizing and suggesting trajectory updates to the flight crew.

Similarly to the airline led concept, such ANSP-led concept presents pros and cons. Pros are that the ATFCM team and ATCO have the bigger picture and oversee the complete flow of operations in their control area. They have the competencies to ensure that the global flow of operations matches all the criteria for safe operations. The cons are that ANSP stakeholders do not 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 suboptimal trajectory optimization (e.g. suboptimal flight level leading to additional fuel consumption and adverse climate effects). In addition, most ANSP stakeholders are not trained and do not have the right tools to perform accurate trajectory optimization tasks. Similarly to the airline led concept, such ANSP led concept should be analyzed in more detail in the frame of research projects to determine its potential feasibility.

Collaboration between Airlines and ANSP

In such a concept, both strategic horizon decisions concerning the pre-flight process encompassing flight planning up to the definition of the approved ATC flight plan and tactical horizon decision concerning the potential tactical in-flight rerouting to cope with changing weather conditions would be taken collaboratively, ensuring a complete compliance to all safety criteria and enabling the consideration of the airline's preferences as part of the decision-making process. Such a concept would bring many benefits but may require additional enablers to ensure an efficient collaborative decision-making process as well as efficient data exchange between multiple stakeholders. Similarly to all other concepts such collaborative approach should be designed and analyzed in more detail to better understand its potential operational feasibility.

2.4 Potential Concepts of Operations (CONOPS)

To bring contrail reduction through navigational mitigation into practice, a concept of operations (CONOPS) is required to indicate the role of each stakeholder involved and define their tasks. The result will be a coordinated mitigation strategy that is consistent with a safe, efficient, and sustainable aviation sector. In summary, when navigational mitigation is feasible and effective, the concept of operations indicates who, what, when and why for all relevant stakeholders.

There are multiple ways to design a concept of operations; options should enable stakeholders to design a concept of operations that factors in operational dimensions. To date, no single concept has been examined in practice, and research did not explore or expand in detail on potential concepts of operations for mitigating the warming effects of contrails.

Current work is being undertaken that provides a good overview of all basic opportunities to mitigate the warming effects of contrails.[88] Possible options defining a concept of operation are illustrated in the figure 2-7.

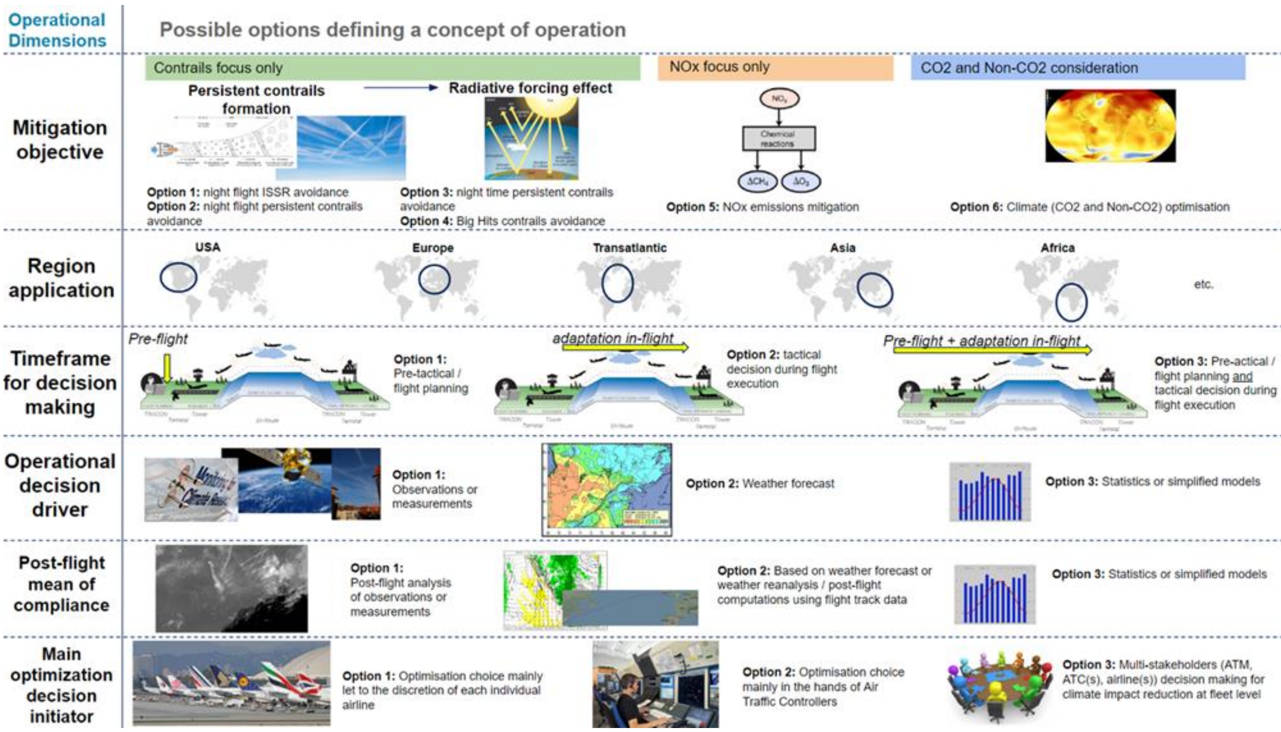

Figure 2--7 Various options to be defined for a Concept of Operations (CONOPS)

As a start, the mitigation objective of a concept of operations should be defined, for example in order of complexity: to avoid contrail formation, to avoid persistent contrails, to mitigate positive radiative forcing from contrails or mitigate all CO_2 and non-CO_2 climate effects (including NO_x).

Following the objective definition, the development of a concept of operations could include the following elements:

- Weather data assessment and forecasting
- Forecasting of contrail formation and persistence
- Contrail observation
- Climate impact modeling
- Flight planning
- Flight execution
- Post-flight analysis, impact measurement and verification.

[88] "Industrial research Project CICONIA- Climate effects reduced by Innovative Concept of Operations - Needs and Impacts Assessment," *SESAR Joint Undertaking* (2023) https://www.sesarju.eu/projects/CICONIA

- Instructions; for flight dispatchers, flight crews, and air traffic control.

Weather Data Assessment and Forecasting

Weather forecasting is the first step in a potential concept of operations and would ideally include forecasting of localized meteorological conditions that are relevant for contrail formation and contrail persistence. The relevant weather conditions for contrail formation are relative humidity and temperature, of which the relative humidity is key but can be unreliable or possess large uncertainty at higher altitudes. Wind, turbulence and overlap cloudiness are relevant for contrail persistence. For the warming potential, other weather phenomena are of interest, such as location and thickness of underlying clouds and the albedo of the earth surface.

In-situ measurements of the relative humidity will greatly support the accuracy of the contrail predictions, because relative humidity with respect to ice (RH_i) is a key parameter for contrail persistence. Combined with (NWP) model improvements, these measurements can enhance the accuracy and reliability of the forecasts of ISSRs. See Chapter 4 for future opportunities and enablers.

Forecasting of Contrail Formation and Persistence

The relative humidity and temperature will lead to the prediction of the presence and location of the ISSRs, where formed contrails will persist. Weather forecasts would be fed as an input into a contrail prediction model. The output of a contrail prediction model will give details of contrail location(s), likelihood of persistence, the timescale of persistence, the optical properties of the contrail and its warming potential. There are currently few contrail prediction models, of which CoCiP, is widely used.[89] CoCiP simulates and predicts the properties of contrails as a function of given aircraft/engine combination, fuel used and atmospheric circumstances and the radiative effect of an individual flight. The model is designed for approximate prediction of contrail cirrus cover and analysis of contrail climate impact.

Weather and contrail prediction models should be made available with an acceptable level of accuracy, granularity, and lead time to allow for inclusion in flight planning or in-flight strategic application or tactical intervention. Forecasts of contrail formation would be made available to airlines to be included in flight planning and to air navigation service providers for informational purposes, tactical use and justification for accepting flight plans.

Contrail Observation

Due to the complexity of the chemical and physical processes related to the formation of persistent contrails and the lack of atmospheric humidity data at higher altitudes, contrails, their optical properties, lifespan and warming potential remain difficult to predict with accuracy. Actual observations can help with contrail identification and prediction through adjusting evaluation algorithms, and for verification of the beneficial effect from the interventions after flight.

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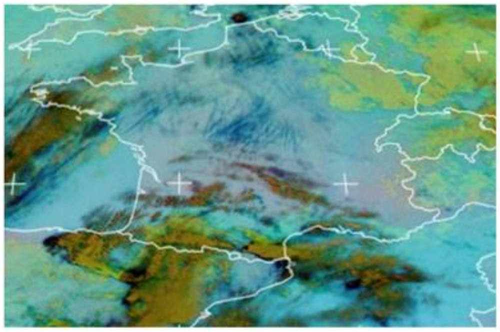
[89] Schumann U., "Contrail cirrus prediction model," (2012)

Data sources can include on-board and ground-based cameras, pilot reports, satellite and LIDAR data, meteorological observations, and related traffic data. Presently contrail detection is in its infancy, but many initiatives are being developed.[90] The use of low-orbit satellites or ground-based (short/medium/long-wave LIDAR or visual) cameras can provide accurate contrail detection, but their coverage is limited. Geostationary satellites have limited resolution and limited update frequency (and will therefore miss young contrails) and no altitude information but can be used on a global scale and to identify long-lived contrails.



Data	Ground Images	Low orbit Images	Geostat Images
Coverage	Fixed, Local 50/80km large	Moving, Intermediate 150-200km	Fixed, Continental
Frequency	Every 15-30 sec	Every 3-5 days	Every 10 mins
Resolution	1 pixels ≈ 10-100m	1 pixels ≈ 30-100m	1 pixel ≈ 2-5km (GOES-MTG) 4-7km (MSG)

Figure 2-8 Characteristics of different observation techniques for contrails – from EUROCONTROL/CANSO Workshop 2023.

For future use, a hybrid form could serve well – see Chapter 4. Artificial Intelligence can assist in identification of contrails and contrail cirrus and can be included in flight planning software. In addition, a standard methodology for contrail annotation should be established and contrail observation data can be shared.[91]

Climate Impact Modeling

Following the contrail prediction modeling and observations, climate impact modeling can be implemented to quantify the climate impact for the planned trajectory. The climate impact may include both CO_2 and non-CO_2 emissions.

This function will enable the flight planner or an automated flight planning system to use the outcome to optimize a flight track with respect to the climate impact, in an unambiguous way.[92] An algorithm calculates the related climate impact (from CO_2 and non-CO_2 direct and indirect emissions (contrails, NO_x, water vapour, aerosols, etc.) for different routings. As indicated in Chapter 1, the metric and the time horizon used to measure the climate impact is important in the optimization to balance between CO_2 and non-CO_2 emission impacts.

Different climate impact models have been described in Chapter 1. As stated, not all models/functions are well suited to integration into flight planning tools, either due to model

[90] Schumann et al., "Contrail study with ground-based cameras," *Atmos. Meas. Tech. vol. 6-12* (2013) https://doi.org/10.5194/amt-6-3597-2013;
Siddiqui Nasir, "Atmospheric Contrail Detection with a Deep Learning Algorithm," *Scholarly Horizons: University of Minnesota, Morris Undergraduate Journal vol. 7-1* (2020) https://doi.org/10.61366/2576-2176.1087;
"Using all-sky imagers to improve contrail detection," *Reuniwatt* (2024) https://reuniwatt.com/en/company_news/eurocontrol-state-of-the-art-contrails-observations/
[91] "EUROCONTROL launches ContrailNet," *EUROCONTROL* (2023)
[92] Matthes et al., "Climate-Optimized Trajectories and Robust Mitigation Potential: Flying ATM4E," *Aerospace vol. 7-11* (2020) https://doi.org/10.3390/aerospace7110156

characteristics or computational inefficiency. Continued focus and further work is needed to develop better models that will provide operational flight planning integration capabilities, see Chapter 4 Future Opportunities.

Flight Planning

When the contrail climate sensitive area is established accurately and with an acceptable level of certainty, from the weather and contrail prediction tools, a cost- and climate efficient route can be planned by the operator, accounting for the operational constraints of the flight (airspace capacity constraints, time, costs) and enabled by the ANSP. A climate impact function can assist to optimize the combined climate impact of fuel, contrails and possibly NO_x. Depending on the specific operational implementation (tactical vs strategic and operator-led vs ANSP-led), contrail management may impact the planning process for the different operational stakeholders.

In practice, the actual flight planning is a combined effort between the operational stakeholders: the airline operator, the pilot, network manager (if applicable) and the ANSP. Using the same principles as for trajectory-based operations (TBO), early coordination will result in a more effective decision making at both flight planning and flight execution phases, meeting the objective of reducing the climate impact and improving single-flight and system efficiency while reducing tactical interventions impacting predictability.

The following steps can be considered within the development of a flight plan.

1. Airline develops trajectory preferences while understanding known constraints through:
    a. identification of environmental factors affecting trajectories (e.g., winds, warming impact of one or more flight),
    b. identification of constraints that may affect decisions across all phases of flight (e.g., airspace capacity time constraints, costs),
    c. development of alternative trajectories, and
    d. comparison of trade-offs (and non-CO_2).
2. Airline submits the flight plan with trajectory information to the ANSP (possibly using the Flight & Flow Information for a Collaborative Environment (FF-ICE) services).
3. Collaborative Decision Making (CDM) processes are applied to manage trajectory negotiation between the airline and ANSP. The agreed trajectory will be used as a basis for managing and controlling the trajectory.

Using such an approach will provide a clear visibility of the planned lateral, vertical or time trajectory and/or generic constraints that define it, as well as of the operational factors that may affect it. Once the trajectory is agreed, it can be executed.

Access to weather information regarding contrail formation predictions and observation data is essential during the planning phase to allow airspace users to plan and negotiate with ANSPs trajectories that avoid or minimize contrail depending on the other applicable constraints.

With an acceptable level of confidence in contrail prediction, flight planners would select flights (or which will likely fly through contrail climate sensitive areas and have strong warming potential. In case of an ATM-led approach, the relevant airspace or a region can be identified.

