D2.4 - Knowledge gaps and research roadmap on aviation impacts on climate

Document Author(s)	Climate Impacts : Ph. Novelli (ONERA) Air Quality : D. Bianco (CIRA)
Document Contributor(s)	V. Grewe (DLR), S. Zhukovska (DLR), E. Terrenoire (ONERA)

Abstract

This report presents a state of the art and a knowledge gap analysis on aviation non-CO_2 effects and aviation impact on local air quality, and propose a high-level roadmap for further research on the topic.

It points out the remaining challenges in climate models for the representation of clouds and aerosols, with impacts on contrail modelling the precise characteristics of which are also not well considered depending on aircraft, fuel and the atmospheric conditions For NOx, it evidences remaining discrepancies between modelling results and the methodological issues for a consistent representation of their impact. Last, it describes the difficulties and uncertainties for representing the interaction between aviation aerosols and natural clouds. Regarding mitigation strategies for non-CO_2 effects, two major challenges are the prevision of ISSR by weather prediction models and the implementation the strategies in the air traffic management system. In evaluating air quality, knowledge gaps particularly concern particulate matters in terms of certification and impact on communities' health.

Keywords

Aviation non-CO2 effects, contrails, air quality

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Information Table

Contract Number	**101140632**
Project Title	Clean Aviation Support for Impact Monitoring
Topic	HORIZON-JU-CLEAN-AVIATION-2023-02-CSA-01
Type of Action	HORIZON JU Coordination and Support Actions
Project Start Date	2024-01-01
Duration	18 Months
Project Coordinator	Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR)
Deliverable Number	D2.4
Deliverable Title	Knowledge gaps and research roadmap on aviation impacts on climate
Version	1.0
Status	Final
Responsible Partner	ONERA & CIRA
Deliverable Type	Report
Contractual Date of Delivery	2025-04-30
Actual Date of Delivery	2025-06-27
Dissemination Level	PU

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Clean Aviation is the EU's leading research and innovation program for transforming aviation towards a sustainable and climate neutral future.

As a European public-private partnership, Clean Aviation pushes aeronautical science beyond the limits of imagination by creating new technologies that will significantly reduce aviation's impact on the planet, enabling future generations to enjoy the social and economic benefits of air travel far into the future.

Visit the website to find out more about Clean Aviation: www.clean-aviation.eu

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Authoring & Approval

Prepared by		
Name & Organization	Position and title	Date
Philippe Novelli (ONERA)	WP2 participant	2025-06-22
Davide Bianco (CIRA)	WP2 participant	2025-06-22

Reviewed by		
Name & Organization	Position and title	Date
Volker Grewe (DLR)	WP2 Lead	2025-06-22
Pascal Bertram (DLR)	WP2 Participant	2025-06-27
Svitlana Zhukovska (DLR)	WP2 Participant	2025-06-22

Approved for submission by		
Name & Organization	Position and title	Date
Volker Grewe (DLR)	WP2 Lead	2025-06-25
Prajwal Shiva Prakasha (DLR)	Project Coordinator	2025-06-27

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Document history

Version	Date	Status	Author	Description
1	2025-06-12		Ph. Novelli, D. Bianco	First released version of the document

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Table of Acronyms and Abbreviations

Acronym/Abbreviation	Description / Meaning
aCCF	Algorithmic climate cost function
ATC	Air traffic control
ATM	Air traffic management
ATR	Average temperature response
BFFM2	Boeing Fuel Flow Method 2
CAEP	ICAO Committee for Aviation Environmental Protection
CCF	Climate cost function
ECMWF	European Centre for Medium-Range Weather Forecasts
DWD	German weather service
ECAC	European Civil Aviation Conference
EF	Energy forcing
ERF	Effective radiative forcing
ESM	Earth system model
GCM	General circulation model
GTP	Global temperature potential
GWP	Global warming potential
HEFA	Hydrotreated Ester and Fatty Acids
HPC	High performance computing
IGRA	Integrated Global Radiosonde Archive
IAGOS	In-service Aircraft for a Global Observing System
INP	Ice nucleation properties (or particle)
ISA	International Standard Atmosphere
ISSR	Ice supersaturated region
M	Mach number
MSG	Meteosat Second Generation
NCAR	National Center for Atmospheric Research
NOAA	National Oceanic and Atmospheric Administration
nvPM	Non-volatile particulate matter
NWP	Numerical Prevision Model
PMO	Primary Mode Ozone
RF	Radiative forcing
RH_i	Relative humidity to ice
RQL	Rich Quench Lean
SWV	Stratospheric Water Vapor

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

UTLS	Upper-troposphere lower-stratosphere
vPM	Volatile particulate matter
WRF	Weather Research and Forecasting model

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Table of Contents

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

List of Figures

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

List of Tables

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

1 INTRODUCTION

As any other sector burning fossil fuels, aviation has a direct impact on climate through its CO_2 emissions. However, as aviation releases its emissions at high altitude, the other engine emissions such as water vapour, NOx or soot also affect the atmosphere radiative forcing[1], directly or through complex atmospheric processes like contrail formation or chemical reactions with other atmospheric species. There is currently a general agreement that these "non-CO_2" effects shall be considered toward aviation climate neutrality, as their effect could potentially be of the same order of magnitude as those of CO_2. However, they are still at a low level of understanding among the scientific community, with significant uncertainties on the quantification of their actual impact. In addition, contrary to CO_2, non CO_2 effects are highly dependent on atmospheric conditions, location (latitude and altitude) and time of the year (and even of the day). Mitigating non-CO_2 effects call for measures that are generally not aligned with those required for reducing fuel burn and CO_2 emissions. As an example, avoiding contrails that form in ice supersaturated regions (ISSR) of the atmosphere may call for rerouting the flight with an increased fuel burn. A precise knowledge of their effect compared to CO_2 is therefore of primary importance for designing and implementing mitigation measures. This is all the more complex that the impact of CO_2 and non-CO_2 effects occur with significantly different life time, CO_2 remaining in the atmosphere for centuries while the lifetime of non-CO_2 effects varies from hours for contrails to years for NOx. This raises the sensitive question of the metric to consider when comparing the effects of both to decide of the implementation of mitigation measures.

One of the objectives of the CLAIM project is to review and synthesize the current knowledge gaps that prevent an accurate assessment of the climatic impact of non-CO_2 effects. The analysis encompasses physical understanding, modelling aspects, data availability, as well as the potential effect of future evolutions of aviation, in particular the introduction of alternative fuels that modify aircraft emissions. It is based on the project team knowledge, literature review,

[1] Radiative forcing is a net flux imbalance at a location in the atmosphere, caused by a change in atmospheric composition. IPCC defines the radiative forcing of the surface-troposphere system (due to a change, for example, in greenhouse gas concentration) as the change in net irradiance (ΔF), at the tropopause after allowing stratospheric temperatures to readjust to radiative equilibrium, but with surface and tropospheric temperatures held fixed [3]. It is commonly presented as the present-day ΔF relative to pre-industrial times.
Radiative forcing can be seen as a shortcut for the global-mean surface temperature change at equilibrium $\Delta Ts = \lambda$ RF, where λ [K/(Wm2)] is a climate sensitivity parameter and RF is the radiative forcing.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

as well as direct exchanges with experts external to the CLAIM project. Having these knowledge gaps in mind, the study also includes a critical review of the available options for mitigating non-CO_2 effects, from the point of view of both the aircraft technology and its operations, taking into account the influence of metrics in the decision process. This knowledge gap analysis and the critical review of the mitigation measures are addressed in the two first chapters of the present report. The third chapter proposes a research roadmap resulting from this gap analysis.

Further, non-CO_2 emissions have a direct impact on local air quality on and around airports, with potential health issues. This aspect is also included in the CLAIM project and the second part of the report presents a dedicated knowledge gap analysis on air quality assessment, starting from current methodologies to evaluate the environmental impact of aircraft operations in airports and surrounding areas. In particular, a research roadmap on the impact of aviation on local air quality is proposed in chapter 6, focusing on the role of particulate matter as an elusive pollutant agent, whose production and effects are currently not completely understood and taken into account. The need for new prediction models, experimental and meteorological data is also considered to propose a research pathway and an optimization of standard procedure for accurate prediction of pollutant dispersion at airport level and near sites.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

2 Non-CO2 effects

2.1 Introduction

Aviation non-CO_2 effects involve multiple emissions and physico-chemical processes taking place at the limit between the troposphere and stratosphere, as detailed by Lee et al. [1], [2].

Under ice supersaturated conditions, water vapour emitted by combustion may condense and form ice crystals generating contrails that may persist and evolve in artificial cirrus depending on atmospheric conditions. The phenomena is favoured by particles emissions of the engine, mostly soot for classical engines and conventional fuel, which serve as condensation nuclei. These artificial clouds retain long wave radiation from earth surface (positive radiative forcing)[2] and reflect short wave radiation from the sun (negative forcing). The net effect of contrail is positive during night and results from the small difference between these two large forcing close to equilibrium during the day: depending on the time of the day (and more precisely on the sun position), it can be positive or negative. In average, the radiative forcing of contrails is considered to be positive.

NOx impact on climate is linked with longer residence time when released at high altitude and their involvement in a chain of chemical reactions. Through a photochemical process, NOx (NO and NO_2) produce ozone, an important greenhouse gas, inducing a warming effect (positive forcing)[3]. Ozone increases the oxidation capability of the atmosphere due to OH formation, which produces a destruction of methane, another important greenhouse gas. The decrease of methane is accompanied, on a longer time scale, by a lower production of tropospheric ozone and stratospheric water vapor (due to lower oxidation of methane), resulting in a cooling effect (negative forcing). The net effect results from these two opposite effects, which are relatively balanced but with different time scales.

Emissions of water vapor (a greenhouse gas) and soot both result in a direct positive radiative forcing, while emissions of sulphur dioxide (SO_2) arising from sulphur in the fuel, which is oxidized to form sulphate particles, result in a negative forcing[4].

[2] Absorption and emission of longwave radiation reduce the outgoing terrestrial radiation because absorbed infrared radiation is emitted from the cloud tops at significantly lower temperatures than from the Earth surface.

[3] At subsonic aircraft cruise altitudes of 8–12 km, O3 production is four times more efficient than near the ground [26].

[4] Radiation-aerosol interaction in the case of soot and sulphate.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Sulphate and soot emissions may also interact with high altitude ice clouds and low altitude liquid clouds, modifying their properties and therefore their radiative impact. The effect is also dependent on background aerosols.

A synthesis of the estimations of the relative impacts of these various effects was produced by Lee et al. in 2021 [1] for the year 2018 and is depicted on Figure 1. It provides the estimates of the effective radiative forcing[5] (ERF) of the various contributors with the associated uncertainty bars assessed by the authors. The non-CO_2 effects were estimated from published studies or recalculated being careful to normalize the forcing to assumed emission rates and emission indices to the same year. Contrail induced cirrus emerge as the larger contributor to aviation climate impact, before CO_2, with an overall warming effect. NOx net effect comes in third position, while water vapor and aerosol-radiation interactions have minor effects. Due to the large spreading of existing results regarding aerosol-cloud interaction, no best estimate could be provided for this effect that could be potentially large. Generally, Figure 1 evidences very large uncertainties and low level of confidence on the respective effects of the major contributors.

From the best estimates of the contributors (and excluding aerosol-cloud interaction), non-CO_2 effects could account for 66% of aviation radiative forcing. However, the uncertainty distribution (5th, 95th percentiles) show that non-CO_2 forcing terms contribute about eight times more than CO_2 to the overall uncertainty in the aviation net forcing in 2018. It is interesting to note that, in this analysis, the way to estimate uncertainties differ between the contributors. For NOx, they were based on a statistical analysis of model simulations (around 50), while for the contrail cirrus, data from only four sets of results from three models were available[6].

The knowledge gaps behind the high uncertainties affecting each of the major contributors to non-CO2 effects will be analysed in the next sections of the document.

Before entering in the details of each contributor, some general considerations and gaps or weakness common to the assessment of all of them are worth mentioning.

A first remark is that assessing the climate impact of non-CO_2 effects is only possible through numerical simulations based on a cascade of complex models, with no straightforward way of

[5] The effective radiative forcing (ERF) is calculated as the change in net top-of-the-atmosphere (TOA) downward radiative flux after allowing for rapid adjustments in atmospheric temperatures, water vapour and clouds with globally-averaged sea surface and/or land surface temperatures unchanged. ERF is preferred over RF estimates because the imposed forcing and rapid responses to the forcing cannot always be separately evaluated, especially for aerosols [1].

[6] Burkhardt and Kärcher (2011), Chen and Gettelman [4], Schumann et al. (2015), Bock and Burkhardt (2016) [5], Bickel et al (2020)[6]

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

validation. This by itself introduces uncertainty, and confidence in the results can mainly be reached through the development and convergence of concurrent approaches.

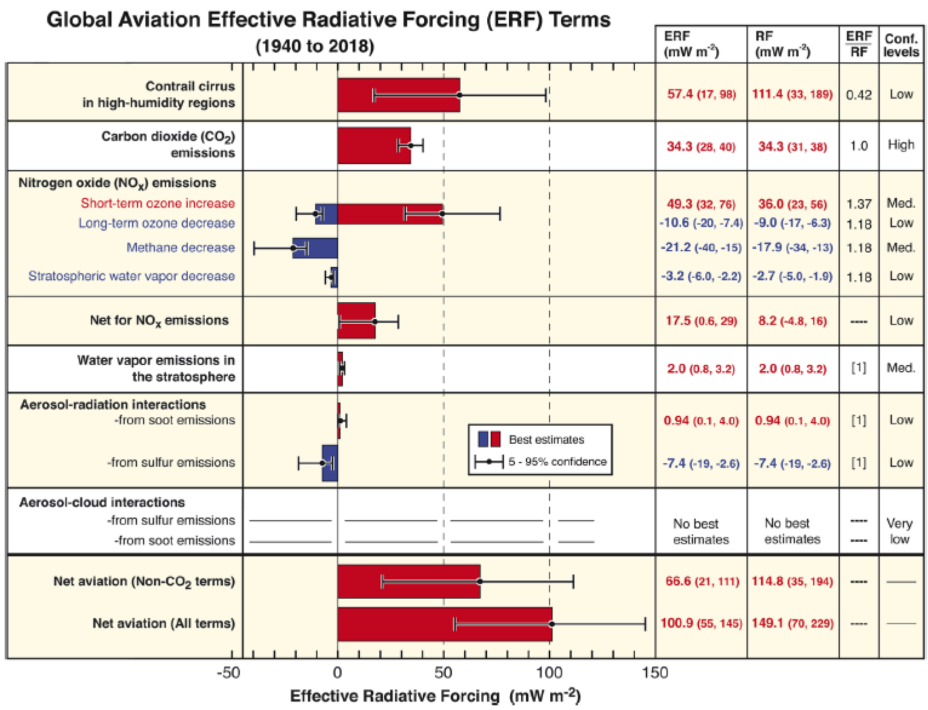

Fig. 1 Best-estimates for effective radiative forcing (ERF) terms from global aviation from 1940 to 2018. The bars and whiskers show ERF best estimates and the 5–95% confidence intervals, respectively. Red bars indicate positive terms and blue bars indicate negative terms. Numerical ERF and RF values are given in the columns with 5–95% confidence intervals along with ERF/RF ratios and confidence levels. RF values are multiplied by the respective ERF/RF ratio to yield ERF values. ERF/RF values designated as [1] indicate that no ERF/RF estimate is available yet. Taken from Lee *et al.* (2021).[6]

Figure 1: synthesis of estimates of effective radiative forcing for the various non-CO_2 effects [1]

Uncertainties and knowledge gaps are to be considered at each level of the modelling and simulation chain, including:

- Climate models – the tools finally used to assess the impact on climate,
- Models representing non-CO_2 effects in climate models,
- Knowledge and understanding of individual phenomena, which underpin models, as well as the potential interaction between phenomena,
- Validation of models and availability of data for model validation,
- Method that is used to identify the aviation contribution,
- Availability and quality of input data for climate assessment.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

In this cascade of models, distinction shall be made between actual knowledge gaps and intrinsic limitations encountered in representing or taking into account a physical phenomenon in a numerical simulation. Affordable resolution associated to available calculation and storage means is a typical example limiting the capability to precisely represent small scale phenomena such as contrails in a global earth simulation. When assessing potential future impacts of aviation, input data are also strongly linked with the considered scenarios, both for air traffic and aircraft fleet, but also for the global society and its emissions. These are intrinsically uncertain.

The purpose and context of the assessment shall also be considered as assessing the impact of a global traffic or of an individual flight may incur different uncertainties and require different tools.

2.2 Observations on climate models

Climate model being the final tool for assessing the impact of non-CO_2 effects, their intrinsic limitations and weakness have a direct impact.

Various level of climate models may be considered for assessing the climate impact of aviation depending on the purpose and context of use.

For scientific purpose and a precise assessment of the overall impact of air traffic, general circulation models (GCM) are to be used, modelling the physics of the atmosphere, of ocean and earth surface, or earth system models (ESM), a more complex class of models including atmospheric chemistry, carbon cycle, vegetation and so on. Aiming at covering the entirety of the earth surface and representing multiple phenomena at various scales, such models per nature are limited in resolution, typically 50 to 100 km horizontally and up to 1 km vertically. Hence, they require simplified representation of phenomena with a parametric representation of those taking place at scale bellow their grid size (this is in particular the case for representing clouds and therefore contrails). Model resolution has been shown to be a key factor in simulating important regional processes and phenomena such as ocean circulation or hydrological processes [4]. Progress is likely to be done at relatively short term with the increase of the computation capabilities allowing a higher resolution of climate models. Yet, parameterizations will still be needed for unresolved processes.

Of particular relevance for non-CO_2 effects, clouds processes and their feedbacks are identified by Jones et al. [4] as the major source of uncertainty in the effective climate sensitivity. Hewitt et al. [8] points out among knowledge gaps identified by IPCC AR6 for climate modelling, the uncertainties on clouds and aerosols properties and on related feedback processes. These affect adjustments, forcing and their efficacy. Lee et al. [2] also points out a lack of understanding of cloud physics important in the formation and persistency

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

of contrails. Clouds are not represented as physical objects in GCM but rather as a statistical representation linked to humidity and providing the cloud fraction as well as the water, vapour and ice content in a grid cell. Increasing resolution could bring improvement but even a kilometric resolution does not allow resolving cloud scale. The representation of the role of aerosols in the formation of clouds also remains a difficult issue.

Jones et al. [4] underlines the importance of improving simulations of the historical climate evolution to increase confidence in ESM projections. This requirement encompasses multiple variables and timescales, with long-term trends in global mean surface air temperature (GMSAT), including the forcing and feedbacks controlling these trends. It also involves improving the ability to constrain key feedbacks and the process controlling these feedbacks.

Lee et al. [2] also point out that, due to computational costs, radiative computation in ESM are simplified and may not include all relevant processes.

An additional difficulty is that aviation perturbation is small compared to climate natural variability ("climate noise") and therefore difficult to distinguish, requiring long integrations of computationally intensive ESMs and/or performing experiments with specific approaches or artificially inflated perturbations, which may have consequences on the results (see for example Chen & Gettleman [4][7] or Bikel & al.[6][8]). Such difficulty seems hard to overcome. Performing sensitivity analysis with ESM is also difficult to fully capture the effect of uncertainties in the drivers of climate change.

There are also needs for assessing climate impact of individual flights. In particular, the European Commission envisages to include non-CO_2 effects together with CO_2 in the aviation Emissions Trading Scheme (ETS). This implies assessing non-CO_2 effects from flight data recorded in the Monitoring, Reporting and Verification system (MRV) that is in operation since the beginning of 2025. GCM and ESM are too costly and time consuming for such application and simplified climate models are required. This is also the case for implementing mitigation measures such as contrail avoidance. Simplified, rapid climate models are required to assess the climate cost of the contrail likely to be generated if the aircraft route is not modified compared to the CO_2 additional cost of the rerouting to avoid an ISSR. Models exist, such as AirClim or FAIR. They would need additional validation with regard to aviation non-CO_2 effects, which is mostly possible compared to detailed simulations on a variety of situations, as well

[7] Chen & Gettleman noted that the approach they adopted, so that contrail and cirrus radiative forcing surpass the radiative perturbation from model variability, could enhance the possibility of contrail formation and the contrail radiative forcing.

[8] Bickel & al. inflated by a factor up to 12 the air traffic intensity. Their results show a non-linear response to traffic intensity and a shift of the contrail cirrus cover and ERF toward lower latitudes.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

as the inclusion of uncertainties in the assessment (some work is underway for that). Simplified models are limited to the prediction of temperature changes and cannot predict other effects of climate change such as precipitations.

2.3 Observations on input data for impact assessment

Input data is an important source of uncertainty for the assessment of all non-CO2 effects. In particular, all are closely related to engine emissions, especially NOx, soot and sulphur, but potentially also others.

When building inventory of emissions to assess non-CO_2 effects at fleet and air traffic level, the primary source of data is the ICAO engine certification database. This records emissions index for CO, NOx, unburned hydrocarbon[9] and nvPM mass and number[10]. These emissions are measured at ground, on isolated engines on test bed, with no other off-takes and loads than those necessary for engine basic operation, for operation regimes representative of the landing and take-off cycle (LTO - take-off, climb, approach and taxi/idle). There is no information for cruise, for which emissions shall be reconstructed through transposition methods, such as the Boeing Fuel Flow Method2 (BFFM2) for NOx. Extrapolations are known to work well for NOx in case of conventional burner ("RQL" type): published comparisons with in-flight NOx measurements have shown that predictions based on fuel flow models and in-flight measurements agreed on average within +/- 12% [10]. However, the most recent estimations published in the context of the ECLIF project tend to show that BFFM2 (or comparable aptFFM2) predict values on average 15 to 20% lower than emissions indexes calculated from in-flight measurement on a Trent XWB-84 modern turbofan [11] [10]. Transpositions are more uncertain for lean burn combustors for which there is no validated or agreed method published[12]. Estimating nvPM in cruise is even more uncertain, developing a method being challenging because of the lack of reliable in-flight data for validation. CAEP is currently working on a new methodology for estimating nvPM emissions in cruise [9]. In addition, LTO emissions of nvPM mass and number are not as well understood as NOX LTO emissions due to greater uncertainties in the sampling and measurement procedures [11].