Flight plans can be adjusted to optimize flights for contrail avoidance and minimize impacts from interdependencies identified in section 2.5 such as time, fuel use and the overall climate impact. Several selection strategies are available: first of all, if capacity allows for it, and secondly based on a contrail EF threshold, an acceptable level of confidence, a geographic, seasonal/hourly criteria or a (fuel) cost criteria.

Available flight planning tools have been assessed[93] to enable horizontal or vertical trajectory adjustment to mitigate contrails, in a similar manner to how these tools are utilized for avoidance of weather phenomena like turbulence or icing conditions. Some flight planning software products, such as FlightKeys and LIDO, incorporate contrail management into existing flight planning software platforms; some products consist of separate contrail management tool, such as Satavia and Thales.

Changing or upgrading a flight planning system for an airline operator is an involved endeavor. However, with other requirements on the horizon in line with ICAO Global Air Navigation Plan (GANP), such as FF-ICE, changes would ideally enable all these future requirements (see Chapter 4).

Pilots and flight-planners should have the same sources available to comprehend the relevant information for contrail avoidance both for preflight replanning as for inflight intervention. The air navigation service providers may also have access to contrail forecasting and have the relevant information to confirm the need for contrail avoidance when accepting or rejecting flight plans. And in case of an ANSP-led concept, take the lead to optimize and suggest trajectory updates to the flight crew / operator. Future automation is expected to provide airlines with the required sources usable by both pilots and dispatchers for contrail avoidance both for preflight replanning as for inflight (tactical) intervention.

Flight Execution

Flight-execution and trajectory negotiation in flight allow the airline and ANSP to meet the specific contrail avoidance objectives. In-flight trajectory adjustment would be considered as an additional resource for contrail mitigation supplementary to adjustments made in the flight planning stage, when:

1. An update to trajectory prediction input data such as forecast of warming contrail formation results in a need for an update to the agreed or planned trajectory.
2. Detection of inconsistencies or new constraints that would impact the agreed or planned trajectory, e.g., change in airspace capacity.
3. No contrail management was incorporated in the flight planning stage.

A trajectory negotiation in flight may result in one of the following outcomes:

1. No change: the change of trajectory is rejected, and the planned trajectory remains to be the trajectory to be flown.
2. A revision: following a positive trajectory negotiation a revised trajectory is agreed and cleared. This new trajectory may require a complete or partial revision of the flight plan within established constraints.

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93 Barten, K.P.A.M., "Contrail Mitigation Flight Planning," (2017);
"Contrails & Climate Change," *Breakthrough Energy* (2023) https://www.fzt.haw-hamburg.de/pers/Scholz/materialFM1/BreakthroughEnergy-2023_Contrails_and_Climate_Change.pdf

It should be noted that trajectory updates resulting from minor time deviations will not result in a change of the agreed trajectory.

In-flight avoidance is technically possible but may be limited by the lack of ability to evaluate, apply, or implement the flight plan changes and assess the trade-offs such as additional fuel requirements, and flight time.

While the agreed or planned trajectory provides a common intent to be achieved, the process by which this trajectory is delivered is through the provision of clearances by ATC which are accepted and executed by the flight crew. A flight execution is based on the agreed trajectory and flight plan, but this does not mean that the flight must be precisely controlled to all dimensions of the trajectory.

The initiation of a request for trajectory adjustment can come from the ATCO or the operator/pilot; the initiator role depends on the concept of operations selected (see paragraph 2.3). In the first case, a system- and area-wide implementation can be adopted; in the latter case, the operator can optimize its own (environmental) performance.

The following steps can be considered for a trajectory negotiation post-departure:

Table 1 Process of trajectory negotiation during flight.

Horizontal tactical deviations will have in general more impact on the flight operation than vertical adjustments. Vertical tactical instructions can be more easily implemented, without the need to adjust the lateral route in the flight management computer. The opportunity to deviate horizontally may be restricted, especially for short-haul flights. The (fuel) trade-offs are discussed in paragraph 2.5. In general, vertical adjustments seem in favor considering the size and form of the contrail sensitive areas and the related fuel penalties for extra mileage versus off-optimum cruise altitudes.

Verification

In an idealized concept of operations, there should be feedback from the quantified contrail impact back to the forecasting and planning stages to check the effectivity of the intervention. The feedback should be available to all stakeholders involved with the planning process to ensure consistency of information.

Verification is required of various factors; there must be some way to track flights diverted for avoidance to verify that no contrails were formed. If contrails appear, all major characteristics of the contrail should be collected: evidence of formation, persistence, size, and location.

The verification of avoided radiative forcing is more difficult as it is the result of a more complex process. The level of certainty is less than for CO_2 emissions. For tactical interventions this outcome is hard to achieve.

Model validation is not part of the concept of operations but may use the same data as for verification. Model validation is an essential part of research to expand the knowledge on contrail formation, the underlying processes and to enhance the reliability and accuracy of the contrail prediction models resulting in more effective contrail management.

Instructions; for Flight Dispatchers, Crews, and Air Traffic Control

Additional training may be needed to ensure that flight crew and dispatchers have basic background knowledge and skills to apply contrail management. Clear instructions and can assist all operational stakeholders involved: dispatchers/flight planners, flight crew and air traffic control.

Dispatchers/flight planners or flight crew, depending on the chosen concept of operations, can be instructed to adapt flight plans in order to avoid climate sensitive areas in accordance with meteorological data and contrail forecasts. Pilots may be informed to cooperate and adjust their flights in accordance with the mitigation strategy.

Inflight connectivity between dispatch and the flight crew will be essential for trajectory adjustments in flight and for information exchange. Clear entry and exit points of the flight plan should indicate the climate sensitive areas with altitude information. On board graphical information can assist in depicting the contrail climate sensitive areas.

Trials and Potential Examples

Different examples of contrail mitigation strategies and related concept of operations are being subject to research in different levels of readiness across various research initiatives. These examples are neither tested nor implemented in practice but could serve as basis for further assessment and research. See the attachment to Chapter 2 for some examples.

2.5 Potential Interdependencies

Current flight paths are mainly designed to minimize flight time or fuel cost, within the existing airspace and route structure. Changes in the optimization strategy to include navigational contrail avoidance efforts will impact other aspects of flight such as flight time and fuel consumption (and associated CO_2 and non-CO_2 emissions). Airspace capacity and potential flight efficiency of other airspace users may be affected as well, especially in congested airspace. As a consequence, navigational avoidance to avoid contrail formation could result in increased climate forcing due to increased greenhouse gas emissions associated with the specific flight and potentially other impacted flights. Clearly, 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.

The following trade-offs and interdependencies should be evaluated when selecting a strategy, not only for the individual flights but also for the overall operations, to include impacts on airspace, airport, other flights and network operations:

a. Impact on safety
b. Impact on flight time
c. Impact on fuel consumption and CO_2 emissions
d. Impact on airspace capacity and predictability
e. Impact on workload for operational staff
f. Impact on schedules and passenger experience
g. Overall climate impact

Numerous studies suggest that a (small) subset of flights is responsible for the majority of warming contrail production - see paragraph 2.1. Avoidance strategies could be prioritized to those flights that are likely to produce significant contrail-cirrus RF to minimize overall interference and trade-offs, if identification of those flights is possible. Alternatively, a strategy can be chosen that will only target those flights when there is minimal fuel or time penalty.[94]

Some interdependencies may turn into an impediment for the use of avoidance strategies, as the "costs" of avoidance will be too high in terms of capacity loss, or overall climate impact. Chapter 4 will explore future opportunities that enable effective contrail mitigation, while minimizing the impact on other aspects of the flight, such as the listed interdependencies in this paragraph.

Safety

For every concept, safety is the prime concern. The assessment of the impact on safety must be integrated in the feasibility and development studies for contrail management. Safety concerns

[94] Teoh et al., "Small-Scale Diversions," (2020)

can be related to increased ATC, flight crew and dispatcher workload, flight separation and increased air traffic complexity, communication, flight management and navigational issues.

Airspace capacity, ATC workload and safety are closely linked. While assuring the same level of safety, the declared sector capacity, as the measure of the ATC system to provide CNS (communication, navigation and surveillance) service to aircraft during normal operation,[95] may be reduced due to contrail management tasks.

Flight Time

Currently, flights are generally planned to optimize flight time and fuel efficiency. Deviations from the optimal routes in terms of flight time to avoid contrails may result in additional flight time, especially with horizontal deviations. The correlation between horizontal contrail avoidance and flight time shows a large variability meaning that for the same increase in flight time, the reduction in contrail distance can vary largely depending on the daily meteorological situation. On average, the impact on flight time is expected to be relatively limited, with variations on the order of ±1% substantially less than airlines' daily operational challenges.

Vertical deviations are likely to have little or no impact on flight time, unless considerably different wind patterns are experienced. A lower altitude may result in a slightly higher True Airspeed (TAS) due to the higher temperature at lower altitude if a fixed Mach number is flown.

Efforts to produce more accurate weather prediction data and persistent contrail forecasting will result in more accurately identified avoidance areas and less impact on flight time. Enhanced collaboration with flight planning departments to favor pre-tactical avoidance strategies will result in more predictable changes to flight times.

Many constraints of flight scheduling depend on accurate timing, such as airport arrival capacity, separation of flights, and connections. If flight time is impacted, so is airport arrival capacity, fleet regularity and connectivity.

Fuel Consumption and CO_2 Emissions

The actual fuel use and CO_2 emissions associated with avoidance will in either case be greater if the track and/or the actual flight altitude deviates from the fuel optimized flight plan. Fuel consumption may increase per affected flight on the order of a few percentage points depending on the mitigation strategy (, vertical or horizontal, strategic versus tactical), the flight cost index (time versus fuel optimized flights) and airspace complexity (see examples below). Additional fuel use may be found from other aircraft (not generating contrail cirrus RF) which may be affected indirectly through ATM measures.

The extra fuel use impacts the flights differently depending on whether pre-tactical or tactical avoidance strategies are implemented. If avoidance is planned before the flight plan is submitted, the change in fuel requirements is known and the flight plan fuel will include the excess fuel for avoidance. If flight trajectories are changed during flight, usually the extra fuel is not planned for and contingency or additional reserve fuel may be used. If a flight can expect tactical avoidance

[95] "Annex 11– Air Traffic Services 15th Edition," *ICAO* (2018) https://store.icao.int/en/annex-11-air-traffic-services

to be instructed by air traffic control, extra planned fuel may need to be accommodated in anticipation of deviations from the flight plan.[96]

Rules of thumb can be given for fuel penalties when flying off-optimum altitude: 1- 2% for 2000 ft off-optimum altitude and 5-6% for 4000ft off-optimum altitude.[97] These percentages are valid for standard atmospheric conditions without vertical wind changes and may be used as a proxy for most speeds. For lateral deviations, the fuel penalty will be related to the increase in flight time (and the fuel consumption per time unit).

A meta-study of several analyses suggests that 50% reduction in contrail length can be achieved with a 1.0 % increase in fuel burn, with an 80% reduction in contrail length requiring a 2% increase in fuel burn for flight deviations.[98] Figure 2-9 indicates several examples of the fuel burn increase related to the contrail length decrement, found in different studies.[99] For more details, refer to the list of studies below.

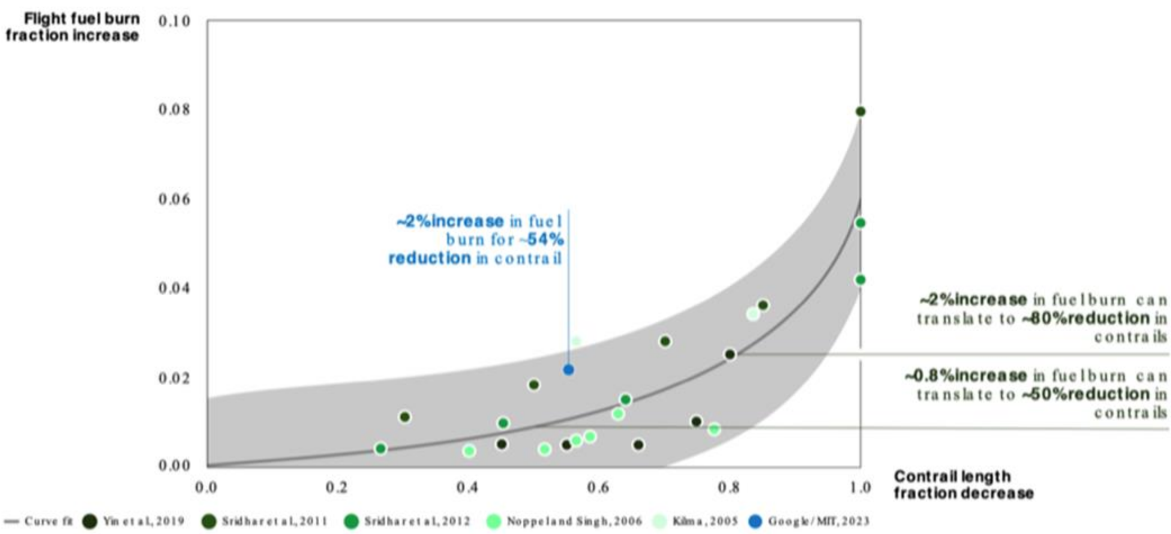

Figure 2-9 Fuel burn increase for contrail avoidance, from several sources. Fuel burn increase applies only to targeted flights; at fleet level, the increased fuel burn is significantly lower.

When considering the total aircraft movements, the additional fuel burn may be minimal when only specific high contrail impact flights are targeted. Primarily because only a few flights will burn additional fuel, and secondly, due to less impact of the air traffic and airspace available.

Uncertainties in (early) predictions in location and size of ISSRs may result in an unnecessary large deviation from the fuel-optimal flight trajectory, which in turn will lead to an excess of fuel uplift and excess CO_2 emissions by flying a sub-optimal route with regards to fuel efficiency.