[9] Total of hydrocarbon compounds of all classes and molecular weights contained in a gas sample, calculated as if they were in the form of methane.

[10] For most recent engines as the standard was changed in 2017. For oldest engine only smoke number was recorded.

[11] Measurements were performed at slightly lower Mach numbers compared to typical cruise conditions

[12] From an interviewed expert's view, it may be questionable whether a universal formulation could be found for lean-burn combustors.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

It is also interesting to note that emissions are likely to vary from an engine to another. Harlass et al. showed that applying BFFM2 method using emissions measured at ground for the actual engine used in flight, instead of the certification data, led to significantly better comparisons with in flight measurements [10]. The conditions of the engine (maintenance and age) affect temperatures and pressures inside the engine, with effects on emissions. During the VOLCAN flight test campaign, it could be observed that the two engines of the same aircraft did not behaved similarly, with only one generating a contrail. Such aspect can hardly be accounted for when building an emission inventory of actual air traffic, for which in addition the actual characteristic of the aircraft are not precisely known. Aircraft are usually tailor made to custom requirements that impact weight and performance (internet radomes, number of toilets, etc. not accounted for in (public) data used to describe the aircraft performance and used for emissions assessments.

On top of that, aircraft emissions depend on the composition of the fuel used, which varies with the origin of the fuel. Especially, nvPM are closely related to the H/C ratio and aromatic content of the fuel, while sulphur emissions are directly related with the fuel sulphur content. Fuel properties are known in average but not for a particular flight and may vary significantly within the boundaries allowed by the fuel standard. In practice, S is thought to be present in fuel at levels averaging 600 to 800 ppm(m), but data are not readily available [11]. The introduction of sustainable alternative fuels (which composition differs from fossil kerosene, especially regarding sulphur and aromatics) brings an additional layer of variability.

As will be addressed later on in the document, it is also suspected that other emissions than soot may play an important role in contrail formation in case of alternative fuels or engine with very low soot emissions. These emissions are not fully characterised today.

Additional inaccuracy and uncertainties are introduced in the process of building inventories. In particular, this involves rebuilding the global air traffic from available traffic databases such as OAG, Flight Radar 24 or others. Not all these database are comprehensive regarding the flights and the related information (e.g. OAG only contains the origin and destination of the planned flights, with no information about the route actually followed), the significant cost of the most complete databases being also a barrier for scientific research. Fuel consumption and aircraft emissions need to be rebuilt along the trajectory using aircraft performance models publically available (and therefore not containing the actual aircraft manufacturer data) such as BADA from Eurocontrol. Accuracy depends on the level of details taken into account, for example whether the computation uses reanalyses of the meteorological conditions encountered during the flight. Yet, it should be noted that the meteorological conditions seen during the actual flight are not those generated by the climate model, which is run on a long duration to reproduce different possible meteorological instances of the climate.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

A last aspect of inventories is pointed out by Chen& Gettelman [4] regarding their time resolution. They performed assessments using hourly, daily and monthly data and evidenced the need to take into account the daily cycle of flights otherwise the simulations failed to capture the pronounced diurnal cycle of linear contrail formation and substantially reduced strong negative shortwave forcing in the afternoon hours, leading to a 29% overestimate of contrail radiative forcing (mean daily emissions move flights from day to night).The use of timely resolved emissions or not is another source of differences between climate assessments (e.g. Bock & Burkhardt [5] use monthly means).

2.4 Contrails and induced cirrus clouds

2.4.1 Contrails and contrail cirrus in climate models

Four different aspects of contrail representation in climate model are at stake for the evaluation of their climate impact:

- The prevision of their conditions of appearance and of persistency (together with the prevision of cloud coverage);
- Their physical representation and associated processes;
- The assessment of their radiative impact;
- The assessment of their efficacy.

2.4.1.1 Prevision by climate models of contrails appearance and persistence conditions

Contrail occurrence and persistence are associated with ISSR, the prevision of which implies an accurate representation of temperature and humidity, as well as a correct representation of the partitioning between condensed (cloudy) and non-condensed (ISSR) fraction of the grid cell. Temperature and humidity are primary variables of the model, while cloud formation and super-saturation are parametrised. Accurate representation of super-saturation is generally a weakness of climate models, as it is also pointed out as a strong weakness of meteorological models in the discussion about contrail avoidance and about the European MRV for non CO2 effects. For the later, this is explained by the limited interest till now for ice super-saturation in meteorological prevision and a lack of measurement data. In their synthesis of existing assessment of climate impact of aviation, Lee et al. [1] considered that about 45% of the uncertainties on the radiative effect of contrail cirrus are associated with the upper-tropospheric water budget and the contrail cirrus scheme, among which 20% comes from a

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

lack of knowledge in ambient conditions and to the ability of models to reproduce the observed statistics of ice supersaturation[13].

There seems to be good confidence that acquiring in-situ data would bring significant progress in the area, which however requires long time series for climate models with seasonal variations. However, acquiring corresponding data is currently a barrier. Satellites could be used but their development is long (and costly) while their vertical resolution is low. The most promising way forward seems to be equipping aircraft fleet with humidity sensors (which is also useful with regard to the MRV implementation). Developing the appropriate sensor, able to measure low level of humidity with no need for frequent calibration for a regular operational use, is still a difficulty. A question is also whether measuring only on aircraft route is enough to constrain an accurate prediction of humidity. For contrail avoidance, accurate observations of atmospheric conditions are also required for initializing the prevision.

Lee et al. [2] also points out that ISSR have their own internal variability and that aircraft-based observations revealed horizontal scale of ISSR has mean and median lengths of 3 km and 1 km respectively, which evidences a much more heterogeneous structure than previously thought, with a 150 km length. The influence of these micro-scale variations (at grid scale) need to be investigated.

The cell size of a GCM is much larger than the contrail scale and does not allow to capture it. In addition, super-saturation is only represented as a fraction of the grid cell with no spatial localisation in it. Therefore, it is not possible to know whether aircraft and contrail are in the super-saturated portion of the cell. This is not an issue when assessing the global impact of air traffic as, in average, errors are likely to compensate. But this shows that a climate model is not the appropriate tool for quantifying the impact of a particular flight.

2.4.1.2 Representation of contrails and associated processes in climate models

The representation of contrails and induced cirrus in GCM suffer from the same issues than those mentioned earlier for clouds. Following the interaction between contrails and natural clouds is poorly taken into account, affecting adjustments. The development of contrails and contrail cirrus decrease the amount of natural clouds as they dehydrates their surrounding atmosphere, which create a negative feedback on radiative forcing. Such rapid adjustments are the rationale behind using the effective radiative forcing (ERF) rather than the classical

[13] The remaining 55% are attributed the evaluation of the radiative response to contrail cirrus. Lee et al. stated that the statistical uncertainty of global contrail cirrus RF could not be estimated from the small number of available studies. In most cases, they could only infer very rough estimates for the uncertainties related to specific processes.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

radiative forcing. Studies show that ERF is reduced compared to RF by about 50% or more (results differ between models) [2]. Bickel et al. [6] showed that the largest factor at play in the reduction of forcing is the impact of contrail cirrus on natural clouds, evidencing the importance of an accurate modelling of this interaction in climate models. A related issue is the selected approach for describing the contrail and its full life up to contrail cirrus in the model. Some models (e.g. Chen & Gettleman) include contrails in existing ice clouds, while others (e.g; Bock & Burkhardt) define a specific class of clouds for contrail and contrail cirrus, which requires defining the interaction between both. Having a specific cloud class for contrails allow to introduce a different size of ice crystals (that tend to be smaller than for cirrus). An underlying issue is also the ability of the model to predict the appearance of a natural cloud if there has been no aircraft.

In addition, there is a weak knowledge of atmospheric turbulence at the scale of interest for the dispersion of contrails (a few hundreds of meter). There is no instrumentation routinely embarked on board commercial aircraft to measure such information. Moreover, measuring precisely the wind at 10 km altitude is quite difficult.

Also related to the poor representation of cloudiness in climate models is the issue of vertical overlapping of contrails between each other's and with natural clouds, which cannot be captured and requires assumptions. This is considered as a large source of uncertainties by Bock & Burkhadrt when assessing the radiative impact of contrails and clouds.

The contrail is represented as a cloudy fraction of the cell. It is characterised by its volume, length, ice content and ice crystals concentration. With regard to potential 3D effects in contrail radiative impact, the parametrisation does not include any information about contrail orientation. The GCM does not represent the initial formation of the contrail that forms based on the Schmidt-Appleman criterion and persists if atmosphere is super-saturated with regard to ice. Contrails characteristics are initialised based on air traffic density and water emissions (from inventories) using a cross section and ice concentration or ice crystal size stemming from observations, experiments or dedicated simulations. Chen & Gettelman [4] used in situ crystal measurements by DLR [12] for crystal size (10 µm, based on contrail aged for 20-30 min) and plume experiments for the cross section (300 m x 300 m). Bock & Burkhardt used a cross section of 200 m x 200 m and ice crystals number concentration (150 cm^{-3}, resulting in 1 µ crystals, assumed to be spherical) from in situ measurement of young contrails after the vortex phase (a value that is lower than recent measurements by Voigt & al. during the ECLIF campaigns - about 1.9 µm [14]).

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Chen & Gettelman noted that the assumptions on the particle shape and size have a significant impact on the contrail radiative forcing (they used spherical ice crystals)[14]. A smaller ice particle size in contrail initialization enhances ice number concentration and reflectance. Also their contrail parametrisation was sensitive to the cross-sectional area of contrails: the volume of contrails upon formation determines how much ambient humidity from the supersaturated region is taken into the contrails. A reduction of the cross-sectional area in contrail initialization decreases the amount of ice mass in contrails and the contrail coverage.

Data collected by Schumann et al. in the COLI database [13] show that observations exhibit a large range of variability in the contrail properties, which increases with age (which is also the case for simulation with CoCip) (Figure 2). Collected observations correspond to different altitudes, atmospheric conditions and different aircraft sizes. Only a general "mean" value is introduced in the climate model. There are also uncertainties associated with the measurements. For example, Voigt et al. [14] reported standard deviation between +/- 10% and +/- 36% on measurements of ice crystal apparent emission indices[15] (range of uncertainty between +/- 20% and +/- 70% with a 95% confidence level – highest values are for the lowest measured ice crystal numbers).

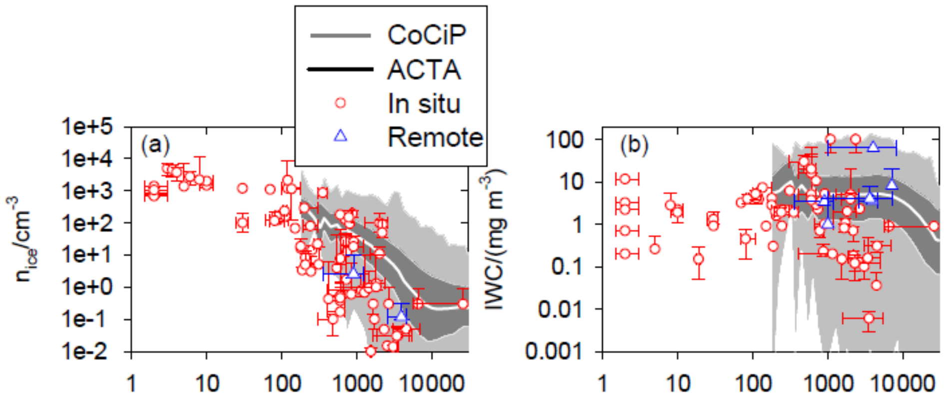

Figure 2: Local contrail parameters from all observations collected in the COLI database versus contrail age from Schumann et al.[13]. CoCip simulation results are shown with percentiles and average.

[14] By the way, for their global synthesis of aviation impact on climate, Lee et al. [1] repeated the simulation of Chen & Gettleman with lower prescribed initial ice-crystals diameter (7 µm) and a larger contrail cross-sectional area (0.09 km^2) in line with measurements collected by Schumann et al. [13].
[15] Number of ice crystals par kg of fuel burned.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Variations between aircraft were illustrated by Jeβberger et al. [15], based on the measurements performed during the CONCERT flight campaign (2008) during which properties of young contrails (~2 mn) were retrieved for an A319, an A340 and an A380[16] for similar atmospheric conditions[17]. Ice concentration number increased from 162 (±18) cm^{-3} for the smaller aircraft to 235 (±10) for the larger (which is in particular connected to the larger fuel burn of the larger aircraft), while vertical extension varied from 120 m to 290 m. Optical depth of the contrail varied from 0.25 to 0.94 (the larger vertical thickness of contrails of heavier aircraft caused by the stronger descent of the vortices contributes significantly to the increase in contrail optical depth[18]). Particle size were close for all aircraft (effective diameter from 5.2 to 5.9 µm). Numerical simulations with the CoCip contrail model of DLR suggested a sensitivity of global contrail parameters to the aircraft type throughout the contrail lifetime. Through numerical simulations performed on six different aircraft types (from CRJ to A380), Unterstrasser et al.[16] confirmed long lasting consequences of difference in contrail depth and ice crystal number after vortex break. Beyond the number and size of ice crystals, the initial depth of the contrail introduced in the climate model is an important parameter as the dynamic of the atmosphere has limited influence on its evolution[19].

Additionally, atmospheric conditions and in particular the level of supersaturation have an influence on ice crystal formation. Kärcher et al. [17] pointed that the kinetics of water droplet formation and freezing becomes complicated in “near-threshold” contrails because the time available for droplets to freeze (from the point where the jet reaches supersaturation) decreases when atmospheric temperature increases toward the threshold temperature for contrail formation. Droplet activation and homogeneous freezing are strongly reduced. This is not taken into account in the initialisation of contrails in climate models. For example, Bock & Burkhardt pointed out that, in their modelling, contrail optical depth was likely overestimated in the tropics, since in the tropics contrails form within a few degrees of the temperature threshold according to the Schmidt–Appleman criterion, limiting ice nucleation in the contrail.

Lee et al. assumed an uncertainty in average contrail ice crystal numbers after the vortex phase of about 50% leading to an uncertainty in contrail cirrus radiative forcing of about 20%

---

[16] Respective mass : 47t, 150 t and 508 t. Respective wingspan : 34 m, 60 and 79.8 m.

[17] T = 217 K RHI between 91 and 94%, Schmidt-Appleman threshold temperature ~223.5 K.

[18] The authors observed that older Lidar observations combined with numerical studies evidenced a clear separation of the secondary wake that can form during vortex descent from the primary wake in the case of a four-engine aircraft. However, measurements from CONCERT show an increase of contrail vertical extension between the A340 and the A380, two four-engine aircraft.

[19] The initial width has limited influence as the width grows linearly with time at meso-scale. Therefore the initial width has limited influence.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

of the uncertainty associated with the upper-tropospheric water budget and the contrail cirrus scheme (an estimate based on simulations with ECHAM5-CCMod). Uncertainty due to assumptions in the initial ice-crystal radii and contrail cross-sectional areas was considered to represent 33%.

2.4.1.3 Radiative impact of contrails

According to Bock & Burkhardt, the uncertainty due to the radiative transfer calculations appears to be one of the largest uncertainties associated with the estimate of contrail radiative forcing. Lee et al. [1] attributed 55% of the uncertainty on contrail radiative forcing to the radiative response to contrail cirrus.

Tools modelling precisely radiative transfer exist but cannot be implemented within climate models for which only simplified models can be used.

Discrepancies already exist between precise tools as can be illustrated by tools comparison against the reference test case of Myhre. However, these discrepancies are not linked to the model but to the input data (spectroscopic data and absorption by water vapour). They are especially large for low solar zenith angle. The net forcing generated by the contrail results from the sum of two large terms corresponding to the short waves (solar incident flux) and long waves (re-emitted flux) possibly of opposite sign but close to equilibrium. Being the small difference between two large terms, it is sensitive to small numerical differences. Simplification increases discrepancies between climate models that are known for long for disagreement even on simple cases. There are attempts to use the more precise line by line models to correct simplified assessments in climate simulations [1] but such corrections are approximate. An additional challenge is that it is difficult to measure the radiative forcing of a contrail to acquire validation data. Uncertainties are in the range of 30 to 50% as the measurement requires numerous assumptions of the properties of ice crystals. All in all, Lee et al. attribute 35% of the uncertainty on contrail radiative response to the model’s radiative transfer scheme.

One of the simplifications applied in radiative modelling is that only 1D computations of radiative transfer are done. 3D effects are not taken into account, such as border effects, influence of the orientation of the contrail or heterogeneity effects (in addition, there is no representation of contrail orientation or heterogeneities in the climate model). Together with cloud overlaps, inhomogeneity of ice clouds within a grid box of a climate model and the use of plane parallel geometry, as compared to full 3D radiative transfer, would account for 35% of the uncertainty on contrail radiative response (Lee et al [1]). Impact of 3D calculations have been investigated by Carles et al. on idealized clouds [18]. The conclusion was that, for the sun at zenith, 3D computations could have an impact on the cloud radiative effect, increasing with optical depth, compared to plane-parallel approximation (for some cloud optical depths, two clouds geometries could even have net radiative effect of opposite signs because of 3D

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

CLEAN AVIATION

Co-funded by the European Union

effects). 3D effects tended to increase positive forcing. 3D computations also showed 3D effects of contrail orientation at large solar zenith angle (Figure 3). Authors concluded that, integrated on the course of the day, the net 3D effects ended up being significant, particularly when a large fraction of the day was associated with large solar zenith angle, typically during winter at high latitudes.

Bock & Burkhardt also pointed out that radiative transfer schemes in GCMs are based on the laws of geometric optics and are therefore limited to particle sizes large compared to the wave length. For their ECHAM5 model, the radiation scheme was limited to ice crystals with an effective radius larger than 10 µm. Since ice crystal sizes in contrail cirrus are often very small, particularly in young contrails, estimating the optical properties and radiative forcing due to contrail cirrus is difficult (Lee et al. attribute 10% of the uncertainty on contrail radiative response to this limitation).

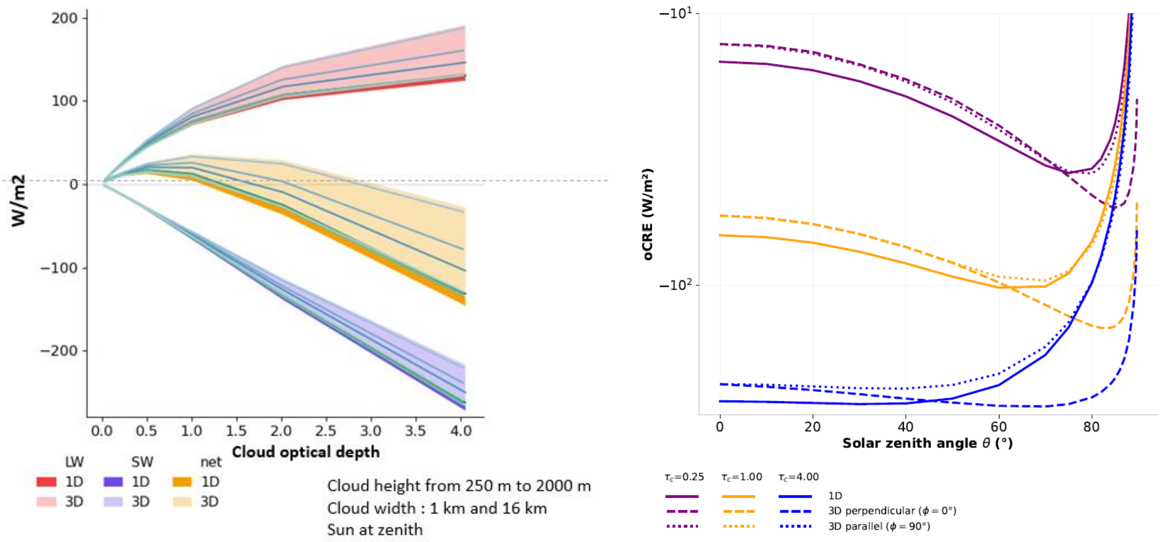

Figure 3: 3D radiative computation effect on cloud radiative forcing; Left: comparison between 3D and 1D computation with sun at zenith – Right: dependence of cloud SW radiative effect to solar zenith and azimuthal angle (rectangular cloud 1 x 0.5 km^2) –Carles et al. [18]

Radiative forcing of contrail cirrus is also influenced by the shape of ice crystals, which is often pointed out as uncertain ([19],[20]) and is influenced by the dynamics of the atmosphere that can lead to various shape and roughness. Crystal shape also evolves along the life of the contrail. Primarily nearly spherical in young contrails, it evolves toward more complex shapes such as plates or aggregates of column shapes. Crystal shape in particular affects short wave

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

radiative forcing by changing the fraction of incident light that is scattered back to space. Lee et al. [1] attributed 20% of the uncertainty associated to radiative response of contrail cirrus to the uncertainty on ice crystal habit. Wolf et al. investigated with 1D computation the effect of prescribing three different ice crystal shapes for similar other parameters of a cloud[20]: droxtals, plates and aggregates [19]. Net radiative forcing decreased from 35.8 Wm^{-2} for plates to respectively 4.5 Wm^{-2} and -4.2 Wm^{-2} for droxtals and aggregates. Sanz-Morère et al. [20] pointed out that because contrail ice forms initially from rapid freezing of liquid droplets, the ice crystals are often assumed to be spherical. Due to the strong forward scattering of spheres, this results in net RFs that are higher than with other crystal shapes. The anisotropy of light scattering is represented by the asymmetry factor g that varies between 0.9 for nearly spherical crystals to 0.7 for others[21]. Measurements in contrails show a decrease of g from 0.9 to 0.75 in a few minutes. Assuming that g remains constant at its maximum value (0.9, perfect sphere), Sanz-Morere et al. assessed that the cooling effect (shortwave radiative forcing) is reduced by up to 50% for contrails with lifetime above 4.5 hours, compared to a case in which a decrease is taken into account[22]. Accordingly, the net radiative forcing of contrails is overestimated. When considering a global contrail radiative forcing, for their reference case, assuming that crystals remain perfect sphere led to a 51% increase of the net radiative forcing compared the value obtained with the evolution of g (15 mW/m^2 against 9.7 mW/m^2 for the considered case). They estimated that the proposed evolution of crystals along the contrail life led to an uncertainty range of 23% on the net radiative forcing of contrails, compared to an uncertainty ranges of 52% if spheres were considered as equally plausible shape as other shapes.

2.4.1.4 Contrails' climate efficacy

Efficacy is related to the increase of earth equilibrium temperature generated by radiative forcing. Radiative forcing is a predictor for the change of the (near) surface earth mean equilibrium temperature: $\Delta T_S = \lambda$ RF, where λ is the climate sensitivity parameter, ideally independent from the forcing mechanism.

---

[20] Thickness : 1000 m, IWC = 0.024 gm^{-3}, r_{eff} = 85 µm, sun at zenith

[21] A g value of 1 means a full forward scattering, 0 means isotropic scattering and -1 full backward scattering.

[22] Sanz-Morere considered a linear decrease from 0.88 to a value ranging from 0.75 to 0.79 in a time ranging from 5 to 40 mn The uncertainty range associated with the possible variation of final g and time of decrease in the suggested range was assessed to be ±8.5% on the short wave forcing, resulting in a uncertainty range on the net forcing between ±7 and ±10.5 depending on the temperature difference between the surface and the contrail.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

This relation is a good approximation for many nearly spatially homogeneously distributed climate forcers, such as global increases of CO_2. However, λ significantly varies for forcers that are heterogeneously distributed either horizontally or vertically; such is the case for aviation-induced ozone perturbations and contrail cirrus or CH4. This led to the introduction of the concept of efficacy: $\Delta T_S = \lambda i$ RF = $E_i \lambda_{CO2}$ RF, E_i being the efficacy of the considered forcing mechanism.

Beyond the Effective Radiative Forcing (ERF) was introduced, which takes into account fast atmospheric response to a given climate forcer, such as for example the rapid cloud adjustments to the appearance of a contrail. Using the ERF, efficacies are much closer to unity but may still differ between short lived or spatially heterogeneous forcing mechanisms [21]. Computing the ERF requires to use a climate model.

Contrail efficacy is not needed when using detailed climate models that compute the answer of the atmosphere to the forcing (providing the ERF) and the increase of the temperature, although large ranges of estimates exist between models. In effect, the ratio between ERF and RF has been estimated to lie somewhere between 0.35 and 0.7, with a mean at 0.42 [11]. The associated uncertainty is thought to be dependent on prevailing aviation traffic and its geographic distribution [1].

Yet, detailed climate models are not practical for sensitivity analysis or exploring scenarios for which simplified models are required. This is also the case when aiming at characterising the climate impact of a particular flight. Then estimating the efficacy is needed and values are still uncertain.

2.4.1.5 Other sources of uncertainties

Additional factors may be relevant when considering the uncertainties associated with the climate impact of contrails.

A first one is the low number of studies on which relies the synthesis made by Lee et al. in 2021: included results came from only four sets of results from three models. For such a complex problem relying mostly on modelling and simulation, with numerous assumptions, a larger set of independent studies would help gaining confidence.

Also when assessing future evolution of contrail impact, climate change shall be taken into account as it will influence temperature and humidity in the atmosphere, as well as the occurrence of ISSR. Together with the unknowns on future traffic, aircraft environmental performances and general evolution of the society, this adds to the uncertainty.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

2.4.2 Knowledge and understanding of contrails

For the initialisation of contrails in climates models, their properties need to be well understood and quantified during their initial life.

For "conventional situations", meaning the use of conventional fossil Jet A-1 and rich-burn combustion chamber (such as RQL chamber), the formation of contrails is rather well understood. Water vapour contained in the engine exhaust gas condenses preferentially on soot emissions and there is a close relationship between ice crystal number and soot number, although it depends also on the saturation level of the atmosphere. For example, during ECLIF in-flight measurement campaigns, measurements with Jet A-1 on a P&W V2500 and a RR Trent engines (respectively on a A320 and a A350) gave a ratio for ice crystal index to soot emission index comprised between 82% and 86%, with however significant uncertainty levels, respectively ±23% and ±68% [22].

Situation is more complex with lean combustion chamber (such as on LEAP engine) that can produce drastically reduced emissions of soot and also with blends of Jet A-1 with synthetic fuel or pure synthetic fuels that contain no aromatics (e.g. purely paraffinic biofuel such as HEFA) and produce less soot emissions than conventional Jet A-1. The reduction of soot emissions has been demonstrated to have a positive impact on ice crystal formation and contrail radiative impact up to a certain level. Less soot create less ice crystals which are larger (due to reduced competition for surrounding water vapour) leading to a lower radiative effect of the contrail and a shorter lifetime (due to increased sedimentation). However, theoretical analyses and in-flight measurement campaign with lean burn (especially the VOLCAN flight test campaigns) showed that for drastically reduced soot emissions, the number of ice crystals formed does not decrease. This is explained by the emerging contribution in such situations of volatiles particles formed from secondary emissions of the engines (e.g. sulphur oxidized in sulphuric acid and possibly organics). In soot-rich regimes, these volatiles do not play any role, which can be explained by multiple factors. Ultrafine plume particles, which contain dissolved H_2SO_4 and organic matter, require much higher supersaturation over water than larger soot particles in order to activate into water droplets due to their extremely small sizes (mean radii 1–5 ηm). In addition, soot particles (and in their absence, entrained atmospheric particles), which activate already at lower supersaturation (i.e., at a younger plume age), act as a condensation sink for water vapor [23]. Soot particles also scavenge these volatile particles.

A recent analysis by Yu et al.[22], based on an aerosol and microphysics model, also suggested an influence of an increased content of paraffinic synthetic fuel that lowers aromatic concentration but also reduces the size of soot (both for aggregates and primary soot). This could explain the reduce ice to soot index ratio observed during some ECLIF flights. Figure 4

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

presents their current vision of the dependence of ice crystal number emission index to the multiple influencing parameters (EI_{soot}, ambient temperature, fuel sulphur content, etc.). This in particular shows that contrail ice numbers could exceed the number of soot in low soot and even in soot-rich or intermediate soot regimes, with an impact on contrail radiative properties in case of lean burn combustion or alternative fuels. This adds a source of uncertainty in simulations of contrail radiative forcing and evidences the need to update and refine the initialisation of contrails in climate simulation.

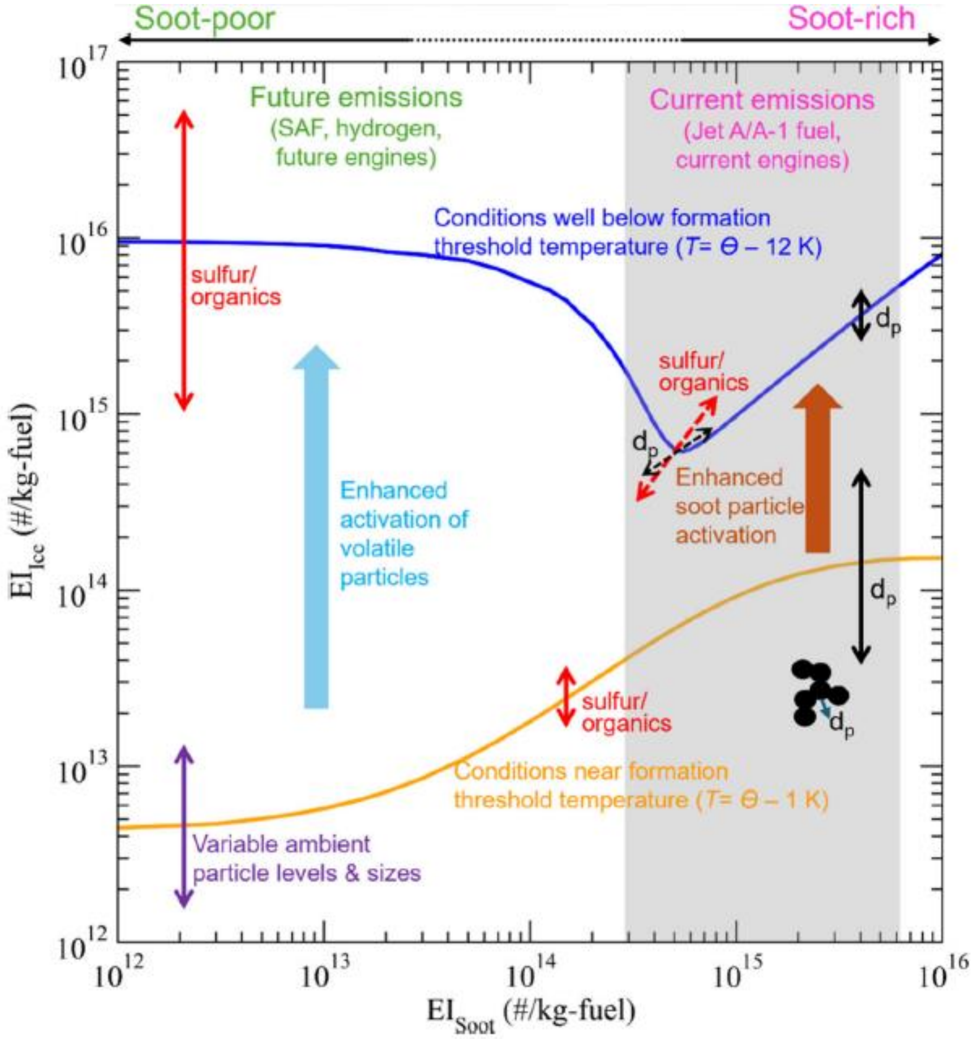

Figure 4: Illustration of the dependence of ice crystal number emission index on the various influencing parameters (from Yu et al. [22])

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

The issue of the relation between the fuel composition, the emissions and the formation of ice crystal is undergoing intensive research and is still open. The possible role of some secondary emissions, such as organics or possibly nitric acid (formed from NOx) still need to be investigated. This raises the need for a characterisation of organics concentration and properties for aviation engines, while in the certification process, only a global measure of unburned hydrocarbons is provided. Research in CLIMAVIATION also evidenced the key role of electric charges in the nucleation processes of some volatile particles, whereas charges are today not characterised in engine plumes. In addition, oil released by engine is suspected to play a role in particles formation and is now under scrutiny (the releases of oil by aircraft engine is not well characterised and seems to be highly variable between two similar engines). Measurements are also lacking regarding lean burn combustion and very low soot emissions situations.

All these open questions currently under research raise uncertainties for the technological choices in aviation and their actual potential benefits.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

2.5 NOx

2.5.1.1 Global picture

Nitrogen oxides emissions from aviation sector changes the chemical composition of the atmosphere. Main consequences of aviation NOx emissions are illustrated on Figure 5. Emissions of NOx into the troposphere result in a short-term increased photochemical ozone production (resulting in a positive climate forcing or warming), and a long-term increased oxidation of atmospheric methane through reaction with the hydroxyl radical OH (resulting in a negative climate forcing or cooling).

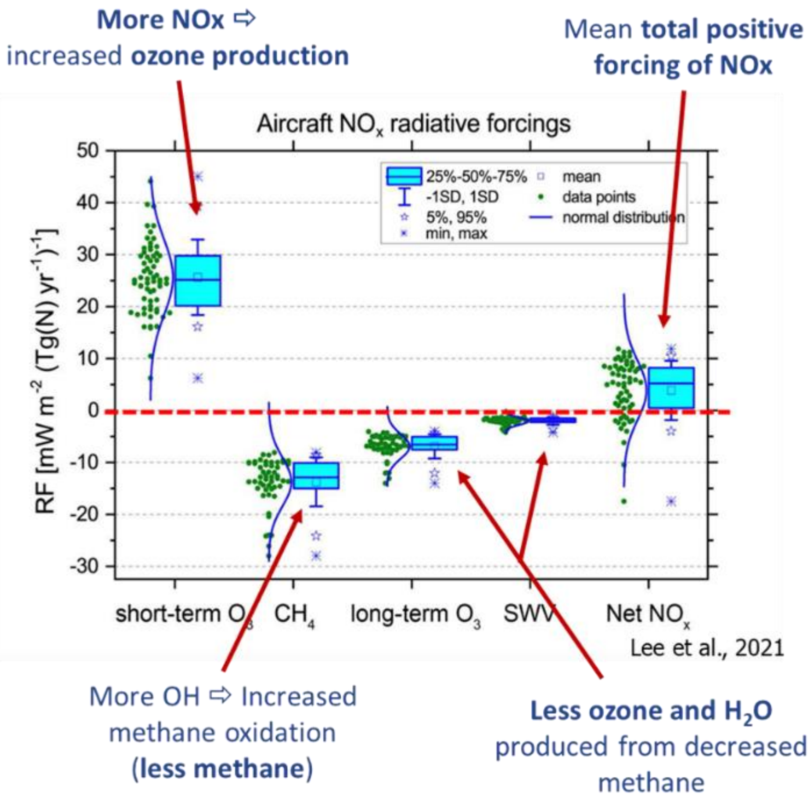

Figure 5: Illustration of radiative forcing components from aviation NOx emissions (from Lee et al., 2021)

The methane reduction further leads, on a longer time scale, to a reduced production of tropospheric ozone (cooling effect) and stratospheric water vapour (cooling effect). The change in CH4 mixing ratio itself represents 75% of this total methane forcing. The indirect changes through long-term tropospheric ozone, stratospheric water vapor and oxidation to

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

CO_2 contribute for 19%, 4% and 1%, respectively according to [24]. Being the consequences of the chemical and photochemical conditions of the atmosphere, the effects of NOx depend on the location (altitude, latitude) and time of emission as well as its background atmospheric concentration.

The resulting effect is the combination of four relatively balanced mechanisms with opposite signs and different timescales, which makes it sensitive to the uncertainties of the four mechanisms. In particular, many factors influence ozone production in the complex transition region between the upper-troposphere and lower stratosphere (UTLS). Ozone production from aircraft emissions depends on the background chemical composition (notably in NOx, ozone and CO), whereas NOx can also be converted in other species such as HNO_3 that can be scavenged rapidly in moist conditions [25]. As each global chemistry-climate model (CCM) and chemistry-transport model has its own chemical scheme, as well as its own parametrisation of convection and precipitation, some uncertainties in the chemical background arise from the inter-model variability.

Cohen et al. [25] performed an inter-comparison, as well as a comparison with IAGOS measurements, for five state of the art models over a four-year period. They observed similar trends for biases with IAGOS data for all models (e.g. all models tend to overestimate ozone in the upper-troposphere and underestimate it in the low stratosphere). However, inter-model variability was noticeable for nitrogen oxide species (NOy), reflecting both different chemical and physical behaviour. It has implications on the model sensitivity to the NOx injection in the UTLS from subsonic aviation as it changes the NOx regime[23].

Significant uncertainty remains on the resulting RF, with discrepancies between model results, as illustrated by the comparison work performed within the European project ACACIA and Table 1. Differences between models are not yet well understood.

There are additional effects of NOx, which have been less accounted for in past studies. NOx also play a role in the formation and destruction of secondary inorganic aerosols such as nitrates and sulphates [2] [24], which may introduce additional negative forcing. In the assessment performed by Terrenoire et al. [24], introducing the radiative forcing of these aerosols turned the net forcing from NOx from a positive value to a negative value. In others words, the indirect NOx effects could compensate the warming effect from the direct effects via the production of cooling aerosols (e.g. sulphates and nitrates). However, the aerosol

[23] Two different regimes can be distinguished for ozone production: the NOx-limited regime, in which the rate of production of ozone increases with NOx concentration, and the NOx-saturated regime, in which the rate of production of ozone decreases when NOx concentration increases.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

indirect forcing is subject to large uncertainties and particularly sensitive to the model chemical scheme. It still needs further investigation.

	Ozone	Methane				
Model	Short-term ozone	Methane direct incl. feedback	Long-term ozone	Stratospheric H_2O	Total CH4	Total
EMAC	27.7	-13.3	-5.4	-1.7	-20.4	7.3
LMDZ-INCA	43.0	-17.3	-7.0	-2.2	-26.4	16.6
MOZART3	42.0	-12.9	-5.2	-1.7	-19.9	22.1
OsloCTM3	34.0	-12.9	-5.2	-1.7	-19.9	14.1
GEOS-Chem	55.3	-24.5	-9.9	-3.2	37.6	17.7

Table 1: Comparative assessment of present-day radiative forcing from NOx emissions with five state-of-the-art models (all in mW/m^2)[24]

2.5.1.2 Dependence of NOx impacts on emissions and emission location

As pointed out, the non-linear NOx chemistry depends intensity and location of aviation NOx emissions, as well as on background concentrations with multiple consequences.

In particular, the efficiency of NOx to produce ozone [24] :

- is largely dependent on the cruise altitude;
- increases with the background methane and NOx concentrations;
- increases with decreasing aircraft NOx emissions.

Based on the REACT4C emission inventory, Terrenoire et al. [24] showed an increase in ozone of about 15% for a 2000 ft altitude increase compared to the baseline scenario (respectively a decrease of 11% for a 2000 ft decrease of the altitude), reflecting longer NO_x residence time at higher altitude as well as higher UV radiation and lower background NOx. This results in an increase in ozone production efficiency reaching 7.5 at higher flight altitudes and a decrease to 5.8 at lower flight cruise altitude. This is also confirmed by previous work done by Sovde et al. [28] and more recently by Maruhashi et al. [29].

[24] CLIMAVIATION presentation at ICAO Symposium on Non-CO_2 aviation emissions, September 2024.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

CLEAN AVIATION

Co-funded by the European Union

Dependence on background emissions makes the climate impact of NOx emissions dependant on the emissions of the other sources, and in particular of other economic sectors, for a same level of aviation emissions[25]. Less background NOx translates in more short-term ozone formed by aviation emissions but also to more CH_4 removed, with a negative net total effect [26]. According to Skowron et al.,[26], decreasing surface NOx emissions plays a larger role in reducing the aviation net NOx RF than decreasing aircraft NOx emissions in percentage terms. As pointed out by EASA report: " *Under future emission scenarios of declining emissions of tropospheric ozone precursors, including CH4 (e.g. RCP4.5) from surface sources, combined with "business as usual" increasing aviation emissions, a net negative RF (cooling) of aviation NOx may result"* [11]. However, Skowron et al. also pointed out that, taking into account the fact that these long-term RFs are fully parametrised, as well as the fact that the CH_4/O_3 ratio is very model specific, the impact of surface NOx emissions on aircraft net NOx RF is relatively more uncertain than the impact of other O_3 precursor emissions. It is also important to note that the updated CH_4 forcing expression used by Skowron et al., which accounts for the short-wave forcing of CH4, increases the CH_4 RF by 25%. This increases the negative terms from the reduction in CH_4 lifetime induced by aviation NOx, turning the net NOx effect from a positive to a negative value with increasing aviation NOx.

2.5.1.3 Perturbation versus tagging approaches

The non-linearity of NOx impact also raises an issue on the way to attribute the impact to a sector or an emission source. A common way of assessing aviation NOx impact is to compare the results of a simulation with air traffic to a reference simulation without aircraft ("100% perturbation method"). This approach can hide the impact of non-linearity (comparing a simulation with all sources with a simulation with aviation alone would give a different result). Another approach consists in source apportionment (or tagging method) in order to quantify contributions by attributing a fraction of the pollutant concentration to each source, which accounts for non-linearity [30]. Sensitivity or perturbation methods are more suited to determine the impact of an abatement strategy [24]. There are however debate on the actual impact of the non-linearity. For Grewe et al. [27], using the simplified approach of the perturbation method leads to significantly underestimate the contribution of aviation NOx emissions to climate change. Yet, recent work using the perturbation method by Hauglustaine,

[25] The emission of NOx from global aviation is estimated to be around 1.4 Tg N yr-1, compared with around 42 Tg N yr-1 from surface anthropogenic sources (EASA)

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

CLEAN AVIATION

Co-funded by the European Union

within the on-going French Climaviation program, did not evidence such a large effect of non-linearity[26].

Grewe et al. also pointed out a second simplification commonly used, consisting in assuming steady state instead of a transient development when computing the methane response[27]. This assumption is correct for tropospheric ozone which has an average lifetime of a few weeks, but not for methane which has a lifetime of about 10 years. For methane, the response does not reach a steady state in any given year and the response in a particular year depends on the historical time evolving emissions.

Together with the perturbation method, Grewe et al. [27] consider that such methodological simplifications largely underestimate the contribution of the aviation NOx emissions to climate change by a factor of 6 to 7 as shown by Table 2. For example, taking this lifetime change as a transient response, which it is actually, reduces the respective methane RF response by 35% and since the primary mode of ozone (PMO) and the stratospheric water vapour (SWV) effects are directly related to the methane concentration change, this reduction also extends to the estimate of RF due to PMO and SWV.