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[96] "Flight Planning and Fuel Management (FPFM) Manual (9976)," *ICAO* (2015) https://store.icao.int/en/flight-planning-and-fuel-management-fpfm-manual-9976
[97] "Operational Opportunities to Reduce Fuel Burn and Emissions (Doc 10013)," *ICAO* (2014) https://store.icao.int/en/operational-opportunities-to-reduce-fuel-burn-and-emissions-doc-10013
[98] Dray, L. et al., "Cost and emissions pathways towards net-zero climate impacts in aviation." *Nat. Clim. Chang. 12* (2022) https://doi.org/10.1038/s41558-022-01485-4
[99] Cathcart et al., "Understanding Contrail Management," (2024)

Several studies provide an estimated quantitative assessment of the extra fuel used due to contrail avoidance strategies:

- *A small-scale strategy of selectively diverting 1.7% of the fleet in Japanese airspace could reduce the contrail EF by up to 59.3% [52.4, 65.6%], with only a 0.014% [0.010, 0.017%] increase in total fuel consumption and CO_2 emissions. A low-risk strategy of diverting flights in the Japanese airspace only if there is no fuel penalty, thereby avoiding additional long-lived CO_2 emissions, would reduce contrail EF by 20.0% [17.4%, 23.0%].*[100]
- *A more intrusive strategy in the same region, that reroutes 15.3% of flights to avoid long-lived warming contrails, reduces the contrail energy forcing (EF contrail) by 105% [91.8, 125%] with a total fuel penalty of 0.70%.*[101]
- *A recent study using flight data from one US airline for domestic and North Atlantic routes, indicated a reduction of 73% of contrail climate forcing at the cost of 0.11% extra fuel.*[102]
- *A study on transatlantic flights, full-year study. A maximum reduction in contrail distance (of 80%) causes an increase in fuel consumption by 0.0 - 0.2% % in summer, 0.5-1.5% in autumn and 0.5-3.5% in winter/spring.*[103]
- *At least 50% of contrails can be mitigated through horizontal and vertical flight adjustments at less than 2% additional fuel which exceeds ground track selection only strategy (i.e. hybrid outperforms a single dimension strategy). The results have confirmed the hypothesis that large shares of contrails can be mitigated against a few percent additional fuel consumption and flight time.*[104]
- *A meta-study of several analyses suggests that 50% reduction in contrail length can be achieved with only a 0.8% increase in fuel burn, with an 80% reduction in contrail length requiring a 2% increase in fuel burn for flight deviations.*[105]

Airspace Capacity and Predictability

Airspace capacity is dependent on available airspace and route complexity, ATM procedures, separation standards, state of equipment (surveillance and communications systems, aircraft navigational performance) and controller workload. A reduction of physical airspace for contrail avoidance can lead to capacity constraints. An increased number of tactical interventions (required for navigational avoidance) may increase the controller's workload and may also lead to airspace capacity reductions.

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. The implications on ATM have to be identified. Although modelled studies have found that safety issues are not

[100] Teoh et al., "Small-Scale Diversions," (2020)
[101] "Contrails & Climate Change," *Breakthrough Energy* (2023)
[102] Frias et al., "Feasibility of contrail avoidance," (2024)
[103] Yin et al., "Impact on flight trajectory," (2018)
[104] Barten, K.P.A.M., "Contrail Mitigation Flight Planning," (2017)
[105] Cathcart et al., "Understanding Contrail Management," (2024)

limiting the results for flows in the North Atlantic flight corridor, they might limit the applicability in areas of higher air traffic densities.[106]

Long term forecasts may lead to more uncertainty in the modeling and prediction which may lead to an oversizing of the contrail climate sensitive areas and an overestimate of the duration of their existence. This would have consequences for the physical available airspace, and potentially the airspace capacity.

Pre-flight interventions (during the flight planning phase) may be preferential from a workload and flight planning perspective, but tactical interventions may be preferential to reduce the actual regions of the atmosphere to be avoided due to more certainty in the prediction. Ideally, the flight is planned accordingly with accurate forecasting.

Until the time of writing, no large-scale assessments or trials have been conducted to assess the impact from contrail avoidance on airspace capacity. As mentioned in Chapter 2.3 (In Flight Intervention), the world's first live contrail prevention trial carried out in 2021 by MUAC, and it was extrapolated that capacity reductions in the range of 20% can be expected in moderate traffic conditions across MUAC airspace; and normal or high traffic conditions will increase the impact of contrail prevention operations exponentially.[107] Another study applied a maximum number of rerouted (1 to 10% of all traffic) to simulate the restrictions from the ATM system in a simulated trial.[108] Other theoretical studies restrict intervention to a maximum of 50% contrail RF reduction in order to simulate airspace restrictions.

One study found that with today's air traffic demand, no capacity limitations will appear when introducing climate-optimized tracks across the North Atlantic oceanic region, including contrail avoidance.[109] However, more congested areas such as Europe and the northeastern US could see congestion or limitations. Regional differences on traffic demand and ATM infrastructure should be taken into account when considering effects on airspace capacity.

A large-scale fleet diversion strategy may not be practical nor necessary given that in the current studies only a small percentage of flights are found to contribute to a large portion of the total contrail energy forcing (for example, from a study using flight track data in the Japanese airspace: 2.2% of flights contribute to 80% of the total contrail EF).[110] For the North-Atlantic region, this number is around 12% of all flights, due to the smaller variations in flight tracks and higher relative number of flights at cruising altitudes.[111] A small-scale strategy addressing only the greatest contributors is expected to address contrail warming effectively and minimize ATM disruptions.

The percentage of flights contributing to contrail warming may not be consistent and the exact percentage will vary day by day. Spatially, the flights requiring diversion may also not be evenly distributed. The variation in the subset of flights also will have varying system-wide effects on traffic. The hypothesis that only a small portion of flights need to be diverted to mitigate contrail

[106] Grewe et al., "Climate-optimized air traffic," (2017)
[107] Sausen et al., "Small altitude adjustments," (2023)
[108] Teoh et al., "Small-Scale Diversions," (2020)
[109] Grewe et al., "Climate-optimized air traffic," (2017)
[110] Teoh et al., "Small-Scale Diversions," (2020)
[111] Teoh et al., "North Atlantic" (2022)

warming should be explored and validated by further research, with consideration in the variation of system traffic effects.

Workload and Human Factors

Any change in controller, flight crew or flight planners' procedures must be carefully evaluated for the impact on workload and on the operating procedures, in relation to the concept of operations, introduced in paragraph 2.4. Pre-flight intervention may have less impact on the mental workload of controllers and pilots than in-flight intervention.[112] Airspace capacity, complexity and controller workload are in general closely related.

In flight lateral or vertical flight re-clearances increase both controller and pilot workload, depending on operational conditions such as airspace complexity, air traffic volumes, coordination between different ATC sectors and supportive tools such as datalink and flight management tools for both controller and pilot. When workload is at a critical level, the traffic volume will be reduced and less contrail avoiding actions can be managed. In general, airspace capacity is limited more by controller workload than it is by separation regulations.[113]

To date, no large-scale live trials have been conducted to review the impact on workload, and traffic management in case multiple aircraft will need to deviate in flight from their planned flightpath to avoid contrail sensitive areas. A modelled study over the North Atlantic confirmed the need to identify the implications on ATM and indicated that safety might limit the applicability in higher air traffic densities.[114] The MUAC trial in 2023, although conducted with low traffic numbers, indicated the increased workload for ATCO and coordinator, and the exponential increment of complexity with larger scale interventions.[115]

Pilot and controller training or instructions may be required for the implementation of any concept of operations related to contrail avoidance to minimize impact on workload and safety. The application of contrail prediction models to date is an elaborate, manual process requiring close coordination among prediction modelers, flight planning providers, and airline operations personnel, pilots and dispatchers. Educational programs with background information on importance and principles of contrail formation and avoidance will be needed.

Operator Issues, Fleet Usage, Schedule Regularity

If flight time is lengthened or departure times adjusted, it will have an impact on crew and aircraft utilization, crew flight time limitations, operator scheduling and schedule regularity for operators and passengers, and on ATFM slot allocation and utilization.

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[112] Cathcart et al., "Understanding Contrail Management," (2024)
[113] Tait et al., "Aircraft Emissions, Their Plume-Scale Effects, and the Spatio-Temporal Sensitivity of the Atmospheric Response: A Review," *Aerospace vol. 9-7* (2022) https://doi.org/10.3390/aerospace9070355
[114] Grewe et al., "Climate-optimized air traffic," (2017)
[115] Sitova I. and Ehrmanntraut R., "MUAC Contrails Prevention project," *(Conference lecture, CANSO/EUROCONTROL Sustainable Skies: Contrails in Focus)*, Brussels, BE, Nov 07, 2023 https://www.eurocontrol.int/sites/default/files/2023-11/2023-11-08-contrails-conference-session-009-sitova-ehrmanntraut-muac-contrails-prevention-project.pdf

If departure times are adjusted in accordance with temporal avoidance (see paragraph 2.3), the operational consequences may be large. Many airports use arrival and departure slots and air traffic flow management restrictions might be in place. Flights during the hours of darkness in whole or part cannot practically be avoided (to avoid warming contrails) in airline operations without significant scheduling impacts (slot constraints, curfews) and resultant costs for the operators.

Adjustments to scheduled time of departure and scheduled time of arrival may have a significant negative impact on flight scheduling flexibility, fleet usage and flight punctuality. At the same time, the impact on the flying public needs to be considered. That is why temporal adjustment, if considered, will require reliable data and prediction/trends to allow effective management of flight schedules.

Overall Climate Impact

For the overall climate impact, all non-CO_2 climate impacts should be included and weighted with a suitable and commonly agreed metric for conversion into an equivalent CO_2 level, see Chapter 1. This should be done not only for the individual flight but for all flights. This will potentially impose further challenges for organizing the (large-scale) air traffic in the light of the limited capacity of the sky. It is not necessary that each individual flight needs to fly on a climate optimal trajectory, but the focus can be on a reduction of the climate impact on average while taking into account the remaining uncertainties on the climate impact of individual flights.

A climate cost change function incorporates the climate impacts of a particular flight, principally currently considering the effects of CO_2, contrails and NO_x impacts. It is based on an agreed relative importance of a unit of individual emissions species for a reduction of the climate impact from air traffic, as well as an agreed metric and time scale.

In both the Reducing Emissions from Aviation by Changing Trajectories for the benefit of Climate (REACT4C)[116] and the Air Traffic Management for Environment (ATM4E)[117] studies, climate change functions were developed whereby a climate impact, using a particular metric or set of climate metrics, is determined on a route by route basis. This would allow the most 'climate-friendly' route, or in the case of ATM4E the most 'environmentally-friendly' route, to be identified at operational flight planning level.

2.6 Concluding Remarks on Trajectory Adjustment

The feasibility and effectiveness of implementing navigational avoidance, whether at pre-tactical or tactical level are affected by:

a. Certainty that the contrail region will form, is highly warming, and is persistent.
b. Traffic volume and airspace capacity, especially in congested airspace where trajectory adjustment at tactical levels may not be possible for safety reasons.

[116] Grewe et al., "Reduction of the air traffic's contribution to climate change: A REACT4C case study," *Atmospheric Environment vol. 94* (2014) https://doi.org/10.1016/j.atmosenv.2014.05.059
[117] Matthes et al., "Flying ATM4E", (2020)

c. The interdependencies and trade-offs as identified in paragraph 2.5 such as fuel burn and CO_2 emissions.
d. Impacts on overall operation.

Large-scale trials have not yet been undertaken and robust statistics on the effectiveness of measures are not yet available. Different examples of contrail mitigation strategies and related concept of operations are being subject to research in different levels of readiness across various research initiatives. These examples are neither tested nor implemented in practice to date but could serve as basis for further assessment and research.

Attachment to Chapter 2: Examples of Concepts of Operations

Different examples of proposed concepts of operation for contrail mitigation are being developed across various research initiatives. These examples are neither tested nor implemented in practice but could serve as a basis for further assessment and research.

These concepts of operations range from airline-led strategies to ATC-led strategies, short-haul/continental airspace to long haul/oceanic airspace and pre-tactical and tactical concepts.

A. Airline-led Contrail Mitigation

Airline-led mitigation can consist of pre-tactical actions taken in the flight planning phase, action taking during flight execution, or a hybrid of both methods.

A1. Pre-tactical Operations Using Forecast Data

In this example, contrail forecasts are provided during the planning phase and the data integrated into the flight planning process. Where multi-step flight planning procedures are carried out and a first draft flight plan is reviewed closer to the departure, evolving ISSR forecast data will be taken into account during this part of the process in order to ensure that the data is as timely and accurate as possible. The flight plan is submitted with an indication that it includes contrail mitigation for a portion of the flight, identifying which sections of the flight this is applicable to, and as far as possible, Air Traffic Control ensures the flight is flown as filed, in particular for the highlighted sections of flight. This method is most suited to short-haul operations, where the forecast is more likely to be sufficiently stable and accurate. The advantage of this option is that there is minimal disruption to the day-to-day ATC operation, however it does need a reliable weather forecast in advance in order to achieve the climate benefits.

A2. Tactical Operations Using Forecast or Nowcast Data

For long-haul operations, or where there is less certainty around the available ISSR forecast data, the actions taken in the flight planning phase can still apply, particularly for the earlier phase of a given flight. Contrail mitigation in the execution phase of flight, however, will also be necessary to complement the planning actions. Updated contrail predictions which become available as the flight progresses can be used in the cruise phase.

The flight crew is supported by the dispatcher to assess possible trajectory adaptations, assessing the impacts on fuel and punctuality as well as the potential to avoid producing warming contrails. These tactical inflight trajectory modification requests are made by the flight crew to ATC following current processes, in the same way as tactical requests are made routinely for weather avoidance. There is no specific pre-coordination necessary between the aircraft operator and ANSP.

For oceanic flights, the latest data can be used to request a modified oceanic trajectory while the aircraft is in flight, but prior to the oceanic entry point, or alternatively the flight crew can request climb or descent tactically at suitable points along the route. ATC will be informed that the reason for the trajectory change is for contrail avoidance and will provide the revised clearance as long as traffic conditions permit.

The advantage of this option is the most recent contrail forecast, or even a now-cast, can be used for contrail minimization. However, the disadvantages are that this strategy potentially increases workload for flight crew and ATCOs (and their support teams), and less time is available to plan and optimize the trajectory from when all the relevant information becomes available.

Figure 2-10 Design Principles for a Contrail-Minimizing Trial in the North Atlantic, Jarlath Molloy, Roger Teoh, Sean Harty, George Koudis, Ulrich Schumann, Ian Poll, Marc E.J. Stettler.

A3. Tactical Operations Using Real-time Observational Data

Contrail occurrences are detected in real-time through satellite observations feeding a decision process owned by airlines. Based on observations of contrails, alternative flight paths are computed and proposed to the flight dispatch teams of the airline operations centre and, if deemed acceptable and feasible, cascaded to the flight crew who take the final decision whether to request a change to their trajectory from ATC.

An advantage of this option is that the airlines can take actual weather conditions and contrails observations into account in order to adjust flights during execution while satisfying their strategic objectives (time, fuel, economic performance).

However, the disadvantage is that the tactical intervention may not be as efficient as a strategic one from a climate impact mitigation perspective (as contrails have already been formed) and consideration of safety aspects related to capacity and separation may lead to rejection by the ANSP of the flight path modification request if no coordination is assured at the fleet level.

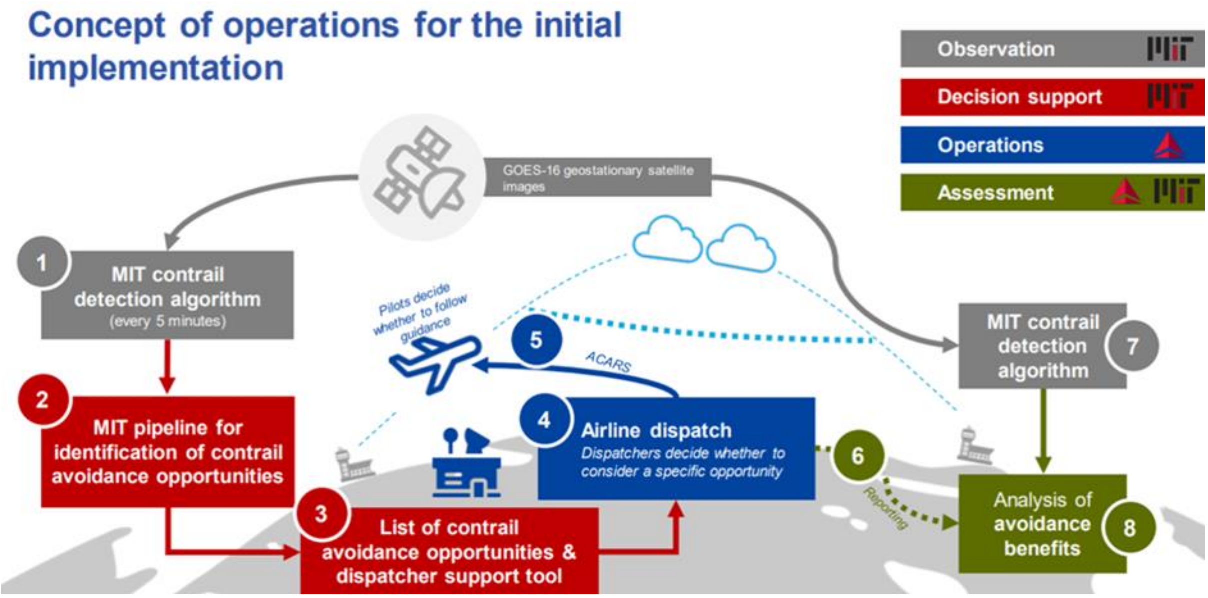

Figure 2-11 Illustration from S.Barrett presentation at the CANSO / EUROCONTROL Sustainable Skies Conference: Contrails in Focus.

B. ATC-led Contrail Mitigation

B1. Pre-tactical Provisions and Tactical Contrail Mitigation

This strategy relies on a two-step approach. The first step is to define the flight plan accounting for potential contrail impacts and network constraints using information on climate sensitive areas shared by the ANSP/Network Manager. This is a collaborative process to converge on the final flight plan definition. The second step takes place during the flight execution phase, where updated weather conditions and/or live contrails observations are monitored by the ANSP in order to evaluate the need for a tactical rerouting. If track adaptation is necessary to avoid a climate sensitive area, ATC will consider whether this can be safely facilitated and the capacity managed, and if so, will request the flight crew to tactically re-route for contrail mitigation. The final decision to implement tactical rerouting remains with the flight crew.

An advantage of this strategy is that the climate, traffic flow and safety implications can be considered for fleet-wide optimization and the latest weather information is considered. A disadvantage is that airline-specific objectives such as optimization of time, fuel and economics might not be adequately accounted for.

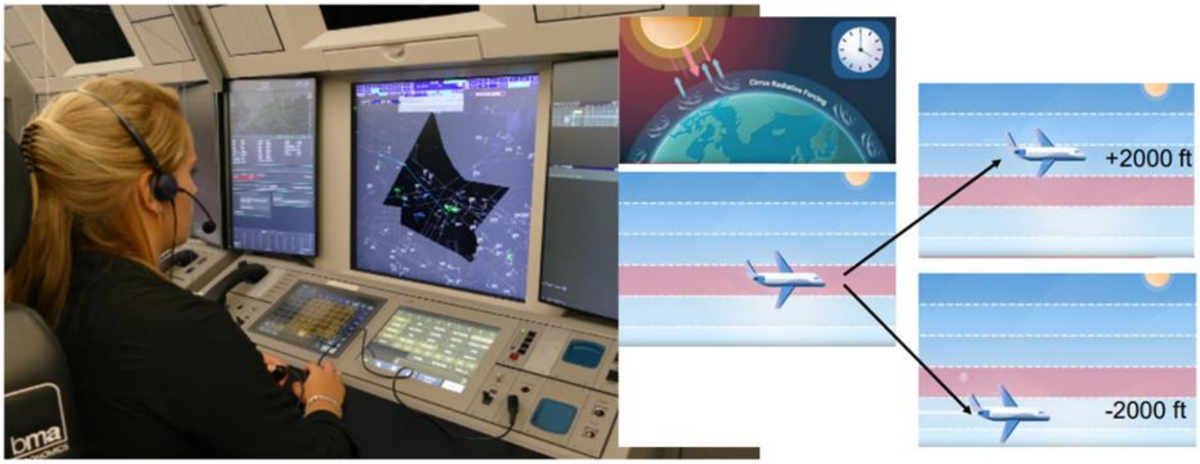

Figure 2-12 Illustration of ATC-led concept from MUAC presentation at the CANSO / EUROCONTROL Sustainable Skies Conference: Contrails in Focus

B2. Pre-tactical Oceanic Operations Using Forecast Data

This ATM strategy would rely on the existing Organized Track System (OTS) process to create a specific 'minimal warming contrail' OTS track, or tracks, to minimize persistent warming contrail formation.

At Day-1, oceanic ATCOs would plot a specific track, or tracks based on weather and contrail forecasts and the preferred route messages (or provisional flight plans) from the aircraft operators, for the next day's tracks. The contrail track(s) would be published with the normal OTS and be available for use by any aircraft operator.

The minimal contrail track has the advantage of creating a dedicated and flight-plannable trajectory for any aircraft, with the track being deconflicted at the time of preparation, therefore not impacting the core flow of traffic oceanic traffic.

The disadvantage of this strategy is that it would require more planning and coordination pre-tactically and needs a reliable contrail forecast in advance. If a more extensive climate mitigation strategy is to be sought by regulators or the industry, one approach would be to design the majority of tracks to avoid persistent contrails or facilitate climate minimum-impact trajectories.

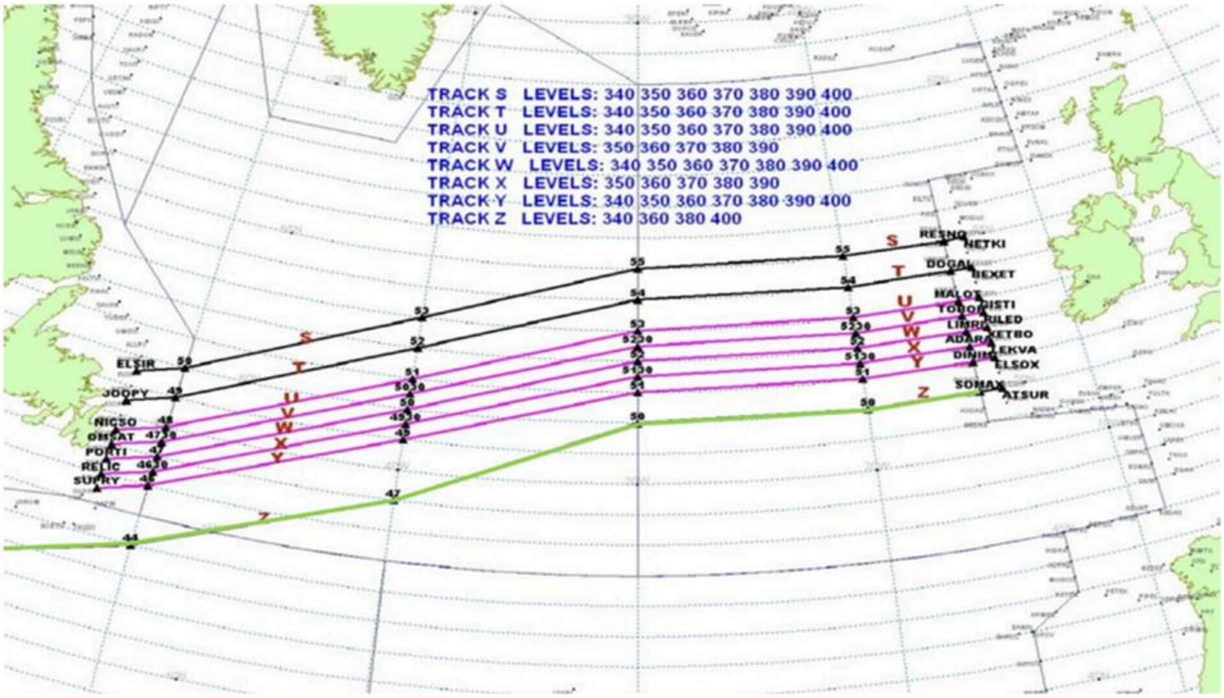

Figure 2-13 Design Principles for a Contrail-Minimizing Trial in the North Atlantic, Jarlath Molloy, Roger Teoh, Sean Harty, George Koudis, Ulrich Schumann, Ian Poll, Marc E.J. Stettler.

CHAPTER 3 – OTHER NON-CO_2 CLIMATE IMPACTS

3.1 Introduction

Besides contrail formation, other non-CO2 engine emissions may cause a climate impact (see fig 1.1). These emissions may directly influence the Earth atmosphere radiation budget, such as water vapour and ozone, or indirectly, through changes in the chemical composition of the global atmosphere (such as NO_x). Either warming or cooling.

The relevant other non-CO_2 emissions are:

- nitrogen oxides (NO_x),
- sulfur oxides (SO_x),
- water vapour,
- soot particles (nvPM),

These aviation's non-CO2 emissions are addressed through technological measures in the engine certification process (nvPM, NO_x) or through aviation fuel specifications (SO_x). In terms of operational opportunities, current literature only identifies strategies for the reduction of NO_x impacts. Based on current knowledge and estimations, the largest other non-CO_2 climate impacts (besides aviation-induced cirrus) are those from NO_x.

Reductions of NO_x are historically driven by concerns of local air quality leading to the adoption of more stringent landing and take-off (LTO) NO_x certification standards. The scientific understanding on the net effect of NO_x on the climate has evolved over the last decade,[118] however, the uncertainty of this impact remains high.[119]

While not a climate warming gas itself, NO_x changes the chemical balance of atmospheric ozone and methane which have radiative impacts, quantified as a 'net - NO_x' effect. The climate impact of NO_x emissions results from an increase in ozone (warming) and a decrease in methane (reduced warming) and depends heavily on existing background concentrations.[120] This study highlights the spatially and temporally heterogeneous nature of the related chemistry, which needs to be accounted for in efforts to minimize aviation's climate impact from NO_x.

The confidence level on the magnitude of the impact of NO_x remains low because of the complex interaction with atmospheric chemistry, which is non-linear and highly dependent on other (surface) sources of NO_x emissions.[121] The current scientific understanding is that NO_x still has an overall positive (warming) climate forcing effect. Based on a recent assessment, aviation NO_x emissions over the 1940-2018 period have contributed to a net warming of the climate system.[122] This may change in the future, when certain chemical contents change (through

[118] Miake-Lye R. and Hauglustaine D., "Impacts of Aviation NOx Emissions on Air Quality, Health, and Climate," *ICAO Environmental Reports* (2022) https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2022/ENVReport2022_Art18.pdf
[119] "[CAEP/12 - WP/51] White paper Independent Expert Group on NOx Impacts," *ICAO CAEP* (2022)
[120] Grewe et al., "The contribution of aviation NOx emissions to climate change: are we ignoring methodological flaws?" *Environ. Res. Lett. 14* (2019) https://doi.org/10.1088/1748-9326/ab5dd7
[121] "EU 2020 Updated analysis of the non-CO2 climate impacts full report," EASA (2020)
[122] "[CAEP/12 - WP/51] NOx Impacts," *ICAO CAEP* (2022)

cleaner surface/background NO_x emissions), and tropospheric ozone formation decreases significantly. This highlights one of the problems of formulating NO_x mitigation policy based on current emissions and atmospheric conditions.[123]

Soot refers to solid particles composed of black carbon and organic carbon issued from the fuel combustion and present in the engine exhaust air; they may undergo chemical and physical processes. As illustrated in the Figure 1.1, soot has a direct and very small positive radiative effect, and probably an indirect effect resulting from their interaction with clouds (no best estimate given at the moment). In addition, soot has an influence on contrails: a decrease in soot particle number may reduce the contrail ice crystal formation, changing their optical depth and lifetime and leads to a reduction of the radiative forcing of contrails. Chapter 5 addresses the reduction of the aromatic content of fuels which relates to less soot emissions.