Table 2: Estimates of the contribution of aviation NO_x emissions to the climate change in terms of RF for the year 2005

				Correction of flaws	
Radiative forcing of aviation NO_x emission in 2005 in mW m^{-2}	**Lee *et al* 2009**	**Additional processes (PMO, SWV)**	**Revised methane RF formula**	**#1 Methane lifetime**	**#2 Ozone contribution method**
Ozone	26.3	26.3	26.3	26.3	41.2
Methane	−12.5	−12.5	−15.4	−10.0	−10.0
PMO		−5.0	−5.0	−3.3	−3.3
SWV		−1.9	−1.9	−1.2	−1.2
Total NO_x-RF	13.8	6.9	4.0	11.8	26.7

A number of studies have applied a transient correction factor to the methane forcing to account for this transient response. Terrenoire et al. [24] underline that a major difficulty is that the determination of the correction factor is strongly model dependant and that, due to the

[26] Work not yet published.
[27] The computation of methane evolution is generally performed off-line for computation cost reason.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

long-time integration needed to investigate the methane response, complex models have not been used to date, and the non-steady state factor was determined based on simplified or parameterized chemistry–climate models. An additional difficulty, especially for future scenarios, is that the correction factor depends on the considered year and the assumed future emission pathway. In any case, applying the correction factor increases future NOx net forcing. This is still a field for further research work.

Overall, Grewe et al. [27] consider that the perturbation approach for evaluating the potential of mitigation options makes the assessment vulnerable to any other emission reduction (also in other sectors), whereas the tagging method results in a much more robust assessment [27][30]).

2.5.1.4 Plume scale effects

From Lee et al. [2], an additional source of uncertainties in the assessment of NOx impact is the influence of the chemical evolutions within the aircraft plume, which modify NOx emissions at scale bellow the grid scale of the climate model ([31][32][33]). The oxidation of S and N species is accelerated by the direct formation of OH in the combustor and turbine section of the engine, and some small emission of OH has been modelled to remain. These higher oxidized states of N effectively remove the NOx from the subsequent larger scale cycling of NOx and HOx that is involved in the formation of ozone. This is not widely included in modelling because of the dependency of what happens in plume on the background conditions (and vice et versa). Modelling often assumes that the emissions are instantaneously available, or diluted, at the grid scale of the climate model and are not modified by plume-scale interactions. A difficulty to account for these chemical evolutions is also the lack of knowledge of OH levels at the engine exit (which is very difficult to measure particularly in-flight).

2.5.1.5 Climate metrics calculations

A consequence of the different response time associated with the four mechanisms involved in NOx radiative impact is that the effect depends on the considered time horizon. The positive forcing due to initial formation of ozone is gradually counteracted by the negative forcing resulting from reduction of methane (and the consequent reduction in ozone) leading to a net negative GTP for time horizons between approximately 20 and 60 years, increasing to small positive/close to zero values at around 100 years [2]. This has impact when considering the metric of equivalence with CO_2.

It has been highlighted earlier in the document that the preference today goes to effective radiative forcing (ERF) rather than to radiative forcing (RF), the earlier taking into account rapid adjustments. The transposition from RF to ERF is an additional source of uncertainty for the impact of NOx. Determination of the ERF / RF ratio for the different forcing agent depends

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

on the climate model used and requires further investigation [2][11][24] (in Lee et al 2021,[1], it relies on one study only).

A last aspect raised by Lee et al. [2] is related to the temperature answer to NOx forcing. As local temperature response at the earth's surface is predominantly driven by internal climate feedbacks, the local temperature response is not necessarily correlated or collocated with the local forcing. Providing the net global RF for NOx could therefore not reflect regional surface temperature response.

2.5.2 Aerosol / cloud interactions

Particles constitute condensation nuclei for droplets and ice crystals. As such they are likely to interact with cloud formation and modify their radiative properties. Mostly soot and sulphate particles have been considered, being the predominant primary and secondary aerosol produced by aircraft. Soot mainly affect high altitude ice clouds, while sulphates primarily affects low level liquid clouds. However, in their synthesis, Lee et al. [1] considered the uncertainties were too high on published impact assessments to derive a best estimate of the ERF on aerosol-cloud interaction. It should also be noted than these interactions have been and are still much less studied than contrails or the effects of NOx. Nonetheless, Lee et al. compiled and normalised the published results to 2018 aviation fuel consumption and a 600 pm sulphur content of the fuel. These are illustrated on Figure 1 together with the range of uncertainty on non-CO_2 effects when these interactions are not taken into account.

As already mentioned in the section related to climate modelling, the representation of clouds, aerosols and their interaction is a strong weakness of climate models, which is not specific to aviation impact (it is also not known whether the behaviour of aviation aerosol is different from the one of other aerosols). Interaction mechanisms can be studied at limited scale through large eddy simulation (LES), which allows to study how aviation aerosols enter the cloud evolution process and how they compete with background aerosols. However, there are many possible situations and it is difficult to generate generic results, representative of the general average situation.

The analysis involves many questions at different scales. A first one is how far aviation aerosols are transported horizontally and vertically in the atmosphere. The answer requires accurately representing and calibrating the removal processes in the climate model. Identifying the contribution of aviation is also a difficulty as particles interacting with clouds result from different initial particles. Another important source of uncertainty comes from the lack of knowledge on the aerosols: what are the concentrations, sizes, and ice nucleation properties (INP) or condensation nuclei properties of aviation aerosols after their stay in the

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

atmosphere? Ideally, there would be a need for in situ observations but how to perform the observation in order to distinguish particles from aviation is unclear.

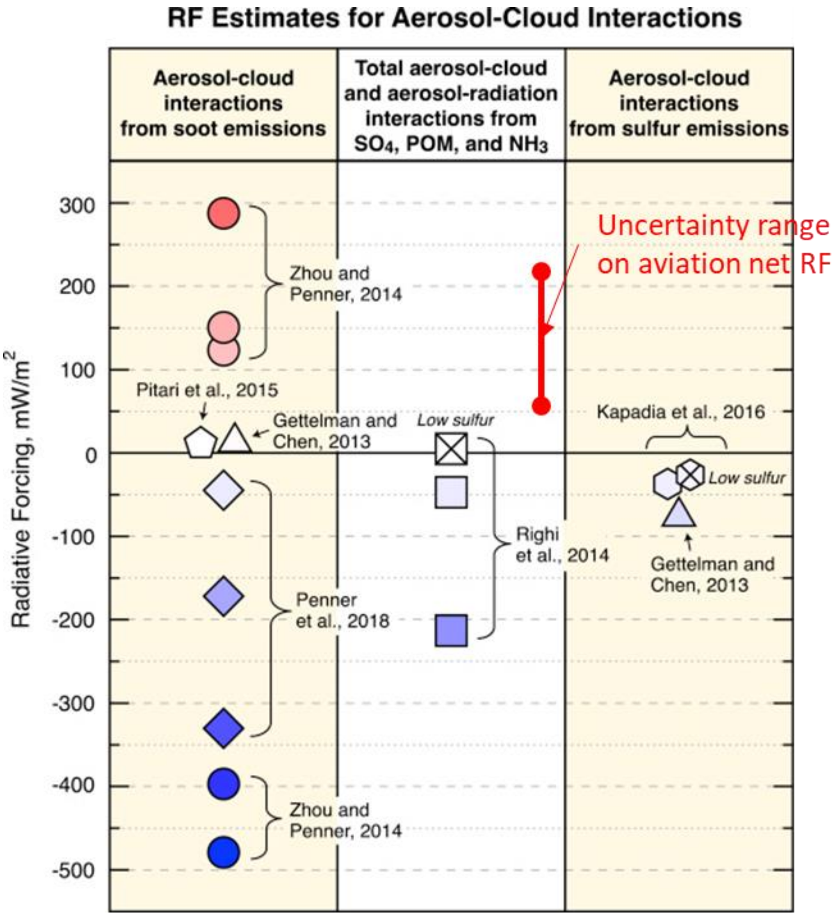

Figure 6: Compilation of assessments of RF from aerosol-cloud interaction (from Lee et al., 2021)

On Figure 6, results for soots span from positive forcing (in a range comparable to total net aviation forcing) to very negative forcing values. Part of the uncertainty comes from the difficulty to accurately simulate the homogeneous and heterogeneous ice nucleation in the atmosphere, as well as the different representations of updraft velocity during cirrus formation. However, a dominant source of uncertainty is related to the aerosols ice nucleation properties (INP). Soot assumed to be efficient nucleation particles may result in a significant negative forcing (e.g. Penner 2018 on Figure 6) due to reductions in ice crystal number in regions dominated by homogeneous freezing. Less negative value can be obtained if secondary organic aerosol are already present in the atmosphere. Soot ice nucleation properties have been studied in laboratory but results are diverse and uncertain. According to Lee et al. [2], in

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

CLEAN AVIATION

Co-funded by the European Union

terms of the aerosol–cloud interactions of soot, soot particles are not efficient ice nucleating particles (INPs) for cold mixed-phase clouds >235 K but there is evidence that at very cold temperatures soot that has been processed by contrails (and latter sublimated) can be an INP through the pore condensation and freezing mechanism. The mechanism is improved by ozone oxidation but is in competition with coating of soot particles by sulphuric acid during ageing, which deactivates their ice forming capability. The uncertainties on the actual in-flight emissions of soot of aircraft engine mentioned in section 2.3 is also to be considered here. In [2], Lee et al. underlined that soot is common to both contrail cirrus and aerosol interaction with cirrus and that the aerosol–cloud interaction of aviation soot in global climate modelling studies remains unresolved. They concluded that “until the latter forcing is better understood, any efforts to reduce soot emissions (with the prime purpose of reducing contrail cirrus forcing, either through operational means or changes in fuel), will, on current understanding, have a net uncertain climate outcome”.

Although available results do not yet support a best estimate for sulphates aerosol-cloud effect, Lee et al. suggested that the sign of the forcing would be negative as for the aerosol-cloud interactions of other anthropogenic sources of sulphate aerosol.

A last remark is that there seems to be a limited number of teams carrying out research on this topic, which is a weakness for confronting results and converging towards a reliable assessment.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

3 Mitigation strategies for non-CO_2 effects

As already underlined, non-CO_2 effects do not depend primarily on the fuel burn of the aircraft but on atmospheric conditions, as well as location and time of the emissions release. Accordingly, their mitigation calls for specific approaches, differing from the long-lasting effort of aviation to reduce its fuel burn and CO_2 emissions. Potentially, a compromise could even be required between CO_2 impact and non-CO_2 effects.

Mitigating non-CO2 effects has been addressed since about 20 years already, with an increasing interest over the last years and a dominating focus on contrail avoidance, although other non-CO_2 effects have been considered in some studies.

In the next sections, we will first review the main strategies that have been proposed and then address the main challenges faced for implementation.

3.1 Proposed strategies for mitigating non-CO_2 effects

Based on the Schmidt-Appleman criteria, Gierens et al (2008) [36] analysed the different possibilities to avoid the formation of contrails. The Schmidt-Appleman criterion states that ice crystal form by water condensation on particles present in the flow and that a contrail appears if, during the plume expansion process, the mixture of exhaust gases and ambient air transiently achieves saturation with respect to liquid water. This happens if the isobaric mixing line of the engine plume, in the water vapour partial pressure against atmosphere temperature diagram, crosses the water liquid saturation curve.

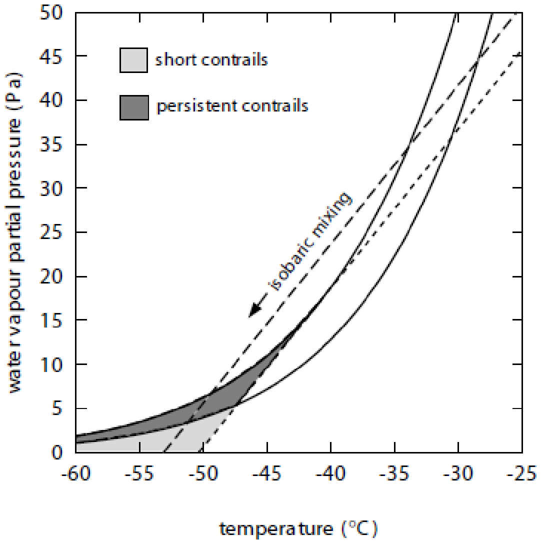

Figure 7: Illustration of the Schmidt-Appleman criteria (from Gierens et al.)

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

The slope of the mixing line is given by: $G = \frac{EI_{H2O} p c_p}{\varepsilon Q(1-\eta)}$

The thermodynamic nature of contrail formation makes impossible to preclude contrail formation by changing the character of the emitted particles (soot, solution droplets, particulate organic matter) or particle precursor gases (SO_2, SO_3). The change of these emissions only changes the properties of the contrail (particle size and number, optical thickness, etc.). Consequently, the only way to avoid the formation of contrail (for a given atmosphere) is to change the slope of the mixing line, G, by decreasing the water vapour emission index, EI_{H2O}, increasing the specific heat content of the fuel, Q, or decreasing the overall propulsion efficiency, η.

The concept of intercooled and recuperated engine [37] has been proposed to reduce the emission index of water vapour. The idea is to cool the exhaust air with an additional heat exchanger (cooled by bypass air) such that water vapour can condense in the unit. In this way, the emission index of water vapour can be substantially reduced, which helps to suppress contrails. The condensed water can be stored or poured away in the form of precipitating water drops or ice crystals. The condensation of water vapour can also be used to scavenge soot particles in the combustion gases and part of the condensed water can be injected in the combustion chamber to reduce NO_x emissions. This concept was recently studied and put forward by MTU with the “Wet Engine”, but was abandoned due to its complexity and the challenges associated with heat exchangers.

Gierens et al. further mentioned the use of fuel additives to reduce the condensation potential of emitted particles but concluded this was not a viable option. A temporary decrease of the propulsion efficiency when crossing ISSR has also been envisaged but involves significant fuel burn increase.

Currently, expectations to reduce or mitigate contrail impact are more focused on the use of sustainable aviation fuels to alter the properties of contrails and on operational measures to avoid their formation by avoiding to fly within ISSRs.

The impact of using sustainable alternative fuels has been addressed already in section 2.4.2. It is related to the decrease of aromatic content of purely paraffinic fuels that reduces soot emissions. This reduction of soot emissions translates in less condensation nuclei for ice crystal formation and, following, to larger crystals that lead to lower optical thickness and life duration of the contrail. This has been confirmed for example by the ECLIF measurement campaigns [14], during which reductions of ice crystal number by 45 to 74% were measured in flight for alternative fuel blends, with a reduced content of aromatics, leading to soot emission reduction between 45 and 53%. Simulations with a global climate model, initialized

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

with 50 to 90% lower ice number concentrations in seven minutes-old contrails, showed a non-linear reduction in the radiative forcing from contrail cirrus by 20 to 70%, mainly caused by the reduced initial ice numbers, and, in addition, by reduced contrail lifetime due to faster sedimentation of the larger ice crystals [38]. However, as seen in 2.4.2, beyond a certain level, the decrease of soot emissions is not a guaranty that ice crystal number decreases. The influence of fuel composition is still under investigation and final conclusion regarding the best fuel strategy is not available yet[28].

Fitcher et al. [39] studied the impact on contrail coverage and radiative forcing of globally decreasing or increasing flight levels for the current aircraft fleet. For the 1992 base year, they built emission inventories for scenarios with flight levels decreased by 2000 to 6000 ft, or increased by 2000 ft (when feasible for the considered aircraft). Simulations of contrail coverage were performed using the ECHAM climate model, including a contrail parametrisation. Compared with standard flight altitudes, decreasing flight levels resulted in a decrease of global mean contrail coverage (45% for the maximum altitude reduction of 6000 ft), while flying at higher altitude (+ 2000 ft) induced a relative increase of global annual mean contrail coverage by about 6 %. At regional scale, situations could differ significantly and opposite effects could be observed, in particular between tropical and mid-latitude regions, also depending on the type of traffic (short range or long-haul) in the considered area. Authors summarized the impact of altitude change as follows: “a downward displacement of air traffic resulted in a decrease of contrail coverage in the tropics, subtropics and the low-level air traffic in mid-latitudes, and an increase of contrail coverage in regions with prevailing high altitude air traffic in the mid-latitudes”. In addition, the effect of changing altitude considerably varied with the season. For example, contrail coverage decreased in nearly all region in July. Fitcher et al. assessed the associated change in radiative forcing. The maximum reduction of radiative forcing by contrails, -45%, was found for the scenario with minimum flight levels (- 6000 ft), which was similar to the relative changes of contrail coverage. The seasonal variation for radiative forcing with associated altitude changes resembled the seasonal variation of contrail coverage. However, flying at lower altitudes with current fleets induced an increase of fuel consumption (about 5.8% for a decrease of 6000 ft), which as not factored in in the study in order to assess a global climate impact. Considering the strong seasonal and geographical differences that were found, the authors concluded that a more sophisticated approach was desirable with adaptation to latitudes, seasons and short-term changes in atmospheric parameters.

Noppel and Singh [40] integrated flight altitude optimisation with regard to contrail formation in the design process of the aircraft. A particular aircraft, in terms of range (max range 8000

[28] Desulfuration and fossil fuel treatment to remove aromatics may be part of the strategy.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

nm), speed (255 m/s, about M=0.86 at 34 kft)) and payload (250 passengers), was optimised (using NASA FLOPS optimisation tool) for minimum block fuel consumption considering different altitudes (from 31000 ft to 37000ft, with a 34000 ft baseline)[29]. The change in contrail formation in terms of contrail-km formed was calculated based on the combination of air traffic data (for the considered type of aircraft) and meteorological data with 6 hour intervals for 2005. The baseline configuration exhibited the lowest fuel burn (+2.4% for 31 kft and +4.8% for 37 kft). For the considered aircraft, optimisation for lower altitudes tended to form more contrails: 58% more contrail for the 31 kft optimised aircraft compared to the baseline, 10% less for the 37 kft optimised aircraft[30]. The results suggested that if aircraft of the considered class were designed for higher altitudes, contrail occurrences would diminish slightly at a non-negligible fuel burn penalty. However, optimisation is dependent on design requirements, technology and where the aircraft are expected to operate. It would not necessarily result to higher flight altitude for all aircraft.

From Terrenoire et al. [24], it should also be noted that changing the aircraft flight altitude has a marked impact on the ozone and aerosol responses to emissions. Based on the emission inventory of the REACt4C project, they assessed the impact of a 2000 ft increase or decrease of the flight altitude for the May period, for which the impact of aviation emissions was found to be maximum. As chemical lifetime increases with altitude, a higher (resp. lower) flight cruise altitude increased (resp. decreases) the change in ozone mixing ratio by about 30% between 150 (~13300 m) and 250 hPa (~10400 m[31]) compared to the baseline scenario. Ozone radiative forcing increased (resp decreases) accordingly by 12% (resp 10%), while the effect of methane radiative forcing was limited. Increasing flight altitude also increased the BC and sulphate concentrations, while it had the opposite impact on nitrates. In their simulation, the net effect of decreasing the flight cruise altitude by 2000 ft was to increase the total negative forcing from -2 to -3.2 mWm^{-2} (+57 %). Increasing the flight altitude by 2000 ft decreased the negative forcing to -0.7mWm^{-2} (-65 %). The variation of the total forcing with flight altitude was dominated by the high sensitivity of the ozone positive forcing to the altitude of the perturbation, with the variation of the negative sulphate forcing being of secondary importance for these sensitivity simulations.

Williams et al. [41] explored altitude restrictions in the airspace, first based on monthly mean atmospheric conditions, then taking into account short-term variability. The studied altitude

[29] In the optimisation process, engine related technology parameters such as maximum turbine entry temperature, overall pressure ratio, fan pressure ratio were held constant for all altitudes.

[30] The authors indicated that further reducing altitude would certainly have had a positive impact for contrails but was increasing fuel too much.

[31] ISA atmosphere

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

restriction policy applied a single maximum cruise altitude restriction across the region analysed (here five European States), set every 6 h according to atmospheric conditions. The altitude restriction was selected from 5 options (31,000 ft, 29,000 ft, 26,000 ft, 24,000 ft or no restriction), and was chosen to maximise the ratio of reduction in contrail to the additional fuel required. Using a one-day traffic samples, the amount of contrail formed was estimated for different periods of the year (January, April, July and October). For January and April, restriction to 29000 ft or 26000 ft would increase average contrails produced. Cruise altitude had to be reduced to 24000 ft. For July and October, all restrictions decreased the average contrail formation (with however a large range of variation). For the proposed restriction policy, the altitude restriction were selected for each time period of the day to give the largest ratio of contrail reduction to carbon dioxide emission increase. The variable policy consistently reduced the amount of contrail predicted by the model by between 65% and 95% (on the contrary, fixed monthly restrictions could increase contrail production by up to 30% from January to April). Global fuel burn increased by 2.5 % (in July) to 7.25% (in January and April). In addition to the fuel burn and air traffic congestion penalties associated with imposing lower cruise altitudes, this variable policy presents additional difficulties associated with the transition between restrictions that change along the day.

Airspace restrictions were also investigated by Niklaβ et al. [42] taking into account both contrails and NOx impact through climate cost functions. This airspace restriction approach was proposed as an interim strategy, which could be implemented in the short term, considering that the implementation of weather-optimised trajectories required better weather prediction than available and faced challenges with air traffic control and management. In the proposed approach, highly climate sensitive regions were closed for a period of time (e.g. for several hours, a day, or a month) and affected flights were re-routed around them; contrary to approaches of climate optimized trajectories minimizing time and emissions in these regions. The climate cost of a single flight was measured by total climate change functions (CCF_{tot}) depending on location and time of CO_2 and non-CO_2 emissions. A threshold value of CCF_{tot} was defined in order to determine restricted airspaces (regions were restricted both in altitude and horizontal directions). The CCFs could be based on climatological mean data or weather forecasts and computed individually for each forcing agent and summed. If CCFs are based on weather forecast, restriction on periods of few hours are possible. However, considering the time and cost for computing CCF for actual weather forecasts, this option was not considered feasible in the near term. CCFs based on climate data were therefore proposed as a first step to test the concept of restriction, yet they did not allow shorter time resolution than one month. The approach was assessed on a flight from Helsinki to Miami based on the cash operating cost and the average temperature response metric over 100 years, ATR100, to aggregate CO_2 and non-CO_2 effects. Three different trajectories were simulated: a reference one, consisting of the great circle, a trajectory optimised with regard to both climate

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

and cost, and a trajectory optimised for cost taking into account the restricted areas for different threshold values. For the considered flight, the climate impact could be reduced, without any increase of cash operating costs, either by 12.0% by minimizing time and emissions in regions with high climate sensitivities, or by 8.7% by closing 28.8% of the total airspace. For a 2% increase of the cash operating cost, global warming could be reduced by 26.5% for the climate-optimised trajectory or by 21.9% with restricted airspace. Considering that severe area restrictions are probably difficult to implement, the concept required further investigation in a global network framework. As the climate cost function simulations are too computationally intensive for real-time calculation and thus cannot be applied operationally, van Manen et al. [43] proposed the use of algorithmic approximations of the global climate impact (i.e. algorithmic climate change functions - aCCFs). They approximated water vapour concentration changes from local aviation water vapour emissions, ozone changes from local NOx emissions and methane changes from local NOx emissions from instantaneous model weather data using regression analysis. They used the CCF data from the REACt4C European project to develop their aCCfs for the North Atlantic region. The aCCFs represented the CCFs with different accuracy for the different emitted species. The water vapour impact was represented with the highest accuracy, whereas the NOx emission effect on ozone had a lower accuracy. Further work was required to show that the use of aCCFs for climate-optimised aircraft trajectories was meaningful and would provide the expected result.

The various strategies presented till now are based on a global approach, imposing constraints – most often altitude restrictions – uniformly to all aircraft on more or less long time period. They avoid complex management at individual flight level but may impose constraints to an excessive number of flights and finally not be optimal from the climate point of view. Strategies have been considered also at individual flight level and can be classified into two categories: strategic, or pre-tactical, and tactical. In a strategic manoeuvre, contrail avoidance is planned at the level of flight preplanning, which means that the occurrence and location of ISSR must be predicted in advance (e.g. 12 h ahead or more) to allow for fuel, load, and route planning. In a tactical manoeuvre, rerouting is decided in flight to avoid the ISSR, which implies the capability to detect or predict in real time the occurrence of an ISSR ahead of the aircraft. However, till now, tactical approach has not really been studied in the reviewed literature.

An example of the strategic approach is given by Avila et al. [44]. Applied to the Contigus United States (CONUS) airspace, the proposed concept of operation is based on the fact that on the considered area, in average 15% of the flight produce contrails (the range being between 1.3% and 34.6%), with most of contrail generation located in south-east/mid-west and on the Pacific coast. The analysis of ISSR and air traffic distribution in altitude suggested that shifting flights to slightly higher latitude could significantly reduce contrail formation, whereas flying around contrails would be prohibitive considering their potential extent. Based

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

on hourly meteorological data over one year and a typical one day traffic, they assessed the benefit of increasing the flight cruise altitude by 2000 or 4000 ft at flight planning stage for the flights that would cross an ISSR. The results indicated an estimated average daily decrease of 50% of the number of flight forming contrails, with a 51% decrease of the associated contrail length, for a 2000 ft increment in Cruise Flight Level. A reduction of 92% of radiative forcing could be obtained by shifting by an additional 2000 ft those flights that were still forming contrails for an increment of 2000 ft[32]. These changes were considered statistically significant when compared to the original cruise flight level at the 99% confidence interval. The difference in fuel burn between trajectories with the original cruise flight level and trajectories with increased flight level were not statistically significant. Additional Fuel Burn for climb and descent was counter-balanced by the lower drag at higher altitudes for long duration cruise segments (the true air speed for cruise phase was kept corresponding to M=0.78). The study also determined that applying altitude change only during summer (the period most favourable for contrail formation) would allow to capture 66% of the previous benefit. Regarding the impact of changing flight altitude on fuel burn, Filippone [45] also suggested that, at the current level of technology, it is possible to guarantee a 3000 ft (~950 m) vertical flexibility at a cost of the order of 1% of additional fuel consumption, which could be recovered by appropriate management of the cruise Mach number.

Teoh et al. [46] assessed the benefit of a diversion limited to flights with the largest energy forcing, those generating 80% of contrail EF. For these flights, two alternative strategies were calculated with different altitudes, plus or minus 2000 ft (ISSR thickness being estimated to be about 1600 ft), and the trajectory with the lowest EF was selected. The resulting energy forcing and the impact on fuel burn was then assessed. The assessment was performed for flights over Japan for six one-week period from May 2012 to March 2013 based on ERA5 data. For this particular case, it turned out that 2.19% of the flights were responsible for 80% of the contrail EF. The proposed diversion strategy accounted for potential constraint in the ATM: at times of low traffic density (20:00 to 06:00), all of the selected flights were diverted; while a limited number of flights, ranging from a maximum of 1 to 10% of all flights in each time step, were allowed to divert when the traffic density was high but not at its peak (between 15:00 and 20:00). For the considered six weeks, a reduction of contrail EF by about 59% could be obtained by diverting only 1.7% of the flights. On average, contrail EF was reduced by 21.2% by diverting selected flights at night. Because of seasonal variations of the tropopause height, contrail EF was more efficiently reduced when the aircraft was diverted to a lower cruising

[32] In this study, there was no modelling of contrail characteristic with tools such as CoCip. An evolution of contrail width with time was considered and data from literature were applied for contrail optical depth, assuming spherical ice crystals with increasing radius over time.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

altitude during the summer months, and vice versa in winter. On average, the increase of fuel burn was about 0.27% for each diverted flight. Taking into account both CO_2 and contrail, and based on GWP_{100}, the overall energy forcing was reduced by 35.6%.

In the continuation of van Manen, Matthes et al. [47] proposed an approach for strategic flight optimisation based on aCCFs, pre-calculated from weather forecast data, to take into account both CO_2 and non-CO_2 effects beyond contrails. They developed a methodology for performing a multi-criteria environmental and climate impact assessment of aircraft trajectories within the SESAR (Single European Sky ATM Research project) Exploratory Project ATM4E (Air Track Management for Environment). Aircraft trajectories were optimized with respect to direct operating cost and climate impact simultaneously in the trajectory planning process. The provision of climate impact information to the flight planning tool relied on the application of algorithmic CCFs (aCCFs), which calculate climate impacts based on meteorological key parameters, e.g., humidity, temperature, and geopotential. They provided a quantitative measure of climate impact using standard climate metrics, such as the global warming potential (GWP) or average temperature response (ATR), derived from standard meteorological parameters. They were integrated into the overall objective function of the optimisation process, with varying weight attributed to the different components taken into account in this objective function. This allowed computing a set of distinct trajectories for an individual city pair. The methodology was applied in a case study for Europe based on the reanalysis of a real meteorological situation corresponding to 18 December 2015. An overall climate-optimization of the top-2000 routes was performed. The climate-optimised trajectories avoided areas prone to contrail formation, with high aCCF values, by flying slightly lower. Depending on the particular route and meteorological conditions along the trajectory, reductions were dominated by either contrail cirrus avoidance or the reduction in nitrogen oxides effects. Based on the ATR_{20} (a metric that emphasizes short term climate effects and therefore non-CO_2 effects), the optimisation could reduce the climate impact of the top-2000 routes by 46% for a fuel burn increase of 0.5%[33]. The analysis showed that mean flight altitude of the full traffic sample in the climate optimized case was about 5,000 feet lower (it could be noted that the fuel burn increase of 0.5% for this mean decrease of altitude looks quite small compared to the 5.8% increase for a 6000 ft altitude decrease pointed out by Fischer et al.). Yet, the study did not take into account the airspace structure or the ability to accurately forecast the weather conditions sufficiently far ahead for flight planning, which is a requirement to apply the optimisation.

[33] The paper does not say how speed or Mach number was constrained in the optimisation an does not mention consequences on travel time.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Another example of integration of contrail avoidance in the optimisation process for route planning is given by Frias et al.[48]. Using their Flightkeys FK5D commercial platform that calculates the cost optimal flight plan in real time, they implemented a strategy for contrail avoidance that mix individual trajectory optimisation and contrail avoidance region as hard restriction. Using CoCip, cost optimised trajectories were assessed against contrail formation. Those producing persistent contrail with a net positive energy forcing were then optimised (vertically or/and horizontally) to avoid contrail restriction areas. Final optimised trajectories were then again assessed against contrail formation. The approach was evaluated on 84 839 flights of American Airlines (a customer of Flightkeys) distributed over two periods of time, in June 2023 and January 2024. Key performance indicators were computed, including trip fuel, total cost of operation and flight duration, together with climate metrics, the energy forcing of the contrails and the GWP_{20}. Simulations showed that, with no contrail optimisation, 23.7% of flights formed persistent contrails and 13.7% formed warming contrails. Only 1.57% of the flight were generating 80% of the total energy forcing of contrails. After optimisation, the number of flights forming net warming contrails was reduced by 26.3% (apparently the tested strategy did not always succeed in avoiding contrails[34]) and the total energy forcing of contrails decreased by almost 73%. The overall fuel consumption increased by 0.11%, total flight time remained unchanged, and overall costs increased by 0.08%.

To complete this overview of strategies proposed for mitigating contrails or non-CO2 effects, it is worth mentioning some trials that have already been achieved, yet at limited scale[35].

A first one, described by Sausen et al. [51], was performed from January 2021 to December 2021 by DLR and Eurocontrol in the Maastricht Upper Area Control (MUAC)[36]. The objective was to demonstrate that persistent contrails could be successfully avoided for commercial flights in the real world. The trial focused on avoidance of persistent contrails that could be observed from surface and space, and did not consider other non-CO_2 effects nor the climate impact. A goal was in particular to fill the contingency table with correct and false prediction of persistent and non-persistent contrails. In order to compare situations with and without contrail mitigation, air traffic deviations were only implemented on odd days. The trial was mainly restricted to the hours between 16:00 and 22:00 UTC, to minimize the workload of the

[34] Authors pointed out that introducing contrail polygons as strict constraints for rerouting contrail Trajectories was a major limitation. This approach is simpler to implement. However, importing contrail forecast data as a continuous variable on a regular grid would facilitate a cost-based approach.

[35] In addition to the trials reported here, an additional one is being carried out by Thalès with Amelia, but has not been reported yet.

[36] Netherlands, Belgium, Luxembourg, north-west Germany, and the south-eastern part of the North Sea. MUAC represent 17% of all European flights.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

controllers. In addition, the trial was performed during a period of reduced air traffic due to the COVID-19 pandemic. Areas for contrail formation and persistence were determined based on the German DWD model ICON-Europe. Based on the predictions, the project team built a daily action plan indicating which levels should be avoided in each sector and at what time. Contrail avoidance was implemented only when the optical thickness of high altitude clouds was low enough to allow contrail analysis from satellite images. It was also not implemented if condition for contrails formation covered more than five flight levels or in case of adverse weather. A total of 212 aircraft were deviated vertically by 1000 ft or by 2000 ft, up or down, in order to avoid potential persistent contrails. The analyse of persistent contrail formation used images from the SEVIRI radiometer embarked on the geostationary MSG satellite, which allow identifying contrails older than 1 hour[37]. Over 11340 observations over 264 days, 6088 could be exploited to fill the contingency table (3398 for even days with no action, and 2690 for odd days with deviation). Unfortunately, only 23 flights were relevant of case for which persistent contrails were predicted and action decided. Over this 23 flights, five formed contrails, 18 not, meaning a ratio of 3.6, while for case with no action, the ratio between false positive (no contrail when contrails was predicted) and correct prediction (occurrence of contrails when predicted) was 1.2. For the authors this tends to show that the trial was successful. Considering the low number of deviated flights, they had to perform statistical tests to confirm the significance of the results. The authors also underlined the number of assumptions required for the evaluation of the trial and the involved uncertainties (errors of ISSR localisation and prediction, misdetection of contrails, low number of flights, etc.)

A second trials was reported by Sonabend et al. [52]. It was performed by Google and Breakthrough Energy together with American Airlines between January and June 2023 in the USA. Only 44 flights were concerned in a strategy consisting in rerouting 22 flights and keeping 22 flight unchanged as a control sample. The focus was only on the feasibility of rerouting with no evaluation of radiative forcing. The approach was a mix between pre-tactical and tactical rerouting. Candidate flights for rerouting were identified two days in advance based on weather forecasts from ECMWF and prediction tools for “contrail likely zones” (CLZ). They were round trips for which a CLZ was predicted near the destination airport. The avoidance manoeuver consisted in anticipating descending or delaying climb after take-off at destination airport. The day of the flight, pilots coordinated with dispatchers and air traffic control to make the recommended vertical flight adjustments based on updated predictions of CLZ. Prior to the departure of each participating flight, the outward flight was randomly

[37] However, due to the moderate spatial resolution of SEVIRI, observed contrails may consist of overlapping contrails, other cloud structures. Also spreading and overlapping contrail may have loosed their linear shape

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

assigned to either the control group that flew through the CLZ as originally planned, or the rerouted group that adjusted its flight to avoid the CLZ. The return flight was assigned to the opposite group to serve as a matched pair. The idea was that the same flight would flew the same atmospheric conditions within one or two hours, in order to identify confounding factors such as weather conditions or aircraft engines. CLZ were determined using both CoCip and a machine learning system trained on contrail detections and collocated numerical weather data[38]. Occurrence of contrails was checked using satellite data from GOES-16 (infrared false-color images). Four contrails were formed over 22 flights in the rerouted group against 11 in the control group (yet all these control flights were predicted to fly through a CLZ), with a 52% reduction in kilometres of contrails between the two groups. The fuel burn increase was 2% for the rerouted flights (which seems high compared to the flexibility put forward by Fillipone et al.). Although the sample of flights was quite small, the authors considered the result as significant based on statistical considerations and treatments. Yet, the sample looks quite small with regard to the multiple caveats they raised regarding the interpretation of the results (inaccuracy of weather forecast, uncertainties of CLZ prediction, possible missed contrails and mismatches in contrail attribution to a flight, etc.). The trial would need to be extended in future work to a larger number of flights, avoidance of CLZ along the flight and inclusion of radiative impacts.

As a synthesis of this review of proposed strategies for contrail avoidance or climate optimisation of aircraft trajectories, a number of observations can be made. First, there is no technical option at aircraft level to avoid contrail formation. Second, alternative fuels would not suppress contrail but may have a positive impact on contrail properties. Nonetheless, the ideal composition of the fuel is not yet well identified. Operational measures to avoid areas prone to persistent contrail formation is the main option today explored, which is in theory rapidly applicable with current aircraft fleet. Systematic and undifferentiated measures, such as reducing globally flight altitude or imposing global restriction would raise less operational difficulties but are not seen as the most efficient solutions taking into account seasonality and regional variability of ISSR. They also tend to induce higher fuel burn increase. Current orientation is more to act on flight likely to encounter ISSRs and even on flight with the highest climate impact. From this point of view, there is convergence between the published studies that a limited percentage of the flights (below 15 or 20%) would be responsible for most of the

[38] Dynamical proxies were used to improve a prediction model by training a neural network to predict contrail formation. For a given flight waypoint, the neural network takes as inputs not only the weather quantities directly related to contrail formation (humidity, and temperature) but other weather variables: wind velocity, relative vorticity, fraction of cloud cover, cloud ice water content, specific snow water content, and divergence.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

radiative impact of contrails. Accordingly, a significant impact could be obtained by deviating a limited number of flights. Preferred option is to change the flight altitude to avoid flying through an ISSR, with no consensus about whether the altitude should be decrease or increased (DLR studies favour decrease, while increase is more often encountered in US studies). Many studies conclude on a relatively limited impact on fuel burn at fleet level. Yet results are sometime contradictory (e.g. fuel burn increase between Fischer et al. and Matthes et al., or Sonabend et al. and Fillipone et al.) and it is not always clear which constraint was fixed on speed or Mach number in the optimisation process. In addition, not all studies include an impact assessment of climate impact and the impact on flight duration is not reported. From this point of view, it should be noted that the importance of arrival time may differ between companies: it is likely to be higher for “historical” companies compared to low-cost ones.

3.2 Challenges for implementing mitigation options

Balancing fuel burn increase with reduction of non-CO2 effects in a climate optimisation of aircraft trajectories first raises the question of the metric selected for translating non-CO_2 effects in CO_2 equivalent. As many assessments evidence a strong variation in the ratio between CO_2 and non CO_2 climate impacts when considering different metrics (see example from Borella et al. [49] on Figure 8), a strong fear is that the considered metric has a strong influence on deciding of a mitigating option for non-CO_2 effects and on the actual benefit of such decision.

In the analysis of their proposed approach for climate optimised trajectories, Matthes et al [47] assessed the robustness of the optimised route with regard to the metric selected in the optimisation function. They assessed whether the alternative solution had a lower climate impact under different climate metrics (ATR, GWP, GTP) and over different time horizons (20, 50 and 100 years) - a robust solution being characterized by providing a climate benefit for each metric. For a trajectory optimised using the ATR_{20} on three different city-pairs, the benefit was computed for all the other metrics and time horizons. All of the identified trajectories showed a reduction in total climate impact and, therefore, proved to be robust.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

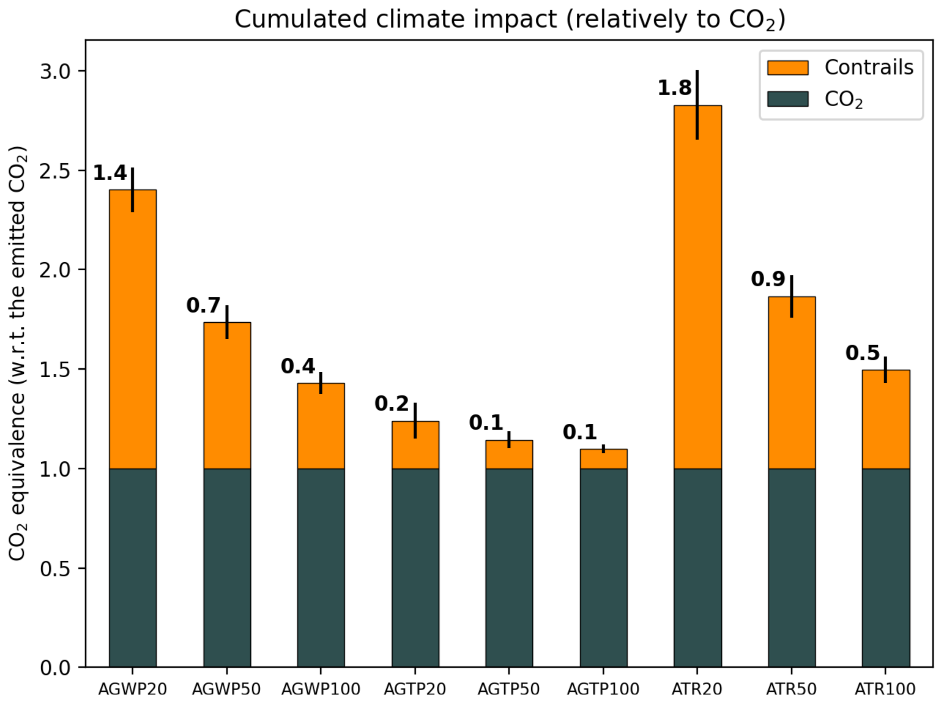

Figure 8: CO2 equivalence of a median North Atlantic contrail with a contrail efficacy of 0.37 (orange) compared to the emitted CO2 during the median flight (grey) when using absolute global warming potential (AGWP), absolute global temperature change potential (AGTP), and average temperature response (ATR) with time horizons of 20, 50, and 100 years. Error bars quantify the 1σ uncertainty arising from the physical climate and carbon cycle of OSCAR, rather than uncertainties in the contrail radiative forcing and efficacy. The values at the top of each bar are the ratio of non-CO2 to CO2 effects for each metric choice. (From Borella et al.)

Borella et al. [49] also investigated the impact of the metric on the decision to reroute a flight in order to avoid contrail formation for two sectors of the North-Atlantic traffic in 2019. Using the dataset from Teoh et al. [50] providing fuel consumption and contrail energy forcing per flown distance, they computed, with the reduced-complexity Earth system model OSCAR, the time evolution of the globally averaged radiative forcing[39] and the globally averaged surface temperature change that occurs in response to that forcing for each individual flight. The benefit of rerouting was assessed using different metrics (AGWP, AGTP and ATR for time

[39] To account for the tropospheric and stratospheric adjustments triggered by the contrail climate forcing, as well as the ability of contrail to change surface temperature, a contrail efficacy of 0.37 was used for all contrails. A sensitivity analysis showed that the value of the efficacy has limited impact on the results.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

horizon from 20 to 100 years) for different associated increases of fuel burn, assuming a fully successful contrail avoidance. They found that, for a given CO_2 scenario and for most contrail-forming flights, all CO_2-equivalence metrics agreed that rerouting would benefit climate. Disagreements between CO_2-equivalence metrics happened for about 10% of the flights, which formed low-energy contrails that did not contribute much to climate damage. This was because when a persistent warming contrail is formed, this contrail is often orders of magnitude more warming than the potential additional emission of CO_2 to avoid its formation. On the contrary, the benefit perceived from rerouting the flight was strongly dependant on the metric (short term horizon metrics gives a much higher benefit).