Sulfate aerosols result from the condensation in the atmosphere of sulfur oxide emissions produced by the engine as a result of the combustion of fuel containing sulfur. They have a direct and negative radiative effect, as well as an indirect effect resulting from aviation aerosol-cloud interactions, the best estimates of which remain undetermined.

The effects of sulphur emissions on cloudiness are very poorly understood and studies indicate forcings that range from large negative through to small positive.[124] SO_x emissions can coat carbon particles and enhance the formation of ice crystals by affecting their initial hydrophobic properties.

3.2 Operational Opportunities to Reduce NO_x Impacts

The formation of NO_x emissions is a thermally driven process in the combustion chamber of the engines. NO_x emissions depend highly on the temperature at which the fuel is combusted and the residence time of the hot air mixture in the combustor. For this reason, mitigation strategies are related to lowering the combustion temperature - for example by reducing thrust at take-off.

Cruise NO_x emissions are not as well characterized especially for many of the new staged combustion technology. However, it is found that a strong relationship exists between (known) NO_x emissions per unit fuel during the LTO phase and the emitted cruise NO_x.[125]

The overall climate impact of NO_x emissions during cruise is dependent on the altitude and other factors such as background concentrations of chemical compounds. Particularly, the persistence of emitted NO_x in the atmosphere varies by region and can remain for up to several weeks in the atmosphere.[126] Hence, changing aircraft trajectory has the potential to reduce the climate impact

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[123] Skowron et al., "Variation of radiative forcings and global warming potentials from regional aviation NOx emissions," *Atmospheric Environment vol. 104* (2015) https://doi.org/10.1016/j.atmosenv.2014.12.043
[124] Lee et al., "Contribution of global aviation" (2021)
[125] Faber et al., "Lower NOx at Higher Altitudes – Policies to Reduce the Climate Impact of Aviation NOx Emission," CE Delft (2008) https://transport.ec.europa.eu/document/download/54917bea-08fa-49db-8749-c6ae4684b47f_en?filename=oct_2008_nox_final_report.pdf&prefLang=fr
[126] Grewe et al., "Aircraft routing with minimal climate impact: the REACT4C climate cost function modelling approach (V1.0)," *Geosci. Model Dev. vol 7-1* (2014) https://doi.org/10.5194/gmd-7-175-2014

of NO_x emissions.[127] Modification of the cruising altitude (generally lower) may reduce the impact of NO_x as well. Both measures would imply an increased fuel burn for a current-day aircraft with a CO_2 penalty.[128]

Clearly, flying fuel optimized trajectories is another way to reduce NO_x, as in general reduction of fuel burn will reduce NO_x emissions (and mostly other non-CO_2 emissions), but to a much smaller scale than through the technological or fuel composition pathway.[129]

The net-NO_x effect of the operational measures on the climate is difficult to comprehend due to the dependence on the background atmosphere and the non-linear atmospheric chemistry, as stated in the introduction.[130] Overall, the reductions through operational measures are found to be small, uncertain and in general related to the distance flown (on the order of 1 or 2% ATR).

Together with avoidance of contrail formation, the potential of reducing the impact of NO_x through operational measures has been the subject of European research through the Tradeoff, REACT4C and ATM4E studies.[131] In another simulator[132] trans-Atlantic air traffic routing is optimized with respect to the combined contributions from NO_x and contrails to climate change. Both lateral and horizontal re-routing have been simulated to avoid climate sensitive regions. No actual flight tests have been done to date on operational measures to reduce NO_x climate effects.

Future forcing from aviation NO_x is uncertain. In case of changes in background atmosphere, combined with increased aviation emissions, aviation NO_x may lead to a net cooling climate effect. Therefore, the actual climate impact should be monitored over time and irreversible policies should be avoided with regard to NO_x cruise emission reduction.

3.3 Interdependencies

Operational measures to mitigate aviation's non-CO_2 impacts that involve a reduction of a short-lived climate forcer (e.g., NO_x), but result in increased CO_2 emissions, need to be considered carefully to ensure that the net impact is beneficial. Since CO_2 has a very long lifetime in the atmosphere, the ratio between benefits and disbenefits will change with the time horizon being considered.

The introduction of a climate impact function may be beneficial to assess the overall climate impacts of a particular flight, principally CO_2, contrail-cirrus and NO_x impacts and identify the most climate-friendly route.[133] This function indicates the climate impact of all emissions (CO_2 and non-CO_2 components) and is based on an agreed relative importance of individual emissions species in relation to the climate impact, as well as an agreed metric and time scale.

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[127] Matthes et al., "Flying ATM4E," (2020)
[128] Søvde et al., "Aircraft emission mitigation by changing route altitude: A multi-model estimate of aircraft NOx emission impact on O3 photochemistry," (2014) https://doi.org/10.1016/j.atmosenv.2014.06.049
[129] Faber et al., "Lower NOx" (2008)
[130] Lee et al., "Uncertainties in mitigating" (2023)
[131] Grewe et al., "A REACT4C case study," (2014)
[132] Grewe et al., "A REACT4C case study," (2014)
[133] Grewe et al., "A REACT4C case study," (2014); Matthes et al., "Flying ATM4E," (2020)

Interdependencies in engine design and technology:

- Fuel vs NO_x: A higher fuel efficiency of the engine requires a higher overall pressure ratio which results in higher combustion temperatures, and consequently may increase NO_x emissions. There are ways to obtain gains in both thermal efficiency and NO_x emissions reduction, but this requires additional technologies and innovations in the engine such as intercoolers or compressor water injection.
  - For example, in one theoretical study, it was shown that a 43% reduction in NO_x through engine design resulted in corresponding increase in CO_2 emissions by 2% and an equal benefit to climate (low to medium confidence).
- nvPM vs NO_x: Lean burn and advanced Rich-burn, Quick-mix, Lean-burn (RQL) NO_x -reduction combustor technologies offer reductions in LTO nvPM emissions. Improved understanding of cruise NO_x and nvPM emissions are required to assess trade-offs in this flight phase.
- LTO vs cruise NO_x: The LTO NO_x certification standard exists principally for the purposes of reducing the engine emissions during the landing and take-off cycle and the impacts on air quality in the vicinity of airports. However, past analyses have concluded that a reduction in LTO NO_x will also result in a reduction of NO_x emissions at cruise (to be confirmed for newer technologies) and, based on the premise that the impacts of NO_x emissions at cruise are overall warming, this will thereby help reduce the climate change impacts of aviation. Cruise NO_x emissions are not currently measured or certified as past analyses concluded there was a correlation between LTO and cruise NO_x emissions. As such, there is no direct incentive for an engine manufacturer to specifically improve cruise NO_x emissions.
- Aircraft age vs NO_x: The global aircraft fleet NO_x performance will improve as older designs will be replaced by newer combustion technologies.[134]

[134] "Updated analysis," *EASA* (2020);
"[CAEP/12 - WP/51] NOx Impacts," *ICAO CAEP* (2022)

CHAPTER 4 – FUTURE OPPORTUNITIES FOR CONTRAIL MITIGATION

4.1 Introduction

This chapter identifies potential future technological and operational opportunities to enable operational avoidance and reduce the contrail climate impact with minimal impact on other aspects of flight. These improvements are twofold:

- better contrail prediction and improved climate impact forecasting, and
- improvements in flight planning and execution.

This report focuses on operational opportunities in flight planning and execution but expands as well on the enabling part of improved weather forecasting, contrail prediction and weather impact modeling. Better contrail forecasting is essential as an enabler for operational implementation. 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.

Other non-CO_2 effects are not addressed in this chapter as these impacts are currently smaller in magnitude and may even change from warming to cooling in the future depending on the future background atmosphere (in the case of NO_x effects) - see Chapter 3. A complicating and unknown factor is the possible interaction between contrail mitigation efforts and other non-CO_2 impacts. This is an opportunity for future exploration and research.

As stated in Chapter 1, the climate impact from contrails is in general quantified with low confidence, compared to that of CO_2. For contrails, 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. Some of the main variables affecting these uncertainties are:

- the humidity field in the upper atmosphere (which is currently estimated from NWP models),
- the particulate matter emission profile of the engines,
- the impact of background aerosols, and
- the interaction of contrail cirrus with existing cirrus. The related upper air chemistry and physical processes are complex and less well understood.

While this chapter will introduce various future opportunities, the importance of quantifying the climate impact of contrails, relative to CO_2, cannot be understated. Any definite choice of pathway or course of policy action is only prudent when it can be based on better quantification of the overall climate effects and the trade-offs between non-CO_2 reductions versus potential CO_2 increases or no trade-offs are clearly identified.[135]

[135] Lee et al., "Uncertainties in mitigating" (2023)

If tactical or strategic navigational avoidance is implemented, ANSPs and operators will need to adapt the planning and operational flight process to include these avoidance strategies in a collaborative manner. The flight planning capabilities of operators, and the required flexibility of ATM and operators, will play an important role in successful implementation of avoidance strategies while minimizing the potential impact on the flight, airspace capacity, and fuel use.

4.2 Enablers

Several enablers of contrail mitigation opportunities are identified in the literature study, and can be categorized into the following topics:

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

Weather data measurement and weather forecasting

A comprehensive contrail prediction and mitigation strategy is enabled by accurate (in space and time) weather forecasts, especially the forecasting of ISSR. This presents an opportunity for improvement in the initialization of NWP models, and their associated forecast reliability and accuracy. Areas of focus for improvement include the spatial and temporal resolution of weather forecasts, accuracy at a timescale to allow for flight planning (i.e., greater than 8 hours in advance), and a particular focus on data assimilation (combining current observations and prior forecasts to reach the best estimate of the atmospheric state to initialize the forecast) and forecasting of relative humidity to ice (RH_i).

A lack of timely, accurate relative humidity measurements, especially in the upper troposphere and on a global basis, is recognized by the scientific community as one of the main obstacles for deployment of operational mitigation. These measurements are required to:

→ get reliable climatology for persistent contrail coverage and refine climate impact assessment[136]
→ validate and calibrate weather models and forecasts that will be used for trajectory optimization, and
→ feed NWP models with the necessary observation data.

As relative humidity output data are based on observed weather data, in-situ measurement of humidity will assist with NWP-based forecasting and will increase the accuracy, reliability, and

[136] Meijer et al., "Contrail coverage United States," (2022)

granularity of RHi forecasts and thus the areas of likely contrail formation and persistence. The research consortium In-service Aircraft for a Global Observing System (IAGOS) has projects underway with the aim of improving the understanding of atmospheric composition using commercial aircraft to obtain the measurements.[137]

These measurements can be acquired through remote and in-situ sensing. Atmospheric measurement remote sensing can be performed through atmospheric sounders installed on both geostationary Earth orbit (GEO) or low Earth orbit (LEO) satellites.[138] Atmospheric measurement in-situ sensing can be performed through humidity sensors installed on aircraft[139] or weather balloons.[140]

Forecasting of Contrail Formation and Persistence

In addition to weather forecasting, accurate and reliable forecasting of contrail formation and evolution (persistence and spread) is essential for contrail management. Only persistent contrails that spread to form contrail-cirrus may have a significant radiative effect. There are currently only a few contrail prediction models in use.[141] A report by the Rocky Mountain Institute offers a comprehensive overview of these models.[142] These models predict contrail formation, persistence, spread and the optical properties, but may also include the impact in terms of RF, see paragraph below on climate impact modeling.

The current models have uncertain outcomes with respect to new engine technology or changed fuel properties.[143] More research and experimental data are required to include these variables into the models (see Chapter 5).

Additionally, improvements in the modelling of wake vortices and microphysical processes could be incorporated into contrail modelling to better represent the early evolution of contrails and enhance the accuracy of forecasting contrail persistence and spread. [144]

Contrail Observations

In addition to contrail forecasting models, real-time observations can be used to identify contrail climate sensitive areas for contrail management. Furthermore, these observations help to validate

[137] "In-service Aircraft for a Global Observing System," *IAGOS* https://www.iagos.org/
[138] Lamquin et al., "A global climatology of upper-tropospheric ice supersaturation occurrence inferred from the Atmospheric Infrared Sounder calibrated by MOZAIC," *Atmos. Chem. Phys. vol. 12-1* (2012) https://doi.org/10.5194/acp-12-381-2012
[139] "Aviation contrails and their climate effect - Tackling uncertainties and enabling solutions," *IATA* (2024) https://www.iata.org/en/pressroom/2024-releases/2024-04-30-01/
[140] Wolf K., Bellouin N., Boucher O., "Upper-troposphere climatology," (2023)
[141] Schumann U., "Contrail cirrus prediction model," (2012)
[142] Cathcart et al., "Understanding Contrail Management," (2024)
[143] Impacts and Science Group (ISG), "Contrail Science Workshop Report," (2025) [to be published]
[144] Impacts and Science Group (ISG), "Contrail Science Workshop Report," (2025) [to be published]; Unterstrasser S., "Properties of young contrails – a parametrisation based on large-eddy simulations," *Atmos. Chem. Phys. vol. 16-4* (2016) https://doi.org/10.5194/acp-16-2059-2016

the different contrail prediction models and monitor effectiveness of contrail avoidance concepts by:

- feeding scientific work to improve contrail model(s) to evaluate their climate impact, a key enabler of mitigation decision (validation),
- allowing the verification and monitoring of the effectiveness of contrail avoidance concepts in effectively preventing persistent warming contrail formation (verification).

Today the lack of contrails observation databases is recognized by the scientific community as a missing input to consolidate the assessment of contrail climate impact.[145]

Observation should include both the detection of contrails, tracking (contrail evolution as a function of time and space), as well as the measurement of its physical properties including microphysical properties (e.g., number of crystal particles, ice water content) and optical properties (e.g. optical thickness).

These observations can be obtained through satellites, ground-based imaging, and airborne measurements. Geostationary satellites (such as GOES-16 & 17, MTG, MSG or HIMAWARI-8) equipped with visible or infrared imaging can detect persistent contrails. The advantage of such satellites is that they provide near-hemispheric coverage that, as part of a mosaic, provide near-global coverage with a high frequency of imagery (often every several minutes) and low latency (near real-time), but at the cost of spatial resolution making young contrails undetectable. Several studies and on-going projects are using geostationary satellite observations for contrails.[146]

LEO satellites such as Landsat-8, Sentinel-2 equipped with visible or infrared imaging can observe contrails. As opposed to geostationary satellites, these satellites provide observation with a higher resolution, thus enable detection of young contrails, but at the cost of less coverage and reduced frequency of imagery (e.g. 90 minutes to complete one full Earth orbit). Several datasets using LEO satellite already exist.[147]

Ground-based sky facing cameras can be used to detect contrail over a limited coverage but with high resolution and frequency of imagery. Several stakeholders such as EUROCONTROL are developing ground camera networks to monitor contrail formation over a given region.[148]

Observations made from aircraft can also be used to detect the presence of persistent contrails, as is being done with the Contrail Observation Program (COOP), led by Air France in collaboration with Metéo France and Climaviation[149]. However, aircraft observations may be limited in accuracy of location and altitude. Inflight observations are not expected to require any

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[145] "EUROCONTROL launches ContrailNet" *EUROCONTROL* (2023)
[146] "Project Contrails – A cost effective and scalable way AI is helping to mitigate aviation's climate impact," *Google* https://sites.research.google/contrails/
[147] Meyer et al., "Regional radiative forcing by line-shaped contrails derived from satellite data," *Atmospheres vol. 107-D10 (2002)* https://doi.org/10.1029/2001JD000426
[148] Schumann et al., "Ground-based cameras," (2013)
[149] "The Other Impacts of Aviation on the Climate," *Air France* https://corporate.airfrance.com/en/other-impacts-aviation-climate

infrastructural changes and can be collected using existing equipment and datalink communication for reporting, such as those commonly used for turbulence reports.[150]

Artificial intelligence may support contrail recognition from (satellite) imagery, and these observed contrails may be matched with known flight tracks.[151] In addition, observational data can be paired with simulation data to provide validation of satellite and ground-based imagery.[152]

Currently, no single source of observation will provide the required coverage associated with the required time and spatial resolution to properly detect and track all persistent contrails. Effective monitoring of the sky will come from the association and combination of these different observation methods to complement each type's resolution, coverage and frequency. Also, no single organization will have the ability to generate the critical mass of required observation to support contrail science, and the verification of contrail avoidance mitigation effectiveness. This may be driven by active partnership and industry- wide collaborative efforts accompanied by open sharing of data - see paragraph on Collaboration, page 65.

Climate Impact Modeling

Climate impact modelling for trajectory optimization requires accurate contrail prediction data in time and space, per flight or per region, and subsequently calculation of the radiative forcing of the contrail or contrail region over its lifespan.

Climate impact modeling and balancing impacts from different sources require a clear choice of metrics. One consistent metric to compare CO_2 and non-CO_2 climate impact will be key in the process of contrail management and flight optimization.

One limitation of current contrail modelling is that the true contribution of contrails to atmospheric radiative forcing compared to CO_2 and other greenhouse gases is uncertain. In practice, the climate impact of individual flight trajectories could be determined by minimizing a total climate impact function (as introduced in section 3.3) that combines contrails and induced cloudiness effects with CO_2 and all other non-CO_2 aviation effects. This would optimize navigational avoidance with respect to the reduction in climate impact of individual flight trajectories.[153]

Another limitation is the computational power, needed for complex climate models, and too expensive for day-to-day airline operations. This limitation can be overcome by simplified (gridded or parameterized) models for optimized flight planning.[154]

In Europe, the SESAR joint undertaking has developed FlyATM4E[155] prototypic algorithmic climate change functions (aCCFs) to derive such climate impact information for flight planning

[150] Cathcart et al., "Understanding Contrail Management," (2024)
[151] Elkin C. and Sanekommu D., "How AI is helping," (2023)
[152] Digby et al., "An Observational Constraint on Aviation-Induced Cirrus From the COVID-19-Induced Flight Disruption," *Geophysical Research Letters vol. 48-20* https://doi.org/10.1029/2021GL095882
[153] "Updated analysis," EASA (2020)
[154] Schumann et al., "A Parametric Radiative Forcing Model for Contrail Cirrus," Applied Meteorology and Climatology vol. 51-7 (2012) https://doi.org/10.1175/JAMC-D-11-0242.1
[155] "FlyATM4E - Flying Air Traffic Management for the benefit of environment and climate," *SESAR Joint Undertaking* (2020) https://www.sesarju.eu/projects/flyatm4e

directly from operational meteorological weather forecast data.[156] The European project REACT4C[157] went a step beyond and focused on climate-optimized routing strategies primarily in the North Atlantic airspace using climate-impact functions.[158]

In contrast to quantifying the climate impact of individual flight trajectories from contrails, it may be practical to examine the climate impact of contrails and aviation-induced cirrus across a region, on a net basis.

Further research is needed to determine the exact origin of the discrepancies between predicted and observed regional contrail coverage, which was observed during the COVID-19 pandemic.[159] These discrepancies may substantively change estimates of climate impacts resulting from aviation and how they might be meaningfully reduced.

Flight Planning

Opportunities for improvement in flight planning include consideration of contrail mitigation as a variable in trajectory planning and optimization. Integration of contrail prediction and avoidance into existing flight planning software applications enables easier and more accurate flight optimization and enables automated flight selection and flight planning.

A planning tool should be able to provide flexibility in choices how to optimize flight according to a weighing function for: costs, fuel/CO_2, climate impact, contrail distance, or time along with features enabling the consideration of meteorological uncertainties (essentially temperature and humidity distribution) to balance the final decision making. Flight planning will clearly benefit from more accurate weather forecasting and the integration of enhanced weather is essential in a flight planning system for effective contrail management.

While from a system perspective, a flight planning software may offer avoidance scenarios according to different optimization strategies, the final decision will be subject to existing operational constraints and will require collaborative decision making between airline and ATC.

Most of the contrails that result in significant warming are believed to be due to a small number of flights, however these flights are not necessarily evenly distributed in time or space. These flights may be concentrated in certain areas or time periods[160] (see Chapter 2.5). Identification of these flights or these areas in the flight planning phase through a decision tool or matrix, should be a topic of further research.[161]

Airspace Capacity and ATM Flexibility

[156] Matthes et al., "Flying ATM4E," (2020)
[157] Matthes, S., "Climate-optimised Flight Planning – React4C," (Conference paper, Aerodays), Madrid, ES, 2011 https://www.researchgate.net/publication/225024463_Climate-optimised_Flight_Planning_-_REACT4C
[158] Grewe et al., "A REACT4C case study," (2014)
[159] Quaas et al., "Climate impact of aircraft-induced cirrus assessed from satellite observations before and during COVID-19," *EGU General Assembly* (2021) https://doi.org/10.5194/egusphere-egu21-14495
[160] "Updated analysis," EASA (2020)
[161] Cathcart et al., "Understanding Contrail Management," (2024)

It is not a coincidence that contrails routinely form in areas with high volumes of air traffic. This congestion poses challenges for the implementation of contrail avoidance without impacts on flight efficiency, potentially including the flight efficiency of aircraft that might not have been forecast to form a contrail.

An air navigation services provider's ability to support contrail mitigation will be influenced by its ability to manage existing capacity, ensure efficiency and offer flexibility where possible within the safety constraints. The implementation of modernization projects whereby new systems and automation provide ATC with better decision support tools can help ATCOs provide needed flexibility. Airspace modernization can also support contrail mitigation actions with improved options for operators to file avoidance, e.g. with FRA implementation. Certain improvements in CNS systems can enable a safe reduction in separation standards, improving capacity and flexibility.

The implementation of operational concepts such as TBO may enable enhanced collaborative decision making for trajectory adjustment and trajectory management, more efficient airspace use and adaptive to dynamic conditions (such as related to ISSR conditions).

Trajectory-based operations (TBO) is a concept in development designed to support an ATM environment where a flown flight path is as close as possible to the user-preferred trajectory, by efficiently reducing potential conflicts and resolving demand/capacity imbalances. Trajectory information exchanged through automation will allow the provision of more accurate, consistent and operationally relevant information, which better supports the human actors in performing their roles and responsibilities using improved methods and techniques, leveraging the enhanced information. The provision of service will be adaptive to dynamic conditions (e.g., weather) and performance-based (independent of aircraft type - unmanned, manned etc.).

A full TBO environment will minimize the gap between scheduled and actual operations. Combined with better weather prediction tools that can identify persistent warming contrail regions, TBO is expected to enable better management and adjustment of trajectories to mitigate the warming impacts of contrails.

More operational trials, particularly in airspace with high density traffic and on a larger scale, would be beneficial to fully understand implications of contrail mitigation efforts on ATM, including potential impacts on ATCO workload and airspace capacity. Initiating various trials utilizing different CONOPs strategies as outlined in Chapter 2.5 would enable the development of processes and procedures for their implementation and use. Live trials can be complemented or planned by fast-time simulations of air traffic.

Special consideration to ATM constraints and operational capacity should be a focus of trials, to identify the specific needs of ANSPs that may hinder the improvement of capacity and flexibility. While many ATM modernization improvements will be technological, staffing and training will also be impacted.

High fidelity aircraft movement and surveillance data will be required to properly study network impacts from contrail mitigation activities. A final hot-spot analysis using a network could be conducted to highlight areas with a significant increase of air traffic density due to changed flight planning concepts.[162]

Flight Execution

When reliable forecasts, flight planning tools, and ATM flexibility allow for intervention, the actual execution (of a tactical strategy) depends on the ability of the flight crew to execute the intervention safely and effectively. Regardless of pre-tactical or tactical contrail avoidance applications, supportive tools and training for ATCOs, flight dispatchers and pilots will need to be developed to ensure the safe and effective application of new procedures.

Datalink communication and automatic flight management system (FMS) upload may prove to be beneficial. An Electronic Flight Bag (EFB) may depict a graphical display of relevant contrail climate sensitive areas and alternative routings, based on real-time (cost/flight-time/climate-) optimization.[163]

The impact on other traffic that is not performing contrail management or flying through contrail sensitive areas may be assessed as well, in terms of fuel use and environmental performance. An area-wide assessment can be more beneficial than an aircraft-based concept to assess the overall climate impact of aviation.

Simulation and flight testing have indicated a possible reduction in fuel burn when flying in formation as a result of a principle called wake energy retrieval.[164] This type of flight has also been found to reduce contrail formation due to the superposition of plumes from aircraft involved.[165] Operational and safety hurdles due to the close spacing of aircraft must be overcome.

Verification

An important closing step in contrail management contains verification and monitoring the effectiveness of contrail avoidance. It is important to acknowledge the uncertainties associated with estimating the climate impact of contrails from aviation.

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162 Matthes et al., "ATM4E: A concept for environmentally-optimized aircraft trajectories," (Conference paper, Greener Aviation Conference), Brussels, BE, Oct 11-13, 2016 https://research.tudelft.nl/en/publications/atm4e-a-concept-for-environmentally-optimized-aircraft-trajectori
163 "Loretta," *FlightKeys*, https://loretta.aero/
164 "[A41-WP/320] Wake Energy Retrieval: An Environmental Opportunity for Aviation (Automated Formation Flight)," ICAO Assembly 41st Session, (2022) https://www.icao.int/Meetings/a41/Documents/WP/wp_320_en.pdf; "fello'fly – Exploring the possibilities of wake energy retrieval," *Airbus* https://www.airbus.com/en/innovation/future-aircraft-operations/air-traffic-management/fellofly
165 Tait et al., "Plume-Scale Effects" (2022)

As scientific research progresses, and contrail observation, model validation and measurement techniques improve, there will be some reduction in uncertainty and more accurate verification. However, given the complexity of the physical and chemical processes that result in contrails, it is unlikely that the non-CO_2 impact of aviation will ever be estimated with the same level of certainty as the CO_2 impact.[166] The uncertainty in the impact estimate should be assessed (and potentially be quantified).

Collaboration and Continuous Improvement Efforts

Collaboration of aviation stakeholders, especially through partnerships, will enable further research and trials and subsequently effective implementation. In the EU, an Aviation Non-CO_2 Expert Network (ANCEN) has been established to facilitate a coordinated approach across a wide range of relevant stakeholders (e.g. scientific community, academia, aircraft manufacturers, aircraft operators, fuel producers, ANSPs, non-governmental organizations (NGOs), regulators, analysts, and policymakers).[167]

Continuous improvement on forecasting and modelling can benefit from shared information and enabled by collaborative platforms for data and information sharing. For example, EUROCONTROL has launched *ContrailNet*, a network to act as a common repository of contrail observation data.[168]

To date, some trials, both simulated and live- and shadow-mode, are primarily being conducted on a regional basis with select stakeholders. Multi-stakeholder activities and trials are encouraged to ensure knowledge sharing, the inclusion of more variety of stakeholders, and the ability to conduct trials over larger areas of airspace. There is a unique opportunity for collaboration for those aviation stakeholders operating within the North Atlantic airspace, which is of particular interest for contrail mitigation efforts because of the volume of night-time traffic, predictability and organization of traffic.

Regular collaboration between stakeholders can be supplemented by conferences and seminars to disseminate information on new research and trial outcomes, particularly with respect to operational considerations.[169]

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[166] Cathcart et al., "Understanding Contrail Management," (2024)
[167] "Aviation Non-CO2 Experts Network (ANCEN)," *EASA,* https://www.easa.europa.eu/en/research-projects/ancen-nonco2
[168] "EUROCONTROL launches ContrailNet" *EUROCONTROL* (2023)
[169] "Sustainable Skies Conference: Contrails in Focus," *EUROCONTROL/CANSO* (2023) https://www.eurocontrol.int/event/sustainable-skies-conference-contrails-focus;
"2024 ICAO Symposium on Non-CO_2 Aviation Emissions," *ICAO* (2024) https://www.icao.int/Meetings/SymposiumNonCO2AviationEmissions2024/Pages/default.aspx

CHAPTER 5 – IMPACT OF FUEL COMPOSITION, NEW ENGINE TECHNOLOGY, INTRODUCTION OF SAF AND HYDROGEN

5.1 Introduction

Operational improvements cannot be addressed without taking note of the (changing) context of fuel composition, the expected further uplift of sustainable aviation fuels (SAF) and newer engine technology. Fuel composition and engine technology will have an effect on the CO_2 net emissions as well as the exhaust temperature, water vapour and nvPM emissions affecting formation, persistence and optical properties of the contrail as well as the balance between CO_2 and non-CO_2 impacts.