From these two publications, it turns out that the choice of the metric and the discrepancies between the benefit assessed by the different metrics would not be an obstacle for the implementation of climate optimisation of flights.

A second aspect of mitigation strategies regarding contrails is the ability to predict the appearance and location of ISSR, which is a prerequisite for the most efficient strategies that aims at limiting rerouting to flights actually producing high impact contrails. During the workshop organized on non-CO_2 effects by Eurocontrol and CANSO in November 2023 [40], the inability of weather prediction models to predict ISSR was pointed out by scientists as a major barrier for contrail avoidance. Hofer et al. [53] noted that the prediction of ISSR, and therefore of persistent contrails, is challenging for multiple reasons. The main one is the strong variability in the water vapour field in the atmosphere, because water is present in three aggregate states and is involved in chemical and aerosols processes. In addition, there is little measurements of humidity at aircraft cruise level for data assimilation that is necessary to keep the simulation of a complex system close to reality. Such measurement are not possible with satellites as their vertical resolution is too low, and the number of aircraft equipped with humidity sensors is low[41]. A third reason for the weakness of models to predict ISSR is that parameterisations of ice cloud physics in weather models are generally kept simple enough in order not to spend too much computing time for a part of the atmosphere that so far has usually not been the main focus of weather prediction, with no influence of ISSR on ground weather. Many general circulation models (GCM) do not permit supersaturation with respect to the ice phase. In most large-scale GCMs, ice clouds artificially form at ice saturation due to a saturation adjustment scheme that converts any excess water vapor above saturation directly into an ice mass mixing ratio [54]. This does not allow the prediction of contrails.

[40] EUROCONTROL-CANSO Sustainable Skies Conference – Brussels, 8 November 2023.

[41] The IAGOS fleet of aircraft flying routinely with humidity sensors is limited to nine airplanes.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Rose Tejwani et al. [55] compared the predictions of ISSR from three atmospheric database: the NOAA's Rapid Refresh (RAP) forecast system, the ECMWF ERA5 reanalysis database and the Integrated Global Radiosonde Archive (IGRA), a comprehensive dataset of atmospheric soundings collected from over 2700 radiosonde and pilot balloon stations around the world. They found significant discrepancies between the three sources. Over a 18-month period at the same geographic location, the radiosonde data (IGRA) and the two atmospheric (RAP and ERA5) databases identified ISS conditions on 44%, 47%, and 77% of the days, respectively. Analysis by flight levels showed further differences. Over 593 days, IGRA data showed the greatest number of days, 116, on which an ISSR occurred at FL 340. The greatest number of days on which an ISSR was recorded was 116 at FL 340, 133 at FL 320 for RAP and 252 at FL 330 for ERA5. The forecast and reanalysis databases overestimated ISSRs compared to the radiosonde data[42]. This was confirmed for ERA5 by other studies [54].

Thompson et al [54] compared the ability of the two most-often used operational global weather prediction models (the Global Forecast System, GFS, from NOAA and the Integrated Forecast System, IFS, from ECMWF) and one non-hydrostatic mesoscale research model (the Weather Research and Forecasting model, WRF[43]) to predict RH_i as measured in situ by radiosondes and IAGOS aircraft. The research model was applied regionally, with a higher spatial resolution (5 km against 9 to 13 km for IFS and GFS) and was a version of the WRF model adapted by the authors for a better representation of supersaturation (increased vertical resolution and explicit modelling of cloud hydrometeors). Comparisons were done each Wednesday from February to December 2022. IAGOS data were only used to compare frequency distribution of ISSR with the other data, without time-matching with the radiosonde and numerical prevision models (NWP). Neither GFS nor IFS properly reproduced the radiosonde observed frequency distribution of relative humidity with respect to ice (RHice)[44], in particular near 100% where the models exhibit pikes, while radiosonde and IAGOS observations were rather consistent (Figure 9). The WRF model upgraded with multi-moment cloud physics and high spatial resolution (S-WRF) better reproduced the observed relative frequency distribution of RH_i, with no overshoot near 100%[45]. Coincidence scores were computed between radiosonde measurements and NWP predictions in the neighbourhood for

---

[42] The authors underlined a key limitation of the analysis which is the need for interpolating data on temperature and RHi to analyse the data at 1000-foot increments. Additionally, radiosondes drift over time, limiting the spatial consistency of the ground data from IGRA.

[43] NCAR

[44] In particular, GFS strongly fail to predict RHi above 100%

[45] The pike near 100% is a consequence of the use of a nearly instantaneous adjustment of humidity towards 100 % by growing existing ice crystals or nucleating new ice, as mentioned earlier.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

the prediction of the occurrence of an ISSR (defined by RH_i > 100%). The IFS and the adapted WRF model obtained close scores (respectively 0.62 and 0.66 in a neighbourhood of 27 km, 1 meaning a perfect match with observation), whereas GFS had a very low score due to its inability to predict supersaturation. The radiosonde dataset showed that ISSR conditions (RHi > 100 %) occurred 11.5 % of the time in the studied region in 2022. S-WRF and IFS had an ISSR frequency of 13.5 % and 14.6 % respectively. Thompson et al. noted that, at typical contrail altitudes, the prediction of RHi by NWP models will always have a high standard deviation of bias (forecast – observation) due to models having relatively coarse vertical level spacing compared to the often thin layers of observed supersaturation.

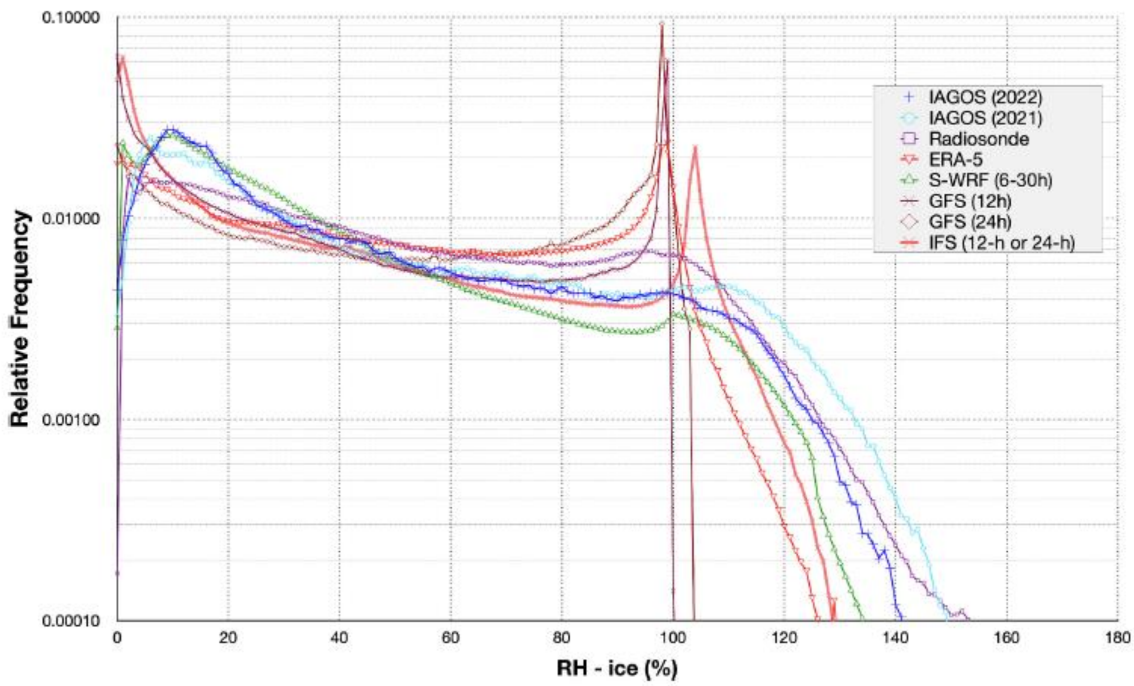

Figure 9: Relative frequency histogram of RHi for 253 IAGOS flights from Jan to Jun 2021, as well as for 383 IAGOS flights from Jan to Dec 2022, as compared with S-WRF, GFS, IFS forecasts as well as ERA5 reanalysis data – Thompson et al. [54]

In spite of the previous discrepancies between observations and models on Rhi and ISSR occurrence, Thompson et al. argued that the ability of the model to predict the non-occurrence of an ISSR is equally important for contrail avoidance. For their S-WRF model, the prediction matched 90.7 % of the observed non-ISSR and 45.9% of the ISSR conditions. The later corresponds to a false negative rate of 54.1% representing missed opportunities to avoid a contrail. On the other hand the false positive rate was 9.3%, which means that a small number

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

of rerouting based on the prediction would lead to reroute an aircraft in an ISSR area. The conclusion of the authors was that, although NWP prediction were not perfect, their performance were good enough to provide on balance a net climate benefit from contrail avoidance strategies. From their point of view, as the warming impact from contrails is so large, the benefit of doing deviations based on NWP forecasts performed by S-WRF or IFS far outweighs the negative consequences of penalty emissions and relatively small prediction errors.

To conclude on the capability of NWP to predict ISSR, it should be underlined that research is going on to improve models with for example work of Meteo France in the context of the SESAR CICONIA project or the development of DWD on their ICON model.

The third challenge raised by climate optimisation of aircraft trajectories is the impact on the air traffic management and the risk of congestion of the airspace, increased flight time, delay at arrival and associated penalties for airlines. Routes optimised for minimum climate impact are planned to avoid airspace with warming impacts, and possibly also to cross areas with cooling effects. This leads to a significant redistribution of air traffic with potential increase and saturation in limited areas, therefore generating air traffic complexity with increased number of conflicts and threats for safety. Studies presented in section 3.1 do not include operational aspects, or only very weakly. In addition, a trial such as the one performed by the MUAC ATC took place at a period during which air traffic was still strongly affected by COVID 19 and flight deviations were only implemented on some periods of the day for which traffic was not too heavy.

A recent paper by Baneshi et al. [56] addresses the issue of managing the complexity for ATM of implementing climate optimised trajectories and presents a cooperative decision-making framework employing multi-agent deep reinforcement learning to plan operationally feasible climate-friendly routes from the perspective of the air traffic management system. In the proposed framework, each aircraft is an agent tasked with making critical decisions about its flight profile, aiming to cooperatively avoid conflicts with other aircraft in the airspace (the airspace being an environment with N decision-makers in a cooperative game where the efforts of individual agents contribute to the overall goal of the system). Two primary objectives guide each agent: (1) reducing the potential conflicts between flights and (2) maintaining new trajectories as closely as possible to the climate-optimal routes. This requires effective communication between aircraft to inform each aircraft about its surrounding traffic. The modification of aircraft speed profiles is used as the main action for agents to avoid conflicts consisting mainly in potential violation of separation distances (vertically or horizontally)[46]. The

[46] The arrival time is not a constraint in the optimisation but a result.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

climate optimisation of routes is based on the aCCFs to include impacts of CO_2, contrails, CH_4, ozone and water vapour, and use a weighting between operating cost and climate impact quantified through ATR20. The authors applied the methodology on the case study of the air traffic on December 2018 within the European Civil Aviation Conference (ECAC) airspace, for flights operating between 12:00 and 14:00 UTC. Weather information from ERA5 reanalysis were used[47]. Maximising the climate weight in the optimisation increased traffic density in areas where cooling contrails formed, as well as the operating cost due to longer routes. A critical increase in potential conflicts was observed by adopting trajectories with higher climate impact mitigation. The proposed methodology was successfully applied to reduce the number of conflicts, yet at the expense of an increase of operational cost (up to 1.5%) and a decrease of climate benefit (bellow 5%). As part of the limitations of the approach, Baneshi et al. mentioned the restriction to speed adaptation, which does not allow to avoid all type of conflict (e.g. head-to-head conflicts) and the need to consider other indicators than the number of potential conflicts to relate the manageability of air traffic. In addition, this study was conducted within the context of a futuristic, fully free-routing airspace, where both the lateral path and vertical profile can be freely optimized. The benefit would be lower if taking into account current structured airspace.

How to practically implement climate optimisation of aircraft route in the ATM definitively appears as a critical research challenge for the coming years. By the way, proposing and testing a concept of operation for climate optimised route is currently the objective of the European CONCERTO project carried out within SESAR JU.

In the current effort for mitigating non-CO_2 effects, a major focus is contrail avoidance. However, some authors also attempt to include the other non-CO2 effects and in particular the impact of NOx. This raises an additional challenge regarding how to include these effects in an optimisation criteria as their relation with the atmospheric conditions on the aircraft trajectory are less straightforward and sensitive regions are more difficult to identify. In most attempts, this has been done by using cost climate function (CCF), and more precisely their derivative the algorithmic cost climate function (aCCF), as the calculation of CCF is too demanding for an operational use.

CCF were introduced in the European project REACT4C and described by Grewe et al. [58]. The project aimed at quantifying the variability of non-CO_2 effects and developing strategies

---

[47] In the proposed methodology, mean values of the aCCF are computed based on an ensemble of weather forecasts. As future development, the authors suggests integrating all possible realizations of meteorological conditions (i.e., ensemble members) into the optimization process, enabling a probabilistic representation of climate effects and conflicts

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

to optimise aircraft route in order to minimise these effects. The CCF modelling approach links potential emissions at locally and temporarily confined regions to their climate impact, measured with climate metrics. CCF characterise the climate impact per unit of the various emissions. They were developed concentrating on the North Atlantic region (including most of Europe and North America). A representative one-day weather pattern was selected for each type of selected weather pattern for the region[48]. For this weather pattern, the global climate impact of an emission was computed with a chemistry-climate model (EMAC in the present case) on a time-region grid that coverered the flight tracks over the North Atlantic and the main cruise levels. These climate impact data on the time-region grid were interpolated to the grid and then gave the final climate cost function grid. The processes taken into account were ozone formation, methane loss, methane-induced ozone change, contrails (including the spread into cirrus), water vapour and carbon dioxide. The approach could not be validated (most of the effects were not yet measured or are per se not measurable). Instead the results were compared with earlier modelling studies, mostly on the soundness of the results (no direct comparison being possible).

aCCFs are algorithmic approximations of the CCFs to represent the correlation of meteorological parameters (e.g. temperature and geopotential) at the time of emission and the respective average temperature response over a time horizon of 20 years (ATR20). Since they are essentially mathematical approximations, obtained by regression methods, they can be quickly implemented in numerical weather prediction (NWP) models, in order to relate the meteorological conditions seen by a particular flight to its climate impact. Developed initially by van Manen et al. [43], they are being further developed [59]. The quality check of the aCCF model was done compared to results from literature for O_3, CH_4, H_2O and contrail cirrus, mostly on trends rather than on quantitative results. Yin et al. [59] considered that the comparisons confirmed that the aCCf can predict the characteristic patterns of ATR20 from H_2O, NOx-induced O_3; and contrail cirrus. The NOx-induced CH4 pattern showed a slight discrepancy in terms of latitudinal variabilities when compared to previous studies. However, since the value of CH_4 aCCF is about 5 times smaller than the O_3 aCCF, they considered the mismatch of CH_4 aCCF to be of minor importance. The aCCF version presented by Yin et al. were considered as prototypes and on-going research activities, facing different uncertainties and limitations. Being developed for the North Atlantic flight corridor for winter and summer, they might not be extrapolated to other regions and seasons. A concept of “robust” aCCFs, integrating information about uncertainties arising from low-level understanding of climate science, was under development at time of publication.

[48] Eight patterns were considered, three for summer, five for winter.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

As a conclusion further work and validation of the concept of aCCFs seems to be required before operational use for climate optimisation of aircraft routes. A general remark is that the approach seems attracting for operational use but piles multiple layers of approximations, starting from a basis, the climate impact assessment of aviation, which is already uncertain. The development of concurrent approaches is also certainly desirable.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

4 RESEARCH ROADMAP FOR THE CLIMATE IMPACT OF AVIATION

In accordance with the analysis presented with the two previous chapters, the proposed research roadmap is articulated around two major objectives:

1. Reducing the uncertainties on the assessment of the impacts of non-CO_2 effects on climate;
2. Developing and implementing strategies for reducing aviation climate impact taking into account both CO_2 and non-CO_2 effects.

4.1 Reducing the uncertainties on the assessment of non-CO_2 effects

Improving the prediction of the impact of non-CO2 effects first goes together with **a general effort to improve climate modelling**. Although this research axis is not directly relevant to a sectorial initiative, some specific needs can be highlighted regarding aviation.

Of particular relevance for aviation and contrails, **a major scientific bottleneck to address in climate modelling is the statistic representation of clouds and of aerosols** that does not allow a satisfying representation of their properties, interactions and associated feedback processes.

In that field, increased resolution allowed by the progress of HPC is likely to bring significant advances. This progress shall be accompanied at research level by works to adapt parametrisation in climate models to this increased spatial resolution. Machine-learning technique is also an axis of work to improve the representation of sub-grid phenomena. Such approach is currently disruptive in weather forecasting and its introduction in climate modelling has started [57]. Based on reanalysis, it requires massive collection of data over long time periods for climate application. Yet, the benefit can be significant for downscaling approaches that can be established over shorter time periods and applied in climate models.

Regarding contrails and contrails-cirrus, **a specific challenge is representing supersaturation in climate model**. This in particular requires acquiring observational data on temperature and humidity at high altitude both for model improvement and validation. Effort should be done to develop humidity sensors able to measure low level of humidity (down to 10 ppmV) with high accuracy (about one ppmV) and that can be used routinely and implemented extensively on commercial aircraft. In a longer time perspective, developing satellites with an improved vertical resolution should be considered. **Improving the knowledge of atmospheric turbulence at mesoscale** is another important axis for the

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

prediction of contrail life, which requires specific measurements that are today difficult and necessitate research and development.

Last, the **calculation of the radiative transfer of clouds, and particularly contrail and contrail cirrus for aviation, is a major scientific bottleneck** to assess the impact of contrails and contrail-cirrus, on which research should be dedicated. This includes reducing the variability in results among various existing models, especially for large zenith angles, better characterising shapes and shape evolution of ice crystals in contrails and **progressing on experimental characterisation of clouds radiative effects** for model validation.

In parallel to the improvement of GCM and ESM, **improvement of reduced climate models shall be pursued** to allow sensitivity and scenario analyses, as well as assessment of individual flights in the context of non-CO_2 effects mitigation strategies or regulatory measures (e.g. potential inclusion of non-CO_2 effects in EU emissions trading scheme – ETS). A larger scope of uncertainties shall be included in these models that should also be validated on a larger number of situations. In addition, these models are not able to take into account feedbacks effects for the various non-CO_2 effects.

At the starting point of any assessment of non-CO_2 effects is **a precise knowledge of aircraft emissions**. With the appearance of situations where soot particles are no longer the main condensation nuclei for ice crystal formation, additional needs for engine emission characterisation appear. This includes species such as organics that are today not differentiated or electric charges in the engine plume. Better characterising emissions would also be beneficial for studying the evolution of NOx in the plume and therefore of their climate impact. Further work is also needed on the transposition of emissions from ground measurement to flight, especially for NOx in case of lean burn combustors and for soot. The variability associated with the fuel properties, which will be increased with the introduction of sustainable aviation fuels, seems more difficult to tackle at general inventory level. At individual flight level, it would require a characterisation of the fuel up-loaded in the aircraft or a fuel quality sensor on board the aircraft. More generally, although quick progress is being made today, the understanding of the fuel and emissions influence of ice crystal formation still need to be further investigated.

Further, **in global assessment with GCM, the initialisation of contrails shall be more differentiated** to account for the various cases of aircraft emissions and associated ice crystal characteristics, for the actual level of supersaturation, and maybe also for aircraft characteristics. It is also important to use a timely resolved inventory.

Regarding NOx, the differences observed between the various chemistry models are still not understood and require further investigation. Even more important is **the issue of the attribution method of NOx impact together with the steady state assumption**, which

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

together lead to a much higher impact of NOx. The impact of non-linearity and attribution of radiative impacts to aviation should be further investigated with other models. Additional axe of work is the modelling of NOx chemistry within aircraft plumes and rapid adjustments.

The topic of **aviation interaction with natural clouds** also clearly needs more research by an increased number of teams so that comparison and cross-checking of results is possible. Beyond the weaknesses of cloud and aerosols representation in climate models, a major scientific bottleneck is the **knowledge of the properties of aerosols after a long stay in the atmosphere**. How to perform experimental data acquisition in this domain is a major challenge.

4.2 Developing and implementing strategies for mitigating non-CO_2 effects

From the overview provided in chapter 3.1, a number of strategies have already been studied and approach for taking into account non-CO_2 effects integrated in flight optimisation tools. The avoidance of contrails appears as the priority because of its large impact but also because of more straightforward applicability. Accordingly, two major challenges emerge for further research.

The first one is the **prevision of ISSR by weather forecast tools**. The work already undergoing to improve forecast capability should be pursued. There is a clear need to support this work by increasing the collection of atmospheric data by aircraft. For that, a reliable and robust sensor needs to be developed, which could embark on a large number of aircraft.

The second challenge is related to the **practical implementation of route climate optimisation in the context of actual air traffic and ATM**. To date, this has been weakly addressed by literature and is clearly a major topic for research and experimentation in the coming years.

In parallel, work shall be pursued to **improve automatic contrail detection on satellite images** in order to be able to check the reliability of prediction models and avoidance strategies. This is also needed in the context of the MRV implementation (and later in case of inclusion of non-CO_2 effects in the EU ETS). Detection shall also be extended to contrail-cirrus that contributes most to climate impact.