The fuel composition and engine technology will have an effect on nvPM emissions with respect to emission level and characteristics, and therefore, on contrail ice crystal formation, persistence and optical properties of the contrail. These future technological and fuel changes and possibilities are essential for the assessment of the effectiveness of operational measures for contrail mitigation.

Reduction in nvPM number emissions is not linearly related to contrail cirrus radiative forcing. Since larger reductions in soot number emissions are expected to lead to increases in ice crystal size and in the contrail cirrus climate impact, a far-reaching decrease of soot number emissions may not be expedient.[170]

Scientific understanding at present is that contrails may continue to be formed, with the use of new low-sulfur fuels and SAF. These contrails will have different (optical) properties and may result in less radiative forcing, depending on the ambient temperature. Experimental evidence is provided that low aromatic SAF can result in 50 to 70% reduction in soot and ice number concentrations and an increase in ice crystal size.[171] Recent flight tests with 100% SAF, indicated a 26% reduced climate impact of contrails.[172]

It should be recognized that SAF and lower aromatic fuels may be limited in supply in the forthcoming years and technology improvements may only be gradually introduced. The increase in contrail cirrus radiative forcing due to the projected increase in air traffic volume is expected to outpace the decrease due to reduced soot emissions and improvements in propulsion.[173] Operational measures will therefore remain meaningful; they can enhance and complement the technological and fuel pathway. Some research outcomes indicate the benefit of combining new fuel components and lower aromatic content with operational measures.

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[170] Burkhardt U., Bock L., and Bier A., "Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions," *Clim Atmos Sci 1-37* (2018) https://doi.org/10.1038/s41612-018-0046-4
[171] Voigt et al., "Cleaner burning aviation fuels," (2021)
[172] "World's first in-flight study of commercial aircraft using 100% sustainable aviation fuel show significant non-CO2 emission reductions," Airbus (2024) https://www.airbus.com/en/newsroom/press-releases/2024-06-worlds-first-in-flight-study-of-commercial-aircraft-using-100;
Märkl et al., "Powering aircraft with 100 % sustainable aviation fuel reduces ice crystals in contrails," *Atmos Chem Phys vol. 24-6* (2024) https://doi.org/10.5194/acp-24-3813-2024
[173] Bock, L. and Burkhardt, U. "Future air traffic," (2019)

In general, modern aircraft cruise at higher flight levels for fuel efficiency compared to the older commercial aircraft. This may lead in certain regions (e.g. North Atlantic) to more contrails with a longer lifespan despite a reduction in nvPM emissions that would be expected.[174] Flying at higher altitudes, these more efficient aircraft form contrails further below the Schmidt–Appleman threshold temperature.

The effects of the use of liquid hydrogen as energy source on the formation and properties of contrails is being explored. With the current scientific knowledge, it is expected that the use of hydrogen-powered (directly or indirectly via fuel-cells) aircraft may significantly reduce the contrail climate impact especially due to the shorter lifespan of the contrails.[175]

5.2 Fuel Consumption, SAF

So far, commercial aircraft have mainly used conventional fossil fuel-based kerosene (mainly Jet A-1 and Jet-A) whose energy content (expressed as the lower heating value, LHV) and chemical composition depend on the origin of the crude oil and the refining processes. Although existing, their variabilities were not sufficient to be considered in the evaluations of the formation and the radiative impact of contrails.

With the progressive introduction of drop-in sustainable aviation fuels (SAFs) blended with petroleum jet fuel and lower-aromatic fuels, more differences will be observed between the fuel characteristics for commercial aircraft.

Sustainable aviation fuels (SAF) are defined as renewable or waste-derived aviation fuel that meets defined sustainability criteria and can be used in blends with or in place of conventional jet fuels if satisfying the fuel specifications.[176] They are sub-divided by carbon feedstock source: biomass, solid/liquid waste, waste CO_2, and atmospheric CO_2.[177]

Lower aromatic fuels: fuel with less aromatic than the standard jet fuels tend to generate less soot during the combustion. Under current jet fuel standards, the aromatic content is limited to a maximum of 25% by volume and a minimum of 8%. The aromatics concentration could be reduced through blending certain

[174] Gryspeerdt et al., "Operational differences lead to longer lifetimes of satellite detectable contrails from more fuel efficient aircraft," *Environ. Res. Lett. vol. 19-8* (2024) https://doi.org/10.1088/1748-9326/ad5b78
[175] Gierens K., "Theory of Contrail Formation for Fuel Cells," *Aerospace vol. 8-6* (2021) https://doi.org/10.3390/aerospace8060164
[176] "Annex 16 - Environmental Protection - Volume IV - Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)," *ICAO* (2023) https://store.icao.int/en/annex-16-environmental-protection-volume-iv-carbon-offsetting-and-reduction-scheme-for-international-aviation-corsia
[177] "Report on the Feasibility of a Long-term Aspirational Goal (LTAG) for International Civil Aviation CO2 Emission Reductions," *ICAO* (2022) https://www.icao.int/environmental-protection/LTAG/Documents/REPORT%20ON%20THE%20FEASIBILITY%20OF%20A%20LONG-TERM%20ASPIRATIONAL%20GOAL_en.pdf

SAF options with conventional Jet A-1 fuel, through hydro-treatment of Jet A-1 fuel or through changes in production processes by refineries.[178]

Fuel chemical composition influences the mass of several emissions. In most SAF, the carbon/hydrogen ratio decreases so that their combustion produces less carbon dioxide (CO_2) and nvPM per kilogram of fuel burned, but more water vapour (H_2O). Water vapour emission index – EI(H_2O) – and fuel energy – lower heating value, LHV – content are two parameters impacting the Schmidt-Appleman criterion and therefore potential contrail formation. An increase of EI(H_2O)/LHV ratio as observed in most SAF results in a potential increase in contrails formed along the flight path.[179]

The reduction of nvPM will induce a reduction of ice crystal number formed in the beginning of the aircraft plume, enhanced by the reduction of hydrophilic characteristics of nvPM.[180] However, a reduction in nvPM emissions is not linearly related to contrail formation and the resulting cirrus radiative forcing.

In conclusion, as confirmed by recent simulations, the use of SAF may lead to: an increase contrail occurrence, a larger diameter and lower number concentration of ice crystals, and a potential reduction in radiative forcing depending on the fuel type and blending ratio and its strategic use in operations.[181]

Newer technology such as lean-burn engines, may show less reductions of soot and nvPM when using SAF than for rich-burn engines as lean-burn engines already feature less particles emissions (see 5.3), nevertheless the contrails produced from a combined usage of lean-burn engine technology and SAF should be analysed further in the future as other processes may be involved to form ice crystals.

The expected positive effect of SAF production and usage on CO_2 and non-CO_2 induced climate impacts does not preclude deployment of operational mitigation measures. Nevertheless, it has to be noted that the impact of fuel composition change on the operational mitigation strategies is still an area of research. The interaction between SAF usage and the extent of avoidance maneuvers required to achieve an efficient climate impact reduction are still to be analyzed further.

Dedicated/Selective Use of SAF

As stated above, SAF can reduce aviation's CO_2 from fuel production, and may also reduce in-flight non-CO_2 impacts, but current availability of SAF is limited. In order to optimize the

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[178] "Updated analysis", EASA (2020)
[179] Caiazzo et al., "Impact of biofuels on contrail warming," *Environ Res. Lett. vol. 12-11* (2017) https://doi.org/10.1088/1748-9326/aa893b
[180] Märkl et al., "Powering aircraft," (2024)
[181] Caiazzo et al., "Impact of biofuels," (2017);
Teoh et al., "Targeted Use of Sustainable Aviation Fuel to Maximize Climate Benefits," *Environ. Sci. Technol. vol. 56-23* (2022) https://doi.org/10.1021/acs.est.2c05781;
De León et al., "Contrail radiative dependence on ice particle number concentration," *Environ. Res.: Climate vol. 2-3* (2023) https://doi.org/10.1088/2752-5295/ace6c6;
Märkl et al., "Powering aircraft," (2024);

climate benefits of available SAF, researchers have explored the concept of targeting the use of SAF on flights responsible for the most warming contrails, specifically analyzing air traffic in the North Atlantic region.[182]

This paper shows a theoretical reduction in the total energy forcing (effect of contrails + change in CO_2 life cycle emissions), going from -0.6% for a SAF blended at 1% ratio uniformly distributed to all flights to -6% for a targeted use of 50% blended SAF on the 1.9% most warming flights. This rather significant conclusion will need to be put in perspective of the most recently published analyses of SAF climate impact[183] which indicates smaller reductions, and also needs to be considered in a real-life operational context.

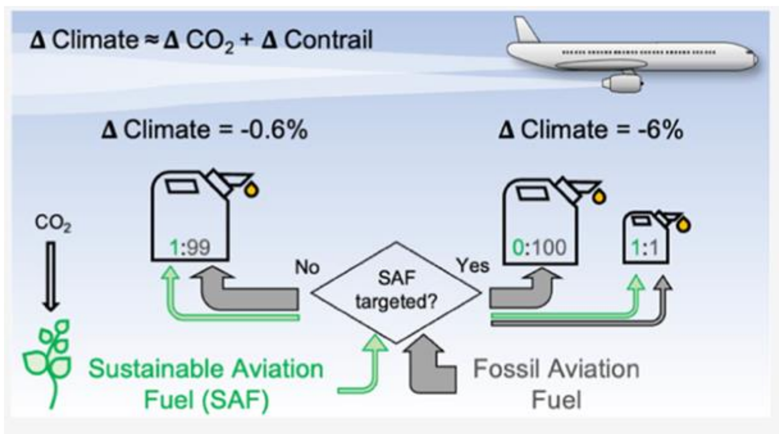

Figure 5-1 Targeted Use of SAF (from Teoh a.o. 2022)

To enable targeted use of SAF, a segregated storage and distribution system up to the aircraft would need to be developed in each candidate airport, requiring specific handling, traceability and monitoring of SAF supply, and related investments. In addition, such a concept would require a very good synchronization with the airport refueling stakeholders. Its efficacy would also be highly dependent on the capacity to forecast contrails impacts several hours in advance to allow for the appropriate selective fuel distribution, which would add both operational complexity and uncertainties.

5.3 New Engine Technologies

Engine technology's effects on contrails formation and characteristics are essentially driven by engine efficiency and (nvPM/soot) emissions. The newest generation of jet engines emit fewer soot particles in accordance with the nvPM certification standards, thanks to a lower fuel consumption, as well as improved combustor technology and/or design.

More efficient engines (higher overall efficiency value) feature in general a lower exhaust gas temperature. A consequence is that this may increase the probability of contrail formation along

[182] Teoh et al., "Targeted Use," (2022)
[183] Märkl et al., "Powering aircraft," (2024)

the flight path.[184] Contrails of more efficient engines form at lower altitudes than those of less efficient engine. An altitude range may exist in which the aircraft with high engine efficiency causes contrails while the aircraft with lower engine efficiency causes none.

Furthermore, modern aircraft in general cruise at higher flight levels for fuel efficiency compared to the older commercial aircraft, partly due to enhanced engine performance. This difference in the optimal cruising altitude may impact persistent contrails generation depending on geographic location, the local height of the tropopause and the atmospheric conditions during the flight. This difference is illustrated in a recent scientific publication showing more modern and higher cruising aircraft generate more longer-lived contrails in a specific region across the North Atlantic.[185] Such a result should nevertheless not be extrapolated as a completely different trade-off may occur depending on the tropopause altitude.

> *Note. Regarding soot emissions, the evolution of engines (and in particular of the combustor technologies) can significantly affect the number of emitted nvPM and emission of some precursors of volatile particles, both acting as condensation nuclei for ice crystal formation. Simulations have underlined that an aircraft emitting less nvPM tends to form less ice crystals,*[186] *comparable to the use of low aromatic fuels. However, in soot-poor regime the number of ice crystals can grow again due to other formation processes at temperature below the threshold condition for contrail formation; this would imply an optimum number of nvPM to be validated that could lead to a minimum number of ice crystals.*[187]
>
> *The persistence of a contrail and therefore also the radiative forcing (associated with its lifetime), is also influenced the aircraft wake characteristics (through the microphysics of young ice crystals during their formation phase and their evolution in the vortex regime of the aircraft plume).*[188]
>
> *Simulations show that ice crystal growth is more important over their lifetime when fewer are formed in the young contrail, noting this is dependent on ambient weather conditions as they are fed by available local atmospheric water vapour. Bigger ice crystals will go down faster by sedimentation, and thus disappear faster by sublimation when they exit the ISSR.*

As for the new fuel composition (see 5.2), the deployment of new engine technologies should not preclude the application of operational mitigation measures and the relationship between those technologies and the benefits of operational measures with respect to contrail management should be analyzed further.

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[184] Schumann, U., “Propulsion efficiency,” (2000)
[185] Gryspeerdt et al., “Operational differences,” (2024)
[186] Kärcher et al, “Factors controlling contrail cirrus optical depth,” *Atmos. Chem. Phys. vol. 9-16* (2009) https://doi.org/10.5194/acp-9-6229-2009;
Caiazzo et al., “Impact of biofuels,” (2017)
[187] Kärcher, B., “Formation and radiative forcing,” (2018)
[188] Tait et al., “Plume-Scale Effects” (2022);
Lewellen D.C. and Lewellen W.S, “The Effects of Aircraft Wake Dynamics on Contrail Development,” *Atmospheric Sciences vol. 58-4* (2001) https://doi.org/10.1175/1520-0469(2001)058<0390:TEOAWD>2.0.CO;2;
Gerz T., Dürbeck T., and Konopka P., “Transport and effective diffusion of aircraft emissions,” *Atmospheres vol. 103-D20* (1998) https://doi.org/10.1029/98JD02282

5.4 Hydrogen

Liquid hydrogen as a power source, both direct and indirect via a fuel cell, will have larger water vapour emissions.[189] Although there are no or few combustion particles (soot), it is likely that the contrails will form with different characteristics in terms of density, lifetime and radiative effects.