Beyond these two axes, **research shall be pursued on approach allowing to take into account other non-CO_2 effects**, in particular NO_x. aCCF concept should be further investigated and validated, while other approaches should also be considered.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

5 THE IMPACT OF AVIATION ON LOCAL AIR QUALITY

5.1 Pollutants and their impact on communities and environment

In recent years, a number of researchers have found an association between aviation emissions and potential adverse impacts on the environment and human health, shedding light on deteriorated ambient air quality by massive amounts of air pollutants emitted. Thus far, aircraft engines are considered to be one of the major sources of both gaseous and particulate pollutants at the airport (Masiol and Harrison, 2014). Various campaigns have reported both physical and chemical properties of particulate and gaseous emissions (Kinsey, 2009; Kinsey et al., 2010, 2011; Mazaheri et 57 al., 2011; Hudda et al., 58 2016). Aircraft activities, particularly landing and take-off (LTO)[49] cycles (USEPA, 1992), generate a large amount of harmful air pollutants, among which nitrogen oxides (NOx), sulfur dioxide (SO2), carbon monoxide (CO), hydro-carbons (HC), unburned or partially combusted hydrocarbons also known as volatile organic compounds (VOCs) and black carbon (BC) have been recognised (Song and Shon, 2012). These emissions interact with each other and adversely impact the ambient atmospheric environment, leading especially to haze or smog weather at the ground level (Mahashabde et al., 2011) and a long-range effect on the ozone layer (Janić, 1999; Brasseur et al., 1998).

However, several questions still remain to be answered regarding the chemical composition of aircraft plumes, and the health risks associated with the exposure to the pollutants originating from airports in neighbouring communities, particularly those originating from the exposure to particulate matter (PM). Airports' contribution to primary and secondary inhalable and fine particulate matter (PM10 and PM2.5, mass of particles with aerodynamic diameters <10 µm and <2.5 µm, respectively) make them a driver of the air quality in cities and a significant issue for the local air quality management. Extended exposure to these harmful air pollutants (particularly PM2.5) seriously threatens human health, particularly with respect to heart and lung diseases (Boldo et al., 2006; Franklin et al., 2007; Kampa and Castanas, 2008),

[49] All activities near the airport that take place below the altitude of 3000 ft (914 m). LTO therefore includes taxi-in and out, take-off, climb-out and approach-landing.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

immune system impairments, cancer, and premature death (Yim et al., 2013; He et al., 2018; Jonsdottir et al., 2019).

5.2 The state of the art: evaluating emissions

ICAO, EPA and EEA/EMEP employ three different methods for evaluating emissions from aircraft engines. The pollutant emissions of NOx, CO and HC can be approximatively reproduced by all methodologies, while only EEA/EMEP Tier 2 and 3 methodologies can consider all pollutant emissions. In particular, ICAO considers the pollutant emissions of NOx, CO, HC, SO2, CO2 and Sox, and EPA VOC, NOx, CO and SO2, whilst EEA/EMEP considers pollutant emissions of CO, NOx, NMVOC, CH4, N2O, PM2.5, CO2, SO2 and PM10. However, there is still a gap in knowledge about airport-related PM emissions (see, for instance, Masiol and Harrison, 2014), in terms of (i) apportioning PM to individual sources at airports, (ii) specifying their chemical composition, and (iii) the wider impacts of PM on local communities.

5.2.1 ICAO

ICAO has covered three approaches to quantifying aircraft engine emissions, two in detail and one in overview: simple approach, advanced approach and sophisticated approach (ICAO, 2007a,b).

a) Simple Approach requires the minimum amount of data and provides the highest level of uncertainty often resulting in an over estimation of aircraft emissions. This approach considers the emission pollutant of NOx, CO, HC, SO2 and CO2. The formula used for calculating pollutant emissions does not account for specific engine types and operational modes as it assumes that the conditions under study are the same or similar to the default data being used

$$Emission\ of\ species\ X\ (kg) = \sum (Number\ of\ LTO\ cycles) \times (Emission\ Factor) \quad (1)$$

b) Advanced approach reflects an increased level of refinement regarding aircraft types, emission indices calculations and Time-In-Mode (TIM). This approach represents a

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

more accurate estimation of aircraft engine emissions compared to the simple approach and considers the pollutant emissions of NO_x, CO and HC.

$$E_{ij} = \sum (TIM_{jk} \times 60) \times (FF_{jk} /1000) \times (EI_{jk}) \times (NE_j) \qquad (2)$$

Where E_{ij} represents the total emissions of pollutant i, in grams, produced by aircraft type j for one LTO cycle, EI_{jk} the emission indices for pollutant i in grams per pollutant per kilogram of fuel (g/kg of fuel), in mode k (e.g. takeoff, climb out, idle and approach) for each engine used on aircraft type j, FF_{jk} the fuel flow for mode k, in kilograms per second (kg/s), for each engine used on aircraft type j, TIM_{jk} the time-in-mode for mode k, in minutes, for aircraft type j, and NE_j the number of engines used on aircraft type j.

c) Sophisticated approach is expected to best reflect actual aircraft emissions. It is often not exploited in practice and should be considered in order to account for particulate matter species, that is thought to be the most impacting pollutant in terms of effectiveness on communities' health. Use of this approach requires a greater knowledge of aircraft and engine operations and the use of propriety data or models that are not normally available in the public domain. The actual and refined data required for the analysis is obtained from real-time measurements under this approach. The data and information typically required for computing aircraft engine emissions using the sophisticated approach are listed as follows:

- Times-in-mode measurements for different aircraft/engine types under different load, route and meteorological conditions.
- Reverse thrust deployment measurements for different aircraft/engine types under different meteorological conditions.
- Airport meteorological conditions, where modeling of aircraft/engine performance accounts for variation in meteorological conditions.
- Frequency and type of engine test runs.
- Frequency of operational aircraft towing.
- Airport infrastructure and constraints (e.g. runway length).
- Typical or actual throttle settings used during reverse thrust operation.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

- Actual aircraft/engine configuration data.
- Actual fuel flow data.
- Actual idle engine-type idle speeds.
- Typical or actual throttle settings for approach take off and climb out (e.g. reduced thrust take-off procedures).
- Approach and climb profiles.
- Frequency of less than all engine taxi operation.

5.2.2 EPA

EPA recommended emissions calculation methodology for a given airport in any given year and can be summarized in six steps:

- Determine the mixing height to be used to define a LTO cycle.
- Determine airport activity in terms of the number of LTOs.
- Define the fleet make-up at the airport.
- Select emission factors.
- Estimate TIM.
- Calculate emissions based on the airport activity, TIM, and aircraft emission factors.

Steps two through five are repeated for each type of aircraft using a given airport. This methodology is essentially the same as that used in the FAA Aircraft Engine Emissions Database (FAEED) model (EPA, 1999). For Time in Mode calculations, the duration of the approach and climb-out modes depends largely on the mixing height selected. EPA guidance provides approach and climb-out times for a default mixing height of 3000 ft, and a procedure for adjusting these times for different mixing heights. The adjustments are calculated using the equations (EPA, 1999)

Climb out:

$$TIM_{adj} = TIM_{adj} \times \left[\frac{Mixing\ Height - 500}{3000 - 500}\right] \quad (3)$$

Approach:

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

$$TIM_{adj} = TIM_{adj} \times \left[\frac{Mixing\ Height}{3000}\right] \quad (4)$$

Where the mixing height is expressed in feet. For emissions calculation, the total emissions per LTO cycle for a given aircraft type is calculated using the following equation

$$E_{ij} = TIM_{jk} \times \frac{FF_{jk}}{1000} \times \overline{EF_{ijk}} \times NE_j \quad (5)$$

Where, similarly to the ICAO model, TIM_{jk} represents the time in mode k (expressed in minutes) for aircraft type j, FF_{jk} the fuel flow for mode k (in lb/min or kg/min) for each engine used on aircraft of type j, $\overline{EF_{ijk}}$ the weighted-average emission factor for pollutant i, in pounds of pollutant per 1000 lb of fuel (or in kilograms pollutant per 1000 kg fuel) for aircraft type j in operating mode k, and NE_j the number of engines on aircraft type j. The weighted-average emission factor per 1000 lb of fuel is calculated as follows

$$\overline{EF_{ijk}} = \sum_{m=1}^{NM_j}(X_{mj} \times EF_{imk}) \quad (6)$$

where EF_{imk} is the emission factor for pollutant i, in pounds of pollutant per 1000 lb of fuel (or kilograms pollutant per 1000 kg fuel), for engine model m and operating mode k, X_{mj} is the fraction of aircraft type j with engine model m, and NM_j is the total number of engine models associated with aircraft type j. It is worth to note that, for a given aircraft type j, the sum of X_{mj} for all engine models associated with aircraft j is 1. Once the preceding calculations are performed for each aircraft type, total emissions for that aircraft type are computed by multiplying the emissions for one LTO cycle by the number of LTO cycles at a given location:

$$E_i = (E_{ij} \times LTO_j) \quad (7)$$

where E_{ij} represents the total emissions for pollutant i from aircraft type j and LTO_j the number of LTOs for aircraft type j. The total emissions for each aircraft type are summed to yield total commercial exhaust emissions for the facility according with

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

$$ET_i = \sum_{j=1}^{N}(E_{ij} \times LTO_j) \quad (8)$$

where ET_i stands for the total emissions of pollutant i from all aircraft types, E_{ij} is the emissions of pollutant i from aircraft type j, LTO_j the number of LTOs for aircraft type j, and N the total number of aircraft types.

5.2.3 EEA/EMEP

EEA/EMEP uses a decision tree (Tier 1, Tier 2 and Tier 3) to select the methods for estimating the emissions from aviation that are applicable to all nations (EEA/EMEP, 2009). When estimating aviation emissions, the following should be considered:

- use as detailed information as is available;
- if the source category is a key source, then a Tier 2 or Tier 3 method must be used for estimating the emissions.

The Tier 1 and Tier 2 methodologies are both based on LTO data and the fuel used is assumed equal to the fuel sold. The emission estimation can be made following either the Tier 1 or Tier 2 methodology. For estimating the total emissions of CO2, SO2 and heavy metals the Tier methodology is sufficient, as the emissions of these pollutants are dependent on the fuel only and not technology (EEA/EMEP, 2009). The emissions of PM10 or PM2.5, on the other hand, are aircraft and payload dependent. Therefore, when estimating the total emissions of these pollutants, it may be appropriate to consider the aircraft activity in more details, using the Tier 2 methodology. The Tier 3 methodology may be used to assess an independent estimate of fuel and CO2 emissions from domestic air traffic.

The Tier 1 approach for aviation emissions is based on quantity of fuel consumption data for aviation split by LTO and cruise for domestic and international flights separately. The method uses a simple approach to estimate the split of fuel use between cruise and LTO. This approach was labelled the ‘very simple methodology’. This approach considered emission pollutants SO2, CO2, CO, NOx, NMVOC, CH4, N2O, and PM2.5. The Tier 1 approach for pollutant emissions calculation uses the general equation (EEA/EMEP, 2009):

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

$$E_{pollutant} = AR_{fuel\ consumption} \times EF_{pollutant} \quad (9)$$

where $E_{pollutant}$ is the annual emission of pollutant for each of the LTO and cruise phases of domestic and international flights, $AR_{fuel\ consumption}$ the activity rate by fuel consumption for each of the flight phases and trip types, and $EF_{pollutant}$ the emission factor of pollutant for the respective flight phase and trip type. Tier 1 emission factors ($EF_{pollutant}$ and fuel type) assume an averaged technology for the fleet, and knowledge of the number of domestic and international LTO cycles for the nation. Default emission factors and fuel use (jet kerosene and aviation gasoline) are available in the EEA/EMEP Guidebook 2009.

The Tier 2 approach applies information on LTO per aircraft type but does not take into account other factors as cruise distances. The level of details for this methodology is the aircraft types used for both domestic and international aviation, together with the number of LTO carried out by the various aircraft types. The calculation algorithm, however, is the same as for the Tier 1 approach.

The Tier 3 methodologies are based on actual flight movement data, either for Tier 3A origin and destination (OD) data or for Tier 3B full flight trajectory information. These methodologies are bottom-up, flight-based, rather than top-down calculation-based on the fuel consumed.

Tier 3A takes into account cruise emissions for different flight distances. Hence details on the origin (departure) and destination (arrival) airports and aircraft type are needed to use this approach, for both domestic and international flights. In Tier 3A, inventories are modeled using average fuel consumption and emissions data for the LTO phase and various cruise phase lengths, for an array of representative aircraft categories. The data used in Tier 3A methodology takes into account that the amount of emissions generated varies between phases of flight. The methodology also takes into account that fuel burn is related to flight distance, while recognizing that fuel burn can be comparably higher on relatively short distances than on longer routes. This is because aircraft use a higher amount of fuel per distance for the LTO cycle compared to the cruise phase as shown in Table 5. Tier 3B methodology is distinguished from Tier 3A by the calculation of fuel burnt and emissions throughout the full trajectory of each flight segment using aircraft and engine specific

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

aerodynamic performance information. To use Tier 3B, sophisticated computer models are required to address all the equipment, performance and trajectory variables and calculations for all flights in a given year.

Models used for Tier 3B level can generally specify output in terms of aircraft, engine, airport, region, and global, as well as by latitude, longitude, altitude and time, for fuel burn and emissions of CO, HC, CO2, H2O, NOx, and SOx. To be used in preparing annual inventory submissions, the Tier 3B model must calculate aircraft emissions from input data that take into account air traffic changes, aircraft equipment changes, or any input-variable scenario.

The components of Tier 3B models are ideally incorporated so that they can be readily updated; therefore, the models are dynamic and can remain current with evolving data and methodologies.

EEA/EMEP only described the algorithm of the Tier 3 methodology related to Tier 3A. As for Tier 2, the emission factors are calculated on a flight-by-flight basis using emission factors and the fuel used for all the components of a flight (LTO cycle) available from the accompanying spreadsheet (EEA/EMEP Guidebook 2009) for the representative jet and turboprop aircraft types.

An interesting aspect of the EEA/EMEP approach over the ICAO and EPA counterparts is the evaluation of the uncertainties of the estimated aircraft pollutant emissions, that are closely associated with the emission factors. In fact, it is clearly state that the use of representative emission factors in Tier 1 approach may contribute significantly to the uncertainty, that may lie between 20–30% for LTO and 20–45% for the cruise factors. In Tier 2, a higher uncertainty is assumed in association with the cruise emission factors. In Tier 3, the uncertainty of different LTO factors is approximately 5–10%, while for cruise the uncertainties are assumed to be 15–40%.

5.3 Knowledge gaps

The accuracy of the scheme employed for certificating the emissions of an aircraft can strongly affect the evaluation of its actual impact on local air quality, in particular for what concerns the dispersion of fine (PM2.5, PM1) and ultrafine (<PM1) particulate and the transformation of

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

VOCs and semi-volatile organics into secondary PM. Tier 3B is currently the only approach capable of describing the details of an aircraft's emissions, even though it can be considered more as a paradigm of representation than an proper algorithm in the sense of ICAO and EPA. Future research will be required to produce a considerable amount of experimental and meteorological data, feeding a predictive modelling and dispersion simulation activity that can enhance a large-scale application of the Tier3B approach.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

6 RESEARCH ROADMAP FOR THE IMPACT OF AVIATION ON LOCAL AIR QUALITY

6.1 Impact of aviation on community health

Aviation is a significant and growing source of air pollution, particularly at and around airports. While emissions of regulated pollutants such as NO_x, CO, and VOCs are relatively well characterized, the contribution of particulate matter (PM) – especially ultrafine particles (UFPs) and organic-rich volatile PM – remains insufficiently understood and poorly regulated. Aircraft operations, including taxiing, takeoff, landing, and idling, emit a complex mixture of gaseous and particulate pollutants, with PM2.5 and PM10 being of particular concern due to their established impacts on human health (WHO, 2021).

The chemical composition, sources, transformation processes, and health effects of aviation-related PM are not fully accounted for in current regulatory models such as those by ICAO, EPA, and EEA/EMEP. A more comprehensive understanding and improved tools for prediction and mitigation are urgently needed, especially as exposure to PM2.5 is associated with cardiovascular and respiratory diseases, cancer, and premature mortality (Boldo et al., 2006; Franklin et al., 2007; Kampa & Castanas, 2008; Yim et al., 2013).

6.2 Research Gaps and Strategic Goals

The roadmap aims to obtain data and insights to address the following research gaps:

- (i) **Apportioning PM to individual sources at airports**, including engines, auxiliary power units (APUs), ground support equipment, and aircraft towing;
- (ii) **Specifying the chemical and physical composition of PM**, including primary emissions and secondary organic aerosol formation;
- (iii) **Understanding the broader impact of PM on local communities**, including exposure pathways, health effects, and social vulnerability.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

These goals have to be pursued through a phased research effort combining experimental field campaigns, modeling development, and health impact assessments. This effort is also intended to support the **optimization of standard procedures** for predicting and mitigating pollutant dispersion from aviation activities.

6.3 Roadmap

Studies have shown that aircraft-related emissions produce a high number of UFPs (<100 nm) rich in OC and metals, especially during idling and taxiing (Hudda et al., 2014). However, many current models underestimate or ignore the secondary transformation of these compounds into SOA. A first task of a research roadmap would include the **advanced characterization of PM in airport environments**, based on the in-situ measurements of PM concentrations **and size distributions** (PM10, PM2.5, PM1, UFPs), the analysis of chemical composition of pollutants, emphasizing elemental carbon (EC), organic carbon (OC), metals (e.g., Ni, V, Cr), PAHs, and secondary aerosols (SOA precursors like VOCs). In order to be useful for Tier3B approach, these data should be obtained with mobile platforms (as UAV, for instance), capturing spatial gradients and plume behaviour near runways, taxiways, and residential areas.

From a dispersion modelling point of view, it has to be considered that Standard ICAO/EPA approaches often rely on simplified LTO cycle assumptions, as discussed in chapter 5, overlooking local meteorological variability, that critically influences dispersion, dilution, and transformation of PM plumes, and reverse thrust and long taxi times, that significantly increase PM emissions at low altitudes. These approximations lead to large uncertainties in PM exposure predictions (Mahashabde et al., 2011; EEA/EMEP, 2009), determining the need of **new** sophisticated **models**, **integrating real-time operational and meteorological data** to simulate true dispersion dynamics.

Finally, exposition dynamic and epidemiology deserve more investigations, since chronic exposure to aviation-emitted PM, especially UFPs and metal-rich particles, has been linked to oxidative stress, respiratory inflammation, and cardiovascular dysfunction (He et al., 2018; Jonsdottir et al., 2019) even if few studies differentiate between aviation-specific PM and urban

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

background PM. There is then the need to correctly estimate population exposure to PM using geospatial modeling and **personal monitoring data**, and assessing its impact conducting **in-vitro** toxicology assays (e.g., ROS generation, cytokine release), **in-vivo** studies and performing **epidemiological analysis** in airport-adjacent communities, considering vulnerable subgroups. The objective, from a regulatory point of view, should be the **harmonization of methods** across ICAO, EPA, and EEA/EMEP standards, in particular for PM measurement and reporting, and the **update of LTO-based emissions factors** in order to include UFPs and volatile PM, fully implementing Tier 3B-like methodologies using real-world activity and emissions data.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

REFERENCES

[1] D.S. Lee a, D.W. Fahey, A. Skowron, M.R. Allen, U. Burkhardt, Q. Chen, S.J. Doherty, S. Freeman, P.M. Forster, J. Fuglestvedt, A. Gettelman, R.R. De Le´on, L.L. Lim, M.T. Lund , R.J. Millar, B. Owen, J.E. Penner, G. Pitari, M.J. Prather, R. Sausen, L.J. Wilcox – “The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018” - Atmospheric Environment 244 (2021) 117834.

[2] D.S. Lee, M.R. Allen, N. Cumpsty, B. Owen, K.P. Shine, A. Skowron – "Uncertainties in mitigating aviation non-CO2 emissions for climate and air quality using hydrocarbon fuels" - Environ. Sci.: Atmos., 2023, 3,693. - DOI: 10.1039/d3ea00091e

[3] J.S.. Fuglestvedt1, T.K. Berntsen, Odd Godal, R Sausen, K.P. Shine, T. Skodvin - Metrics of climate change: assessing radiative forcing and emission indices - Climatic Change 58: 267–331, 2003.

[4] C.C. Chen, A. Gettleman – “Simulated radiative forcing from contrails and contrail cirrus” - Atmos. Chem. Phys., 13, 12525–12536, 2013. doi:10.5194/acp-13-12525-2013

[5] L. Bock, U. Burkhardt – “Reassessing properties and radiative forcing of contrail cirrus using a climate model” -J. Geophys. Res. Atmos., 121, 9717–9736, 2016. doi:10.1002/2016JD025112

[6] M. Bickel, M. Ponater, L. Bock, U. Burkhardt, S. Reineke – “Estimating the Effective Radiative Forcing of Contrail Cirrus” - 2020 American Meteorological Society- DOI: 10.1175/JCLI-D-19-0467.1

[7] C.G. Jones et al. – “Bringing it all together: Science and modelling priorities to support international climate policy” – EGUsphere preprint, 2024 - https://doi.org/10.5194/egusphere-2024-453

[8] C.D. Hewitt, F. Guglielmo, S. Joussaume, J. Bessembinder, I. Christel, F. J. Doblas-Reyes, V. Djurdjevic, N. Garrett, E. Kjellström, A. Krzic, M. Máñez Costa, and A. L. St. Clair – "Recommendations for Future Research Priorities for Climate Modeling and Climate Services" – BAMS, https://doi.org/10.1175/BAMS-D-20-0103.1

[9] D. Arhens, Y. Méry, A. Guénard, R. C. Miake-Lye - A New Approach to Estimate Particulate Matter Emissions From Ground Certification Data: The nvPM Mission

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

Emissions Estimation Methodology - Journal of Engineering for Gas Turbines and Power, MARCH 2023, Vol. 145 / 031019-1 - DOI: 10.1115/1.4055477

[10] T. Harlass et al. - Measurement report: In-flight and ground-based measurements of nitrogen oxide emissions from latest-generation jet engines and 100% sustainable aviation fuel - Atmos. Chem. Phys., 24, 11807–11822, 2024 - https://doi.org/10.5194/acp-24-11807-2024

[11] EASA – "Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to the EU Emissions Trading System Directive Article 30(4)" – September 2020.

[12] F. Schröder, B. Kärcher, C. Dujoure, J. Ström, A. Petzold, J.F. Gayet, B. Strauss, P. Wendling, S. Boorman – "On the Transition of Contrails into Cirrus Clouds" – Journal of the Atmospheric Sciences, volume 57, 2000.

[13] Schumann, U., Baumann, R., Baumgardner, D., Bedka, S.T., Duda, D.P., Freudenthaler, V., Gayet, J.-F., Heymsfield, A.J., Minnis, P., Quante, M., Raschke, E.,Schlager, H., V´azquez-Navarro, M., Voigt, C., Wang, Z., 2017. Properties of individual contrails: a compilation of observations and some comparisons. Atmos.Chem. Phys. 17, 403–438. https://doi.org/10.5194/acp-17-403-2017.

[14] Ch. Voïgt, J. Kleine, D. Sauer, R. H. Moore, T. Bräuer, P. Le Clercq, S. Kaufmann, M. Scheibe, T. Jurkat-Witscha, M. Aigner, U. Bauder 4, Y.Boose , S. Borrmann, E. Crosbie, Glenn S. Diskin, Joshua DiGangi3, V. Hahn, Ch. Heckl, Felix Huber, J. B. Nowak, M. Rapp, B. Rauch, C. Robinson, T. Schripp, M. Shook, E. Winstead, L. Ziemba, H. Schlager & B. E. Anderson - Cleaner burning aviation fuels can reduce contrail cloudiness – Communication Earth & Environment, 2021. https://doi.org/10.1038/s43247-021-00174-y

[15] P. Jeßberger, C. Voigt, U. Schumann, I. Sölch, H. Schlager, S. Kaufmann, A. Petzold, D. Schäuble, and J.-F. Gayet - Aircraft type influence on contrail properties - Atmos. Chem. Phys., 13, 11965–11984, 2013. doi:10.5194/acp-13-11965-2013

[16] S. Unterstrasser, N. Görsch (2014) – Aircraft-type dependency of contrail evolution - Geophys. Res. Atmos., 119, 14,015–14,027 - doi:10.1002/2014JD022642.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

[17] B. Kärcher, U. Burkhardt, A. Bier, L. Bock, and I. J. Ford (2015) – The microphysical pathway to contrail formation - J. Geophys. Res. Atmos., 120, 7893–7927, doi:10.1002/2015JD023491.

[18] J. Carles, N. Bellouin, N. Villefranque, J.L. Dufresne – The subtleties of three-dimensional radiative effects in contrails and cirrus clouds- EGUsphere Preprint Repository, 2025 - https://doi.org/10.5194/egusphere-2024-3642.

[19] K. Wolf, N. Bellouin, O. Boucher - Sensitivity of cirrus and contrail radiative effect on cloud microphysical and environment parameters - Atmos. Chem. Phys., 23, 14003–14037, 2023 - https://doi.org/10.5194/acp-23-14003-2023

[20] I.Sanz-Morère, S.. Eastham, R.L. Speth, and S.R. H. Barrett - Reducing Uncertainty in Contrail Radiative Forcing Resulting from Uncertainty in Ice Crystal Properties - Environ. Sci. Technol. Lett. 2020, 7, 371−375

[21] V. Ramaswamy, W. Collins, J. Haywood, J. Lean, N. Mahowald, G. Myhre, V. Naik, K. P. Shine, B. Soden, G. Stenchikov & T. Storelvmo. - Radiative Forcing of Climate: The Historical Evolution of the Radiative Forcing Concept the Forcing Agents and their Quantification, and Applications – Meteorological Monographs, American Meteorological Society, 2019. DOI: 10.1175/AMSMONOGRAPHS-D-19-0001.1.

[22] F. Yu, B. Kärcher, B.E. Anderson - Revisiting Contrail Ice Formation: Impact of Primary Soot Particle Sizes and Contribution of Volatile Particles – Environmental Science & Technology 2024 58 (40), 17650-17660 - DOI: 10.1021/acs.est.4c04340.

[23] B. Kärcher, U. Burkhardt, A. Bier, L. Bock, and I. J. Ford (2015) - Themicrophysical pathway to contrail formation - J. Geophys. Res. Atmos., 120, 7893–7927, doi:10.1002/2015JD023491.

[24] E. Terrenoire, D. Hauglustaine, Y. Cohen, R. Valorso, F. Lefèvre, S. Matthes - Impact of present and future aircraft NOx and aerosol emissions on atmospheric composition and associated direct radiative forcing of climate - Atmos. Chem. Phys., 22, 11987–12023, 2022. https://doi.org/10.5194/acp-22-11987-2022

[25] Y. Cohen, D. Hauglustaine, N. bellouin, M. Tronstad Lund, S. Matthes, A. Skowron, R. thor, U. Bundke, A. Petzold, S. Rohs, V. Thouret, A. Zahn, H. Ziereis - Multi-model

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

assessment of climatologies in the upper troposphere–lower stratosphere using the IAGOS data – Preprint EGUsphere, https://doi.org/10.5194/egusphere-2024-2208.

[26] A. Skowron, D. Lee, R.R. de Leon, L.L. Lim, B. Owen - Greater fuel efficiency is potentially preferable to reducing NOx emissions for aviation's climate impacts - Nature Communications, 2021. https://doi.org/10.1038/s41467-020-20771-3.

[27] V. Grewe, S. Matthes, K. Dahlmann - The contribution of aviation NOx emissions to climate change: are we ignoring methodological flaws? - Environ. Res. Lett. 14 (2019) 121003 - https://doi.org/10.1088/1748-9326/ab5dd7.

[28] Søvde, O.A., S. Matthes, A. Skowron, D. Iachetti, L. Lim, L., Ø. Hodnebrog, G. Di Genova, G. Pitari, D.S. Lee, G. Myhre, I.S.A. Isaksen, Aircraft emission mitigation by changing route altitude: A multi-model estimate of aircraft NOx emission impact on O_3 photochemistry, Atmospheric Environment, 95, 468-479, 2014.

[29] Maruhashi. J, Mariano Mertens, Volker Grewe, Irene C Dedoussi, A multi-method assessment of the regional sensitivities between flight altitude and short-term O_3 climate warming from aircraft NO x emissions , Environmental Research Letters, 10.1088/1748-9326/ad376a, **19**, 5, (054007), (2024).

[30] Clappier, A., Belis, C. A., Pernigotti, D., and Thunis, P.: Source apportionment and sensitivity analysis: two methodologies with two different purposes, Geosci. Model Dev., 10, 4245–4256, https://doi.org/10.5194/gmd-10-4245-2017, 2017.

[31] Fritz, T. M., Eastham, S. D., Speth, R. L., and Barrett, S. R. H.: The role of plume-scale processes in long-term impacts of aircraft emissions, Atmos. Chem. Phys., 20, 5697–5727, https://doi.org/10.5194/acp-20-5697-2020, 2020.

[32] Cariolle, D., Caro, D., Paoli, R., Hauglustaine, D., Cuenot, B., Cozic, A., and Paugam, R.: Parameterization of plume chemistry into large-scale atmospheric models: Application to aircraft NO_x emissions, J. Geophys. Res.-Atmos., 114, D19302, https://doi.org/10.1029/2009JD011873, 2009

[33] Kärcher, B.: A trajectory box model for aircraft exhaust plumes, J. Geophys. Res.-Atmos., 100, 18835–18844, 1995

[34] Boldo, E., et al., 2006. Apheis: health impact assessment of long-term exposure to PM2.5 in 23 European cities. Eur. J. Epidemiol. 21 (6), 449–458.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

[35] Brasseur, G.P., et al., 1998. European scientific assessment of the atmospheric effects of aircraft emissions. Atmos. Environ. 32 (13), 2329–2418.

[36] K. Gierens, L. Lim, K Eleftheratos - A Review of Various Strategies for Contrail Avoidance - The Open Atmospheric Science Journal, 2008, 2, 1-7.

[37] Noppel F, Singh R, Taylor M. Novel engine concept to suppress contrail and cirrus cloud formation. International Conference on Transport, Atmosphere and Climate, Oxford, UK, June 2006.

[38] Burkhardt, U., Bock, L. & Bier, A. Mitigating the contrail cirrus climate impact by reducing aircraft soot number emissions. npj Clim. Atmos Sci. 1, 37, https://doi.org/10.1038/s41612-018-0046-4 (2018).

[39] Ch. Fitcher, S. Marquart, R. Sausen, D.S. Lee - The impact of cruise altitude on contrails and related radiative forcing - Meteorologische Zeitschrift, Vol. 14, No. 4, 563-572 (August 2005).

[40] F. Noppel, R. Singh - Contrail avoidance in the aircraft design process - The Aeronautical Journal, December 2008 volume 112 no 1138.

[41] V. Williams, R.B. Noland - Variability of contrail formation conditions and the implications for policies to reduce the climate impacts of aviation - Transportation Research Part D 10 (2005) 269–280 - doi:10.1016/j.trd.2005.04.003

[42] M. Niklaß, B. Lührs, V. Grewe, K. Dahlmann, T. Luchkova, F. Linke, V. Gollnick - Potential to reduce the climate impact of aviation by climate restricted airspaces - Transport Policy (2017), http://dx.doi.org/10.1016/j.tranpol.2016.12.010.

[43] J. van Manen, V. Grewe - Algorithmic climate change functions for the use in eco-efficient flight planning - Transportation Research Part D 67 (2019) 388–405. https://doi.org/10.1016/j.trd.2018.12.016

[44] D. Avila, L. Sherry, T. Thompson - Reducing global warming by airline contrail avoidance: A case study of annual benefits for the contiguous United States - Transportation Research Interdisciplinary Perspectives 2 (2019) 100033. http://dx.doi.org/10.1016/j.trip.2019.100033.

[45] A. Filippone - Assessment of Aircraft Contrail Avoidance Strategies - Journal of Aircraft Vol. 52, No. 3, May–June 2015.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

[46] R. Teoh, U. Schumann, A. Majumdar, and M. E. J. Stettler - Mitigating the Climate Forcing of Aircraft Contrails by Small-Scale Diversions and Technology Adoption – Environmental Science & Technology 2020, 54, 5, 2941–2950. https://doi.org/10.1021/acs.est.9b05608

[47] S. Matthes, B. Lührs, K. Dahlmann , V. Grewe, F. Linke, F. Yi, E. Klingaman and K. P. Shine - Climate-Optimized Trajectories and Robust Mitigation Potential: Flying ATM4E - Aerospace 2020, 7, 156; doi:10.3390/aerospace7110156.

[48] A.M. Frias, M.L. Shapiro, Z. Engberg, R. Zopp, M. Soler, M.E.J. Stettler - Feasibility of contrail avoidance in a commercial flight planning system: an operational analysis - Environ. Res.: Infrastruct. Sustain. 4 (2024) 015013. https://doi.org/10.1088/2634-4505/ad310c.

[49] A. Borella, O. Boucher, K. P. Shine, M. Stettler, K. Tanaka, R. Teoh, N. Bellouin - The importance of an informed choice of CO2-equivalence metrics for contrail avoidance - Atmos. Chem. Phys., 24, 9401–9417, 2024. https://doi.org/10.5194/acp-24-9401-2024

[50] Teoh, R., Schumann, U., Gryspeerdt, E., Shapiro, M., Molloy, J., Koudis, G., Voigt, C., and Stettler, M. E. J.: Aviation contrail climate effects in the North Atlantic from 2016 to 2021, Atmos. Chem. Phys., 22, 10919–10935, https://doi.org/10.5194/acp-22- 10919-2022, 2022.

[51] R. Sausen, S. Hofer, K. Gierens1, L. Bugliaro, R. Ehrmanntraut, I. Sitova, K. Walczak, A. Burridge-Diesing, M. Bowman and N. Miller - Can we successfully avoid persistent contrails by small altitude adjustments of flights in the real world? - Meteorol. Z. (Contrib. Atm. Sci.), Vol. 33, No. 1, 83–98., 2023. DOI 10.1127/metz/2023/1157.

[52] A. Sonabend, C. Elkin, Th. Dean, J. Dudley, N. Ali, J. Blickstein, E. Brand, B. Broshears, S. Cheng, Z. Engberg, M. Gaylen, S. Geraedts, N. Goyal, R. Grenham, U. Hager, D. hecker, M. Jany, K. McCloskey, J. Ng, B. Norris, F. Opel, J. Rothenberg, T. Sankar, D. Sanekommu, A. Sarna, O. Schütt, M. Shapiro, R. Soh, Ch. Van Arsdale & J.C. Platte - Feasibility test of per-flight contrail avoidance in commercial aviation - Communications Engineering | (2024) 3:184. https://doi.org/10.1038/s44172-024-00329-7.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

[53] S. Hofer, K. Gierens, and S. Rohs - How well can persistent contrails be predicted? An update - Atmos. Chem. Phys., 24, 7911–7925, 2024. https://doi.org/10.5194/acp-24-7911-2024

[54] G. Thompson, C. Scholzen, S. O'Donoghue, M. Haughton, R. L. Jones, A. Durant, C. Farrington - On the fidelity of high-resolution numerical weather forecasts of contrail-favorable conditions - Atmospheric Research 311 (2024) 107663. https://doi.org/10.1016/j.atmosres.2024.107663.

[55] A. T. Rose-Tejwani, L. Sherry and K. Ebright - Comparison of Identified Ice Supersaturated Regions for Contrail Avoidance Using Three Standard Weather Forecast Databases - Atmosphere 2025, 16, 149. https://doi.org/10.3390/atmos16020149

[56] F. Baneshi, M. Cerezo-Magana, M. Soler - Network-level aircraft trajectory planning via multi-agent deep reinforcement learning: Balancing climate considerations and operational manageability - Expert Systems With Applications 271 (2025) 126604.

[57] C. O. de Burgh-Day, T. Leeuwenburg - Machine learning for numerical weather and climate modelling: a review – EGU, Geoscientific Model Development, volume 16, issue 22 (2023) - https://doi.org/10.5194/gmd-16-6433-2023.

[58] V. Grewe, C. Frömming, S. Matthes, S. Brinkop, M. Ponater, S. Dietmüller, P. Jöckel, H. Garny, E. Tsati, O. A. Søvde, J. Fuglestvedt, T. K. Berntsen,K. P. Shine, E. A. Irvine, T. Champougny, and P. Hullah - Aircraft routing with minimal climate impact: the REACT4C climate cost function modelling approach (V1.0) - Geosci. Model Dev., 7, 175–201, 2014. doi:10.5194/gmd-7-175-2014.

[59] F. Yin, V. Grewe, F. Castino, P. Rao, S. Matthes, K. Dahlmann, S. Dietmüller, Ch. Frömming, H. Yamashita, P. Peter, E. Klingaman, K. P. Shine, B. L¨hrs, F. Linke - Predicting the climate impact of aviation for en-route emissions: the algorithmic climate change function submodel ACCF 1.0 of EMAC 2.53 - Geoscience Model Dev., 16, 3313–3334, 2023. https://doi.org/10.5194/gmd-16-3313-2023.

[60] EEA/EMEP. Emission Inventory Guidebook; 2009.

[61] EPA. Evaluation of Air Pollutant Emissions from Subsonic Commercial Jet Aircraft; 1999 Apr. Report No.: EPA 420-R-99-013.

CLEAN AVIATION

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

[62] FAA. Aviation & Emissions A Primer. Office Environment and Energy; 2005.

[63] Franklin, M., Zeka, A., Schwartz, J., 2007. Association between PM2.5 and all-cause and specific-cause mortality in 27 US communities. J. Expo. Sci. Environ. Epidemiol. 17 (3), 279.

[64] He, R.W., Shirmohammadi, F., Gerlofs-Nijland, M.E., Sioutas, C. and Cassee, F.R., 2018. Pro-inflammatory responses to PM0. 25 from airport and urban traffic emissions. Science of the total environment, 640, pp.997-1003.

[65] C.D. Hewitt, F. Guglielmo, S. Joussaume, J. Bessembinder, I. Christel, F. J. Doblas-Reyes, V. Djurdjevic, N. Garrett, E. Kjellström, A. Krzic, M. Máñez Costa, and A. L. St. Clair – "Recommendations for Future Research Priorities for Climate Modeling and Climate Services" – BAMS, https://doi.org/10.1175/BAMS-D-20-0103.1

[66] Hudda, N., Simon, M.C., Zamore, W., Brugge, D. and Durant, J.L., 2016. Aviation emissions impact ambient ultrafine particle concentrations in the greater Boston area. Environmental science & technology, 50(16), pp.8514-8521.

[67] ICAO. Airport Local Air Quality Guidance Manual; 2007a.

[68] ICAO. Environmental Report; 2007b.

[69] Janić, M., 1999. Aviation and externalities: the accomplishments and problems. Transport. Res. Transport Environ. 4 (3), 159–180.

[70] Jonsdottir, H.R., Delaval, M., Leni, Z., Keller, A., Brem, B.T., Siegerist, F., Schönenberger, D., Durdina, L., Elser, M., Burtscher, H. and Liati, A., 2019. Non-volatile particle emissions from aircraft turbine engines at ground-idle induce oxidative stress in bronchial cells. Communications biology, 2(1), p.90.

[71] Kampa, M., Castanas, E., 2008. Human health effects of air pollution. Environ. Pollut. 151 (2), 362–367.

[72] Kinsey, J.S., 2009. Characterization of emissions from commercial aircraft engines during the Aircraft Particle Emissions eXperiment (APEX) 1 to 3. Office of Research and Development, US Environmental Protection Agency.

[73] Kinsey, J.S., Dong, Y., Williams, D.C. and Logan, R., 2010. Physical characterization of the fine particle emissions from commercial aircraft engines during the Aircraft Particle Emissions eXperiment (APEX) 1-3. Atmospheric Environment, 44(17), pp.2147-2156.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

[74] Kinsey, J.S., Hays, M.D., Dong, Y., Williams, D.C. and Logan, R., 2011. Chemical characterization of the fine particle emissions from commercial aircraft engines during the Aircraft Particle Emissions eXperiment (APEX) 1 to 3. Environmental science & technology, 45(8), pp.

[75] Lee, D.S., Pitari, G., Grewe, V., Gierens, K., Penner, J.E., Petzold, A., Prather, M.J., Schumann, U., Bais, A., Berntsen, T. and Iachetti, D., 2010. Transport impacts on atmosphere and climate: Aviation. Atmospheric environment, 44(37), pp.4678-4734.

[76] D.S. Lee, M.R. Allen, N. Cumpsty, B. Owen, K.P. Shine, A. Skowron – "Uncertainties in mitigating aviation non-CO2 emissions for climate and air quality using hydrocarbon fuels" - Environ. Sci.: Atmos., 2023, 3,693. - DOI: 10.1039/d3ea00091e

[77] Mahashabde, A., et al., 2011. Assessing the environmental impacts of aircraft noise and emissions. Prog. Aero. Sci. 47 (1), 15–52.

[78] Masiol, M. and Harrison, R.M., 2014. Aircraft engine exhaust emissions and other airport-related contributions to ambient air pollution: A review. Atmospheric Environment, 95, pp.409-455.

[79] Mazaheri, M., Johnson, G.R. and Morawska, L., 2011. An inventory of particle and gaseous emissions from large aircraft thrust engine operations at an airport. Atmospheric Environment, 45(20), pp.3500-3507.

[80] I.Sanz-Morère, S.. Eastham, R.L. Speth, and S.R. H. Barrett - Reducing Uncertainty in Contrail Radiative Forcing Resulting from Uncertainty in Ice Crystal Properties - Environ. Sci. Technol. Lett. 2020, 7, 371−375

[81] Smith, L.D., Allan, J., Coe, H., Reyes-Villegas, E., Johnson, M.P., Crayford, A., Durand, E. and Williams, P.I., 2022. Examining chemical composition of gas turbine-emitted organic aerosol using positive matrix factorisation (PMF). Journal of Aerosol Science, 159, p.105869.

[82] United States Environmental Protection Agency (USEPA), 1992. Procedures for Emissions Inventory Preparation, vol. IV Mobile Sources.

[83] WHO, 2021. Air quality guidelines: Global update 2021.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union

[84] Yim, S.H., Stettler, M.E. and Barrett, S.R., 2013. Air quality and public health impacts of UK airports. Part II: 668 Impacts and policy assessment. Atmospheric environment, 67, pp.184-192.

[85] Yu, Z., Timko, M.T., Herndon, S.C., Richard, C., Beyersdorf, A.J., Ziemba, L.D., Winstead, E.L. and Anderson, B.E., 2019. Mode-specific, semi-volatile chemical composition of particulate matter emissions from a commercial gas turbine aircraft engine. Atmospheric Environment, 218, p.116974.

[86] Zhu, Y., Fanning, E., Yu, R.C., Zhang, Q. and Froines, J.R., 2011. Aircraft emissions and local air quality impacts from takeoff activities at a large International Airport. Atmospheric Environment, 45(36), pp.6526-6533.

The project is supported by the Clean Aviation Joint Undertaking and its members.

Funded by the European Union, under Grant Agreement No 101140632. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Clean Aviation Joint Undertaking. Neither the European Union nor Clean Aviation JU can be held responsible for them.

Co-funded by the European Union