With the current scientific knowledge, it is expected that the use of hydrogen-powered aircraft may significantly reduce the contrail climate impact especially due to the shorter lifespan of the contrails. As these predictions rely on many theories and assumptions, these must first be properly simulated and validated with in-flight measurements, and the climate impact must be calculated using appropriate models and in accordance with expected flight operational conditions (e.g. short/medium-haul, lower cruising altitudes).

The direct radiative forcing of water vapour emission (distinct from their effect on contrails) is currently assessed to be small (for current kerosene-fueled aircraft). A major determinant of this effect is the height of emission relative to the tropopause. The residence time of water vapour is short (a few days) when emitted into the troposphere and lower stratosphere where current subsonic aircraft operate, but months to years when emitted higher into the stratosphere at typical supersonic cruise altitudes of 20 km or more.[190]

To date, insufficient knowledge exists on the relevant chemical and physical processes and the resulting climate impact of contrails emanating from hydrogen power sources.[191] Measurements on H2 contrails are rare. Airbus and the DLR have conducted measurements behind a glider equipped with a small H_2 combustion engine within the Blue Condor campaign.[192]

> *Note. A recent model study indicated that due to the absence of soot particle emissions, the ice crystal number in H2 contrails is typically reduced by more than 80 %–90 % compared to conventional contrails. The contrail optical thickness will be significantly reduced, and H2 contrails either become visible later than kerosene contrails or are not visible at all for low ambient particle number concentrations. However, contrails can form at lower flight altitudes where conventional contrails would not form.[193] For higher ambient nvPM concentrations, the outcome may differ significantly.*

Using fuel cells, condensation of the exhaust water vapour can happen even at the Earth's surface in sufficiently cold (a few degrees above zero) weather. Contrail formation from fuel cells will occur frequently in the lower troposphere and is unavoidable below moderate temperature limits, in the upper troposphere and in the stratosphere. Despite the high frequency of contrail formation from fuel cells, their climate impact will be lower than that of contrails from jet engines. Most

[189] Schumann, "Conditions for Contrail Formation," (1996)
[190] Dokken et al., "IPCC Special Report – Aviation and the Global Atmosphere," *IPCC* (1999) https://www.ipcc.ch/report/aviation-and-the-global-atmosphere-2/
[191] "Analysing the contrails of the future," *DLR* (2022) https://www.dlr.de/en/latest/news/2022/03/20220720_analysing-the-contrails-of-the-future
[192] "How Blue Condor will accelerate Airbus' first hydrogen-powered test flights," Airbus (2022) https://www.airbus.com/en/newsroom/stories/2022-07-how-blue-condor-will-accelerate-airbus-first-hydrogen-powered-test-flights
[193] Bier et al., "Contrail formation on ambient aerosol particles for aircraft with hydrogen combustion: a box model trajectory study," Atmos. Chem. Phys. vol. 24-4 (2024) https://doi.org/10.5194/acp-24-2319-2024

fuel cell contrails will be short –lived and those persistent ones will be optically thinner and have on average a shorter lifetime than traditional persistent contrails.[194]

5.5 Concluding Remarks

As mentioned in the introduction, contrails will not disappear with new fuels or new engine technology and operational measures for contrail management will remain meaningful.[195]

Contrail generation and persistence may be greatly influenced by aircraft and engine combustor technology, aircraft performance and fuel composition choices, through changes in:

- fuel optimal aircraft cruising altitudes,
- exhaust gas temperatures which change the probability to form contrails (Schmidt Appleman criteria),
- fuel types (hydrogen content, energy content) also modifies the probability to form contrails (Schmidt Appleman criteria),
- the quantity of all emissions released by the engines and especially nvPM which impacts contrails lifetime and radiative forcing.

Variability in technology and fuel should be acknowledged when defining an operational concept for operational climate impact mitigation as the climate balance (CO_2 and non-CO_2) may be affected by these parameters.

[194] Gierens K., "Contrail Formation Fuel Cells," (2021)
[195] Bock, L. and Burkhardt, U. "Future air traffic," (2019)

CHAPTER 6 – CONCLUSIONS

6.1 General Conclusions

1. The global annual mean radiative forcing (RF) attributable to contrail cirrus is of the same order of magnitude as the RF from aviation's cumulative CO_2 emissions. The CO_2 related RF has low uncertainty and the contrail cirrus net RF uncertainty is relatively high.
2. Only persistent contrails that spread to form contrail-cirrus may have a significant radiative effect.
3. While there is scientific consensus that persistent contrails, on balance, contribute to global warming, uncertainty on the magnitude of the contribution is considerable, especially on smaller scale / locally or for individual flights.
4. The quantification of the underlying physical and chemical processes is poor and uncertain. The net forcing of contrails and aviation-induced cirrus is the result of a small residual of opposite shortwave and longwave forcings which have inherent uncertainties.
5. The other non-CO_2 emissions (other than contrails) are in general addressed through technological measures in the engine certification process (nvPM, NO_x) or through aviation fuel specifications (SO_x). In terms of operational opportunities, current literature only identifies operational strategies for the reduction of NO_x impacts.
6. The net-NO_x effect of the operational measures on the climate is difficult to comprehend due to the dependence on the background atmosphere and the non-linear atmospheric chemistry and may change in time.
7. Guidance for operational measures to avoid non-CO_2 climate effects is not yet available. No research data is yet available to establish a proof of concept or readiness level.
8. Because of the uncertainties and trade-offs involved, a cautious approach is recommended on definitive courses of action on aviation non-CO_2 emissions since they may be of limited effect or have unintended consequences on the global climate.
9. Long term forecasts may lead to more uncertainty in the modelling and prediction (of persistent contrails) which may lead to an oversizing of the contrail climate sensitive areas and an overestimate of the duration of their existence.
10. The operational measures should be reviewed in the context of changing circumstances such as SAF implementation, ATM architecture improvements, increased traffic demand and climate change.
11. The assessment of the impact on safety must be integrated in the feasibility and development studies for contrail management.
12. The potential climate benefits warrant efforts to address the scientific gaps and study potential operational concepts.
13. It is found that the uncertainties of non-CO_2 effects can be two orders of magnitude larger for individual flights than the fleet-average/system-wide values.

6.2 Conclusions on Trajectory Adjustment for Contrail Mitigation

14. Four elements will play an important role for a successful implementation of trajectory adjustment for contrail mitigation: the availability of relevant meteorological data, the prediction capabilities on contrail formation and the climate impact of persistent contrails, the flight planning capabilities of operators, and the required flexibility of the ATM system.
15. Different examples of contrail mitigation strategies and related concept of operations for trajectory adjustment are being subject to research in different levels of readiness across various research initiatives. These examples are neither tested nor implemented in practice but could serve as basis for further assessment and research. In particular, RH_i measurement will improve the reliability and accuracy of contrail forecasting.
16. Weather and contrail prediction models should be made available with an acceptable level of accuracy, granularity, and lead time to allow for inclusion in flight planning or in-flight strategic application or tactical intervention.
17. Multiple theoretical and simulated assessments of the feasibility of trajectory adjustment for contrail management have been conducted, but actual tests for implementation are lacking. More full-scale trials and exploration of potential concepts of operations are needed.
18. Together with the feasibility and efficacy of measures, the assessment of trade-offs will be an important factor for successful implementation.
19. Preflight interventions (during the flight planning phase) may be preferential from a workload and flight planning perspective, but tactical interventions may be preferential to reduce the actual regions of the atmosphere to be avoided. Ideally, the flight is planned accordingly with accurate forecasting.
20. If identification is possible, navigational avoidance strategies can be selectively applied to a subset of flights, as only a (small) portion of flights is responsible for most of the warming contrail formation. Targeting only the flights with significant contrail climate forcing may prove to be effective and less operationally impactful.
21. Because no operational evidence is available and assessments are only based on modelling studies, an option could initially be to divert flights only if there is minimal or no fuel penalty, avoiding additional CO_2 emissions.
22. Contrails will not completely disappear with new fuels or new engine technology and operational measures for contrail management will remain meaningful.

APPENDIX A – REVIEWED PUBLICATIONS

	Document/Project name	Year	Link
1	Aviation Contrail Climate Effects in North Atlantic from 2016-2021, EGU	2022	https://doi.org/10.5194/acp-2022-169
2	EU 2020 Updated analysis of the non-CO2 climate impacts full report	2020	https://www.easa.europa.eu/downloads/120847/en
3	RAeS report 2021, Easy does it for greener skies	2021	https://ifairworthy.com/raes-easy-does-it-for-greener-skies/
4	Impact-on-flight-trajectory on formation contrails transatlantic flights	2018	https://www.sciencedirect.com/science/article/pii/S1361920917309987?via%3Dihub
5	Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption	2020	https://www.imperial.ac.uk/
6	The-contribution-of-global-aviation-to-anthropogenic-climate forcing for 2000 to 2018	2021	http://www.elsevier.com/locate/atmosenv
7	Contrail Mitigation through Flight Planning, TU Delft	2017	https://repository.tudelft.nl/islandora/object/uuid%3A54fef264-4585-49b4-9ffc-0280d49f9ff5
8	US EPA Aircraft Contrails Factsheet	2000	https://www.epa.gov/regulations-emissions-vehicles-and-engines/information-contrails-aircraft
9	MUAC trial. Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world?	2023	DLR/EUROCONTROL; elib.dlr.de
10	Design Principles for a Contrail-Minimizing Trial in the North Atlantic 2022	2022	https://www.mdpi.com/2226-4310/9/7/375
11	Targeted Use of Sustainable Aviation Fuel, ACS, 2022	2022	https://pubs.acs.org/doi/full/10.1021/acs.est.2c05781
12	Feasibility of climate-optimized air traffic routing for trans-Atlantic flights, DLR	2017	https://iopscience.iop.org/article/10.1088/1748-9326/aa5ba0/pdf
13	Individual Condensation Trails in Trajectory Optimization, US/EU ATM R&D Seminar	2019	
14	Long-term Upper-troposphere of Potential Contrail Occurrence Paris Areas, 2022	2022	https://doi.org/10.5194/acp-2022-584
15	Contrail coverage over the United States before and during the COVID-19 pandemic, MIT	2022	https://iopscience.iop.org/article/10.1088/1748-9326/ac26f0/pdf

16	Operationalizing Contrail Avoidance (Virtual) Workshop, NASA	2022	https://nari.arc.nasa.gov/ContrailAvoidanceWorkshop
17	An Observational Constraint on Aviation-Induced Cirrus from the COVID Induced Flight Disruption, Victoria	2021	
18	Aircraft Emissions, Their Plume-Scale Effects, Bristol	2022	
19	RMI, Contrail Impact Task Force: Understanding Contrail Management, Opportunities, Challenges and Insights	2024	https://rmi.org/insight/understanding-contrail-management-opportunities-challenges-and-insights/
20	A cost-effective and scalable way AI is helping to mitigate aviation's climate impact (Google/American Airlines)	2023	https://sites.research.google/contrails/
21	Beyond contrail avoidance: efficacy of flight altitude changes to minimise contrail climate forcing	2020	https://doi.org/10.3390/aerospace7090121
22	Uncertainties in mitigating aviation non-CO2 emissions for climate and air quality using hydrocarbon fuels	2023	https://pubs.rsc.org/en/content/articlepdf/2023/EA/D3EA00091E
23	Feasibility of contrail avoidance in a commercial flight planning system: an operational analysis	2024	https://iopscience.iop.org/article/10.1088/2634-4505/ad310c/pdf
24	Cleaner burning aviation fuels can reduce contrail cloudiness	2021	Cleaner burning aviation fuels can reduce contrail cloudiness | Communications Earth & Environment (nature.com)
25	Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous United States	2019	Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous United States - ScienceDirect
26	Air traffic and contrail changes over Europe during COVID-19: a model study	2021	https://doi.org/10.5194/acp-21-7429-2021
27	Contrail cirrus radiative forcing for future air traffic	2019	https://doi.org/10.5194/acp-19-8163-2019
28	Operational differences lead to longer lifetimes of satellite detectable contrails from more fuel efficient aircraft	2024	e.gryspeerdt@imperial.ac.uk https://iopscience.iop.org/article/10.1088/1748-9326/ad5b78
29	Aviation Contrails and their climate effect: Tackling uncertainties and enabling solutions, IATA	2024	https://www.iata.org/contentassets/726b8a2559ad48fe9decb6f2534549a6/aviation-contrails-climate-impact-report.pdf
	D-KULT, DFS DLR a.o.	2023	On-going
	CICONIA	2023	On-going

	Concerto/SESAR III	2023	On-going
	MIT/Delta	2023	On-going
	Satavia contrail management trials with aircraft operators	2024	On-going
	European ECLIF3	2024	On-going

APPENDIX B – REVEIEW QUESTIONNAIRE

1. Title, organization, year of publication
2. Reviewed by:
3. Short description (e.g., based on trials or theoretic research, which region).
4. Does the report cover research on contrails, aircraft-induced cirrus or other non-CO_2 effects? Which other non-CO_2 effects?
5. Which operational measures are mentioned in the report to avoid persistent contrail formation? For example: pre-tactical and tactical avoidance of ISSR.
6. Are these measures already feasible? Is a timeline for implementation mentioned?
7. Does the report mention issues or restrictions to be resolved before effective implementation of these measures can be accomplished? Which ones?
8. Does the report expand on a concept of operations for the ATCO, for the flight crew or for the flight planners?
9. Is the reduction of the climate impact assessed? Qualitatively or quantitatively? Please specify if so.
10. Are any interdependencies identified with other environmental parameters and operational aspects, such as flight time, fuel use, airspace capacity, or ATC workload? With a quantitative or qualitative assessment?
11. Are there any potential future technological and operational opportunities identified to enable navigational avoidance or mitigate non-CO2 climate effects with minimal impact on other aspects?
12. Are these opportunities based on improvements in:
    a. Flight planning
    b. Flight operations
    c. Communication and navigational capabilities
    d. Weather forecasting
    e. Prediction of contrail formation
13. Does the report address operational measures to address other non-CO2 climate effects?
14. Are any regulatory or procedural changes needed to enable mitigation and avoidance.
15. Is the impact of the future implementation of SAF discussed?